Volume 1

Construction Research Congress 2010

Innovation for Reshaping Construction Practice



Proceedings of the
2010 Construction Research Congress

Edited by
Janaka Ruwanpura, Ph.D.
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VOLUME ONE

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Preface

We are very pleased to welcome you to the 2010 Construction Research Congress sponsored by the Construction Institute (CI) of the American Society of the Civil Engineers (ASCE) and the University of Alberta, in collaboration with the University of Calgary and the Canadian Society for Civil Engineering. The 2010 Construction Research Congress is being held at the Fairmont Banff Springs in Banff, Alberta, Canada - one of Canada's premiere hotels in the heart of the Canadian Rockies.

The theme of the Congress is "Innovation for Reshaping Construction Practice". The Congress aims to provide academics and industry professionals a forum to present and discuss revolutionary research findings, technological advances, emergent trends, and functional characteristics that are shaping the future of the architecture-engineering-construction industry. The purpose of the Construction Research Council is also to advance engineering knowledge and practice related to construction through stimulating and guiding research and assisting the financing thereof; to interpret and promote the utilization of the findings of research for the construction industry; and to identify future needs in the construction field and publicize them to stimulate appropriate research.

The two-volume Proceedings contain 156 peer reviewed papers covering the following 15 general state-of-knowledge research areas in construction engineering and management. There were 259 abstracts initially submitted that were reduced to 169 accepted draft papers following a peer review. From this, a final 156 papers were accepted for publication and presentation based on the same peer review process used in selecting abstracts.

- Automated/Real-Time Systems
- Construction Modeling and Simulation
- Disaster Planning and Mitigation
- Information Technology and Computer Applications
- Infrastructure Management and Underground Construction
- Knowledge Management
- Productivity, Benchmarking and Workforce Issues
- Organizational Leadership and Management
- Procurement, Contracting and Legal Affairs
- Project Planning and Control
- Project Risk Assessment and Management
- Quantitative Methods and Models
- Sustainable Construction and Facilities
- Construction Education
- CII Research

We are delighted to see that this event is truly global with representation from 14 countries including Australia, Canada, China, Egypt, Hong Kong, India, Indonesia, Korea, Netherlands, Saudi Arabia, Taiwan, Turkey, United Kingdom and United States.

We believe that you enjoy these Proceedings and have a memorable experience of both the Congress and spectacular Banff.

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3D Visualization for Tunnel Boring Machine Steering and Alignment Control in Microtunneling

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Abstract:

On tunneling projects, a tunnel boring machine (TBM) operator heavily counts on experiences to steer TBM and control tunnel alignment, which can be error prone due to lack of visualization of the underground working environment. Any alignment errors may considerably increase the chances of a TBM accidentally ramming into unexpected man-made barriers or hidden boulders, potentially damaging the drill bits of the TBM or even causing the TBM to be trapped underground. To improve the situation, an innovative TBM guidance system was developed by integrating automated site data collection technologies and 4D construction planning models. The as-designed tunnel, the existing facilities nearby are integrated in a 4D production model, and the data collected by total station and sensors are transformed to kinematic parameters through on-line computing which generates a 3D graphic interface for visualizing the underground situation and the orientations of the rear and cutter head of the working TBM.

Keywords: TBM; Alignment control; Automated data collection; 3D visualization

1. Introduction

As hardware and software for computer graphic processing advance, visualization technologies have expanded applications in science, education, entertainment, and engineering. The Architecture, Engineering and Construction (AEC) industry is also applying visualization technologies for improvement in various processes of a construction project, including but not limited to: architectural design and structural analysis, project planning and management, monitoring, inspection, and construction equipment teleoperation.

The visual perception is the main source of information that operators rely on for making decisions on controlling construction equipment. However, in contrast with construction aboveground, the underground workspace situation can not be

sensed through operators' naked eyes.

The alignment control is crucial for tunneling in a complicated underground space that is composed of a mixture of sand, clay, boulders and artificial obstructions. The Pipe Jacking Association (PJA, 1995) recommends that the acceptable tolerance for pipe jacking project is ±50 mm of a true line and ±75 mm of true level. Although a modern TBM is designed to tackle various ground conditions likely to be encountered, the TBM's head would tend to drill faster toward softer materials in the event of encountering boulders or manmade obstructions in the soft ground. If such abnormal rotations of TBM are not detected and corrected in a timely fashion, the TBM may rotate its body in unexpected and undesirable ways, potentially causing the TBM to be damaged or even trapped under the ground. In consequence, replacement of the damaged parts of the TBM or rescue of the stalled TBM would be time-consuming and costly, severely affecting project progress.

In current TBM guidance systems, the position and orientation of the TBM can be continuously tracked by instruments, such as laser, inclinometer, compass, and total station etc. However, the representation of the tracking information is largely two dimensional graphics that show the position of the laser point projected at the rear of the TBM and the dashboards that read the three orientation angles of the rear part of TBM(Yaw, Pitch and Roll in Figure 1, where the Y axis is the direction of TBM drilling). Figure 2 shows a TBM control station with a CCTV monitor, several dashboards and control switches.

Traditionally, when an operator detects that the lasor point deviates from the as-designed center, he will read the angles shown in the dashboards and imagine the complex status of the TBM by synthesizing all the parameters in his brain, so

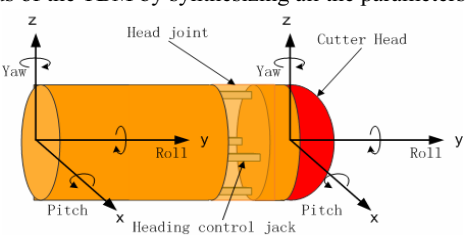


Figure 1. Three orientation angles at the rear and cutter head of the TBM



Figure 2. TBM control station

as to make decisions on how to adjust the heading control jacks to correct any

deviations. Due to the lack of straightforward visuals in three dimensions (3D), the operator heavily counts on experiences to steer TBM and control tunnel allignment, which is error prone. In contrast, the on-line 3D visulization can exactly show the orientation angles of the cutter head and the rear body of the TBM and relative angles bettwen them and the as-designed center line. All can be viewed by changing viewing positions, orientations, and by different zooming patterns.

Futhermore, the current visualization systems for TBM control are developed to cater for specific surveying systems, making it difficult to be used in a variety of scenarios. For example, the information important to TBM drilling operations such as the existing utilities in the vicinity of the designed tunnel cannot be easily modeled into the current TBM guidance visualization systems.

The theme of this research is to develop a generic framework for on-line 3D visualization of construction equipment operations by integration of computer graphic technology with automated data collection systems. In the following sections, the research background will be first described. Then a generic approach used for developing the on-line 3D visualization system for TBM alignment control is presented, followed by a detailed discussion on the issues involved in practical application process. Lastly, the developed system and the TBM steering simulation interface are presented.

2. Literature Review

Many emerging technologies such as robot, laser scanner, global positioning systems (GPS), total station, wireless networks etc. have been used for improving construction equipment control, among which computer supported visualization systems are widely applied to track the machine status and to maintain site situational awareness. Seo et al. (2000) addressed the development of graphical control interfaces with real-time updated graphical models of equipment and work environments. They also classified the architecture of graphical control interfaces into two categories, namely active and passive. Compared with passive graphical control interface, the active graphical control interface can directly control the equipment based on the preplanned and simulated operation. Although the active graphical control interface plays an important role in autonomous construction equipment systems which improve productivity and safety, it is required to model the entire objects in the workspace that could potentially affect the equipment operation.

In general, the models relevent to workspace will not be created during the design stage. Moreover, modeling the exact workspace is difficult in the complex construction environment due to the fast changing site situation and the uncertainty of underground soil profile. As suggested by Seo et al. (2000), when complete work environment models are not available, a passive graphical interface becomes a more appropriate approach. The passive type interfaces are more appropriate for the TBM steering in that (1). the operation is relatively simple; (2). the complete work environment models are not available and the

TBM operator in the control room must resort to on-line visual feedback frequently so to make critical decisions.

In the passive graphical control interface scheme, the operator controls the equipment based on graphical representations of the current status of equipment and work environments updated by sensor data. Seo et al. (2007) presented a tele-operated clinker clearing robot, in which a graphics technique was used to control the robot from a remote distance. Hirabayashi et al. (2006) integrated the visualization of haptic image, force feedback, and similar figure controller for teleoperation of an underwater construction machine. Their experiments demonstrated that the teleoperated control systems with computer aided visual aids are effective under the condition that the availability of direct visual information is not expected. While these systems prove that computer aided visualization of construction work environments and equipment statuses can improve equipment operations, the approach to leverage automated real-time quality control is yet to be developed for integrating the as-designed product model, the specifications of product dimensions and positions, and the as-built data.

The concept of the as-designed and the as-built integration in construction is motivated by the emerging data collection technologies such as laser scanner, embedded sensors, robotic total station and the advances made in integrated project models like 3D/4D CAD in AEC industry. Bernold (2002) proposed the integration of as-designed CAD data with the real-time site information, formalizing the concept of spatial integration in construction by giving three examples, namely, (1). remote position control; (2). design-integrated excavation; (3). design-integrated craning.

In order to leverage the as-built and as-designed integration for construction quality control, Akinci et al. (2006) proposed a formalism which has a project model composed of as-planned, as-built, specification, and defect models. The approach presented in this paper integrates the as-designed model, the specification model, and real-time data captured in the field to visualize the TBM tunneling process in 3D. However, instead of as-built construction product modeling, our approach is focused on visualization of the construction equipment and its interaction with the working environment. The proposed approach is intended to improve the construction equipment control process, enabling equipment operators to take timely corrective actions on any deviation detected by the on-line defects visualization model to avoid further build-up of defects.

3. Overview of the Approach

Although the approach presented in this paper is for improving TBM alignment control during tunneling operations, the system developed is a generic platform that can be adapted for other equipment. Figure 3 describes the architecture of the on-line 3D graphic control system for improving equipment handling and quality control during the course of construction operations.

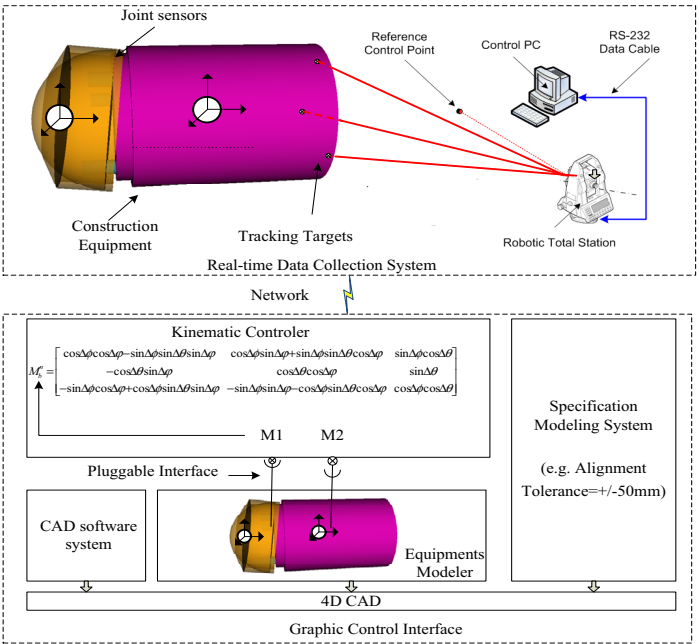


Figure 3. Architecture of the on-line 3D construction equipment control system

The system consists of a 4D CAD platform that enables on-line updating of the 3D models of the construction products and equipment over the timeline to reflect the current, as-built situation. The static models such as the as-designed products and existing facilities in the vicinity of an equipment can be imported from 3D CAD software such as AutoCAD, ArchiCAD, Google Sketch Up and Microstation etc. At present, the commercially available 4D CAD packages are so powerful that they can support various 3D formats, e.g. the Autodesk Navisworks 2010 can support more than forty formats. Nonetheless, there are few commercial 4D CAD systems that can support equipment modeling with kinematic control functions. In this research, we extended an in-house developed 4D CAD system, based on which an equipment modeler and a kinematic controller are developed to support the on-line visualization of the TBM tunneling process.

The equipment modeler enables the modeling of 3D equipment that can be manipulated with forward and inverse kinematic algorithms. However, different types of construction equipment have different joint configurations, and the structures of data captured also vary with the data collection technologies. Thus, the kinematic control algorithms are diverse. In order to develop a flexible and extensible system, we separate the kinematic controller from the equipment modeler and to link them with pluggable interfaces. The data collected by mutiple sensors are translated into the parameters of a kinematic algorithm through on-line

computing, which generates the geometric transformation matrices to control the orientation, position and joint angles of an equipment model. In order to compare the as-built with the as-designed models by 3D visualization, the specification on installation tolerances are modeled in 3D by using the specification modeling module.

The above as-designed, as-built and specification modules are integrated in a 4D CAD environment to generate the 3D graphic control interface for equipment operation control. The following sections further elaborate the approach for TBM alignment control.

3.1 Kinematic Controller

The kinematic controller determines the motion of an articulated equipment consisting of a set of rigid segments connected with joints based on the data collected and the forward and inverse kinematic algorithms. The forward kinematic algorithms generate the pose of the equipment given particular angles between joints. The inverse kinematic algorithms determine the joint angles given the desired configuration of the equipment. Compared with the forward kinematic problem, the inverse kinematic problem is much more difficult, which in general does not have analytical solutions. However, inverse kinematics may be solved via nonlinear programming techniques (Kamat and Martinez 2005).

In the case of the passive graphical interface for equipment control, in theory all the data required to determine the joint angles can be collected by using proper sensors. However it will drive up the system's cost while compromising the system's reliability. In practice, the one who designs the kinematic controller should make best efforts to use inverse kinematic algorithm so as to reduce the burden on data collection in the field. In order to calculate the kinematic parameters of TBM, we propose that three targets at the rear and the heading control jacks are monitored with automated data collection systems.

3.2 Data Collection System

When the control goals are identified and the kinematic controller is designed, the data required will be determined. Then one can select appropriate data collection methods, sensors and make a detailed data collection plan, such as the data collection frequency, communications, power supply, and sensors distribution.

The pipeline installation tolerances on tunneling projects are small thus requiring accurate data collection methods for control purpose. Nowadays, total stations have replaced transits and theodolites, increasingly becoming the predominant instrument used in the surveying practice (Ghilani and Wolf 2008). A modern total station can function like a surveying robot capable of (1) automatic target recognition (ATR) and (2) automatic target tracking directed by preprogrammed surveying procedures. Considering their automatic functions and high precision in surveying results, robotic total stations are used for collecting the data required by the 3D TBM alignment control system. The TBM alignment control needs several points to be automatically surveyed by a robotic total station

in high precision, and the more points to be tracked, the more time to be incurred for one cycle of surveying. In order to determine the attitudes of the TBM in the 3D underground space, at least three points should be tracked continuously. The methods used to transform the points to TBM attitudes can be found in Shen et al. (2009).

The time for tracking the three targets in one cycle is around 30 seconds, which means the 3D visualization system will update the status of TBM every half a minute. In some cases, for example, large scale steel components installation, real-time control is important, then several total stations can work in sychronization to track the targets. However, for TBM allignemnt control, considering the speed of progression is 2 to 15 meters per day depending on soil conditions, a fast update rate is not required. One total station is sufficient for TBM tracking and data collection in commonly seen straight drives.

3.3 Specification of Tolerances

Specification modeling enables defects detection by on-line 3D visualization, and releases the operators from looking up or recalling the specifications during the operation process. Different projects may have different tolerance requirements, hence the specification modeler should be flexible and scalable. Parametric modeling techniques can be appropriate for the modeling of tunneling projects' specifications. As shown in Figure 4 the tolerances on pipeline installation can be modeled as a cylinder with a larger diameter encaptulating the pipe being installed. The diameter difference between the two cylinders is the allowable tolerance on the pipeline alignment. By parametric modeling, the diameter of the tolerance cylinder can be easily changed to cater for different requirements on different projects. It also enables operators to specify a tolerance cylinder with a smaller diameter than the maximum tolerance allowable so as to achieve a higher accuracy.

Compared with 2D visualization of the specification, the proposed 3D visualization approach can give the operators direct guidance on the combined deviations in alignment (line and level) and TBM orientation. The left hand part of

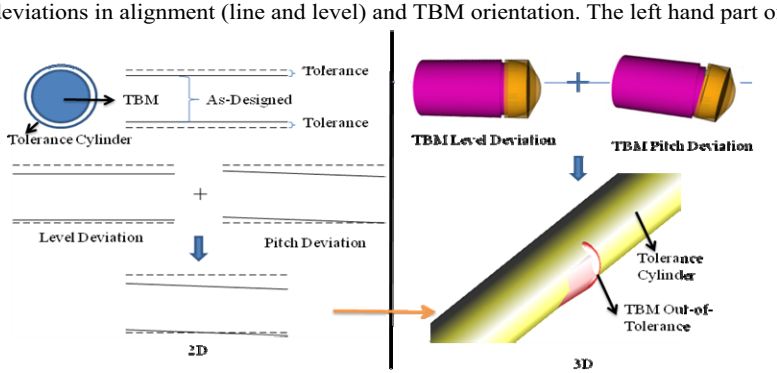


Figure 4: Demonstration of two combined deviations

Figure 4 illustrates a simple case with level and pitch deviations that can be visualized by 2D as well as 3D model. However, when a more complex deviation occurs (e.g. combining yaw, pitch, level and line, as shown in the right hand part of Figure 4 which has incurred orientation angles at the rear and cutter head of TBM), it's impossible to be visualized in one 2D graphic, in which case, complex calculations are required to determine whether the TBM is out-of-tolerance. In the 3D visualization system, all combined deviations can be automatically computed in the kinematic algorithms and visualized in an integrated view with different colours highlightling the out-of-tolerance deviations.

4. System Development and Simulation

To validate the presented approach, an on-line visualization system for TBM alignment control is developed. Figure 5 shows the graphical control interface of the system. On the left is the 3D view window that shows 3D models, such as the existing piles, the shaft, the tolerance cylinder and the TBM which is undergoing "out-of-tolerance" operations at the moment. An operator can adjust the angles of the view by clicking the buttons on the left toolbar, and can also zoom in and out using the buttons on the top toolbar. The right hand side of the user interface contains the two modules, namely, the kinematic controller and the data receiver that link to the site data collection system.

The three targets' coordinates are automatically collected by a total station which is linked with a control laptop via a RS232 serial cable. The total station is controlled by a computer program developed in-house, which provides an interface to initialize the total station, enter tracking commands, and perform on-line data processing (Shen et al. 2009). The data for 3D visualization of the cutter head is sourced from the heading control jacks system.

There are three virtual dashboards showing yaw, pitch and roll angles of the cutter head in Figure 5. The orientation of the cutter head which is important visual information to support the operator on TBM control is automated computed

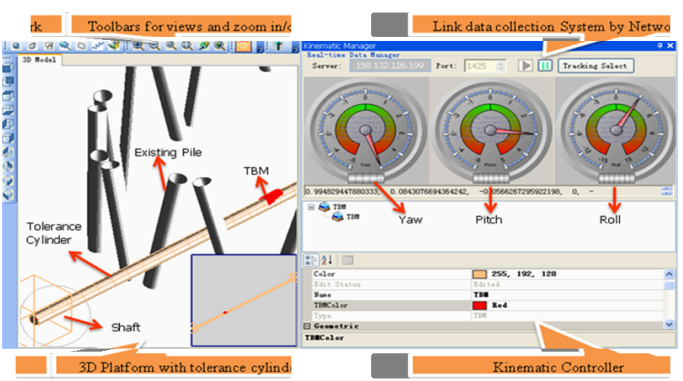


Figure 5. Graphical control interface of the TBM alignment control system

based on the lengh of heading control jacks result from the push-pull operation. In current TBM system, the operators need to estimate the orientations based on their experiences so as to adjust the heading control jacks. In order to give TBM operators guidance on how to control the jacks, the proposed system provides simulation interface.

An operator can use the system to simulate the control of each heading control jack. The system will immediately update the 3D model based on the input of simulation parameters. As shown in the Figure 6, the snapshot (a) shows the status of TBM without cutter head orientations, and the snapshot (b) and (d) show the results from pushing two heading control jacks respectively, and the snapshot (c) show the results from drawing back nother heading control jack. When the rear of TBM has roll angle, it's very difficult for operator to obtain the orientations of the cutter head without the support of the 3D visualization system. In constrast, an operator can verify his decision before pushing the real buttons on the TBM control system by using the developed system. Furthermore, the system can avoid the problem caused by being unaware of the limited orientation capacity of the cutter head, in which case it may be difficult to correct the excessive deviations of the tunnel alignment.

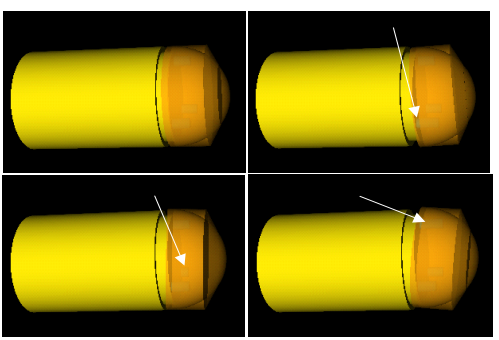


Figure 6. Simulation of the heading control jacks

5. Conclusions and Future Work

The advancement in field data capture and 3D/4D technologies has enabled the on-line 3D visualization of construction equipment operations. However, due to the dynamic nature of the construction environment, applications in construction should be well designed, tested and formalized. This paper has reported an ongoing research of formalizing a generic framework for developing passive graphic control interfaces for construction equipment control, based on which a on-line 3D visualization system for TBM alignment control in tunneling is developed. The system can support the TBM operator on making timely decisions to adjust the heading control jacks. The system will be more useful for complicated TBM systems that have several articulated joints and applied in the tunnel projects with the design of curves. The proposed approach can also be

applied to other fields that need accurate positioning control during construction, for example, the assembly of large-scale structural steel components.

The authors' on-going research will test the visualization system in the field and also will explore on extending the visualization system to be an autonomous TBM navigation system in the near future. There are also some opportunities to link the on-line 3D visualization system to project management tasks. Because the proposed approach integrates the as-design model of the tunnel, the quantity of excavated soil can be calculated automatically based on the progress data continually collected, and such information can be used for an automated material and cost tracking that assists in project management.

6. Acknowledgement

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Automated Multiple Objects Tracking System (AMOTS)

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Abstract

A contractor usually employs observers or employees to collect information from construction sites to verify the progress. The accuracy level of these field data significantly decreases because of the human errors and limitations in data availability. This paper describes a novel conceptual model called "Automated Multiple Objects Tracking System (AMOTS)" using latest technologies such as audio and video surveillance. The system tracks objects (workers, tools, etc.) based on the characteristics of the objects (unique shape of the objects and the unique sound patterns of the tools). A well-known correlation method and image subtraction method are applied to detect and differentiate the objects of the site. AMOTS also measures the real time work performance of the workers.

Introduction

Technologies have increasingly been used in many applications in different fields, such as geotechnical, biomedical engineering and aviation. Even though the construction industry is one of the most influential sectors of the economy in any nation, it has made relatively limited progress in adaptation of these technologies. Construction field is identified as being deficient in the use of cutting edge technologies and data acquisition systems to improve performance and productivity of construction projects (Hewage and Ruwanpura 2008). As a result of that, most of the construction companies do not have a reliable information database to assess the ongoing construction progress. A contractor usually employs observers or employees to collect information from construction sites to verify the progress. The accuracy level of these field data significantly decreases because of the human errors and limitations in data availability. This paper describes a novel conceptual model termed the "automated multiple objects tracking system (AMOTS)" using latest technologies such as audio and video surveillance. Intelligent automated audio visual surveillance system aims to provide an attention-focussing filter to enable the system to extract necessary onsite information. Accurate data is required not only to monitor and control current projects, but also to update the historic database. Such accurate complete information can also provide feedback to designers and planners for future projects in terms of cost, schedule, labour allocation, etc. This paper explains an

integrated system to automatically capture site data using a number of sources to assess worker performance and productivity.

Background

A number of attempts have been made to develop systems for collecting data by researchers for construction management. For an example, a site inspector used a pen-based computer to input image information for a Field Inspection Reporting System (Rojas & Songer, 1997). This particular system sends inspection data to the internet web server to store in a common database, which is accessible to all parties involved in the project. Using a similar concept, a video camera and a microphone connected to a pen-based notebook computer were mounted on a hard hat (Liu 1997), which could be worn by site personnel while walking on site. The data was transferred by means of a wireless network to a desktop server in the site office. This device had the advantage of transferring images to remote experts in real time. Several of these systems were developed for analyzing the data after they were collected and input by the user. Some of the automatic data acquisition systems developed in the past, has limitations and may be applied only in certain circumstances or for a specific construction process (Ghandour 2007).

Furthermore, surveillance and web cameras have been used to monitor certain activities (for example, tracking of a hopper and a hook in concrete placement). The detection in this case was based on one characteristic of the activity, large motion of the hopper, and the properties of the hook (Almassi and McCabe 2008). That is a fully automated system focused only on a specific task and it did not demonstrate the capability to measure human activities.

An automated system which can analyse human poses for the determination of construction productivity in real-time was developed recently (Peddi et al. 2009). In that system, built-in neural network determines the working status of a worker by comparing in-coming images to the developed human poses. The labour productivity is determined from the comparison statistics. This system can only be applied for the selected activities which have specific/unique human poses when workers get involved in the work.

According to the work carried out by previous researchers, the author was able to find a knowledge gap in the following untouched areas. (a) Measuring work performance by analysing real time on site audio (b) Tool usage and the worker movement path

Summary of objectives

The primary objective of this study outlined in the paper is to develop a fully automated worker and tool sound tracking system using integrated audio and video signal processing techniques to extracts real-time information about construction work activities and worker movement patterns without any human involvement to enhance the construction productivity. Furthermore, the study focuses on measuring the tool time and the performance of construction workers.

This paper outlines the concepts of extracting the necessary on-site construction related real-time information from video files and audio files by using signal-processing techniques. This paper presents the conceptual details about how to track human figures from cameras and to use audio files to assess tool time. Figure 1 shows the general equipment arrangement of the proposed methodology. Conceptual research strategies to achieve the objectives are discussed in the paper.

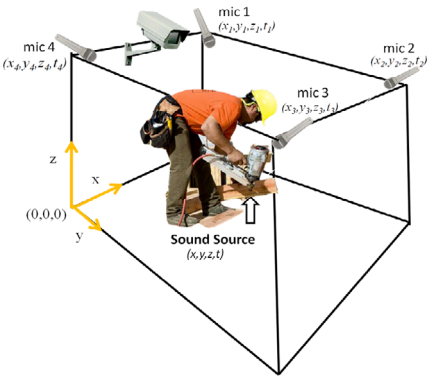


Figure 1: General equipment setup of the work space

Methodology of Tracking:

This study is about a real time and fully automated system using signal processing techniques for data extraction from audio and video files of construction activities This data extraction system is developed to detect the construction workers and their movements within a given work area to measure tool time and to assess worker productivity. The software used for processing the images is MATLAB. The AMOTS images are obtained from a high-end surveillance camera at a resolution of 640x480 pixels. Figure 2 shows the summary of the methodology using a flowchart.

Following assumptions are made for research purposes (1) All the site personnel use similar shaped hard hats when they are on site. (2) All the site personnel follow correct colour coded hard hats according to their job title. [Ex: yellow hard hats for labours, white hard hats for supervisors, etc]. In brief, the system tracks human figures of the video by detecting the hard hat shape. Then the tracked human is differentiated according to the colour of the hard hat. Audio sound monitoring is used to recognize the work activity of each worker and to track the location of the sound source. Consequently, location of each worker and the tool sounds are analysed. Following conditions are used to recognize the activity of each worker; (a) Closeness of the coordinates of workers and tools (b) orientation of the hard hat [if someone works with a tool, orientation of the hard hat should be towards the tool]. Furthermore, tool time of a worker is determined by analysing the time of occurrences of each tool sound at a given time period.

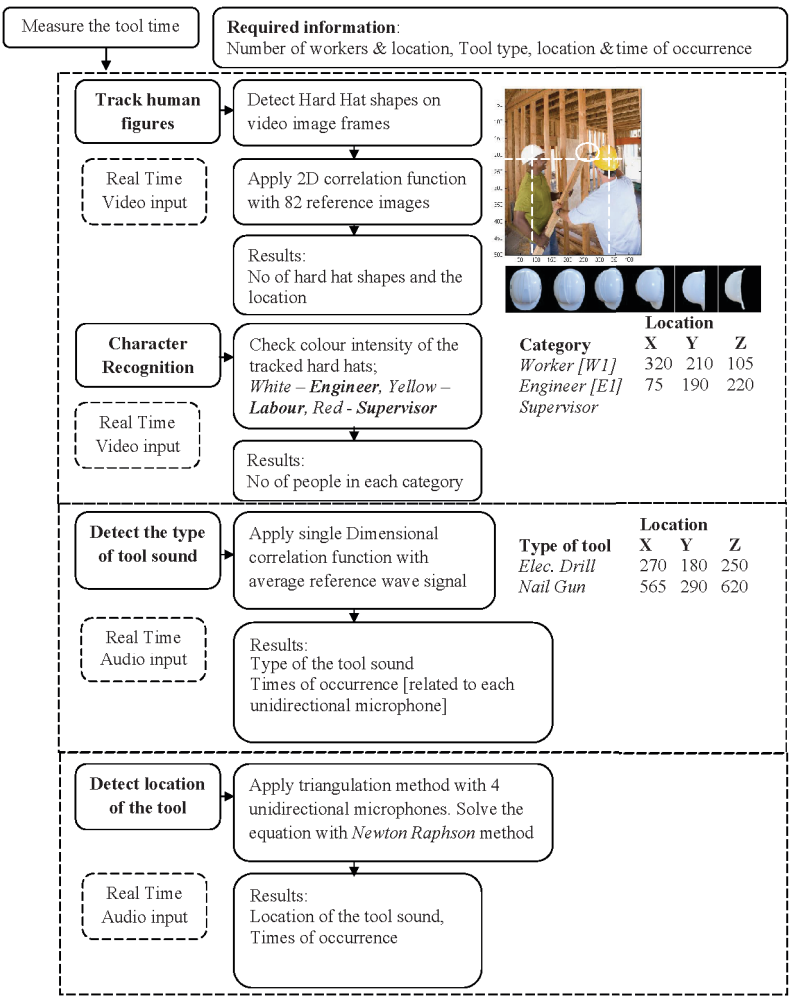


Figure 2: Flow chart of the methodology

Summary of algorithms

Track human figures:

To extract information about an activity from digital video files, the characteristics of that activity and its associated tools are important. In this case, three characteristics were considered: motion, shape and colour.

The method of choice for moving object segmentation in most tracking algorithms is background differencing. At time t, the difference and background images are calculated as follows:

$$\delta(r,c) = \begin{cases} 1 & |I(r,c) - B(r,c)| > T \\ 0 & \text{otherwise} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$B(t) = \beta \times I(t) + (1-\beta) \times B(t-1) \quad \text{if } \delta(r,c) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where r and c are the row and column subscripts of a single pixel, δ is the difference image, I is the input image, and B is the background image. If the difference δ(r,c) is greater than the threshold, T = 12, the pixel is labelled as foreground, while background pixels are modified by expression 2, where β=0.1 and controls the rate of the background update (Owens et al. 2002). After this process, object [hard hat] recognition algorithm is applied to the tracked moved objects. The worker tracking system is based on the characteristics [shape and colour] of the hardhat. A well known correlation method is used to track the hard hat shape (See equation 3).

In order to recognize objects, the researcher must first prepare a database against which the matching takes place. To do this, the researcher first takes a number of images of each object, covering the region on the viewing sphere over which the object may be sighted. Images of the object were taken against a clean black background over the whole viewing sphere. The exact number of images per object may vary depending on the features used and any symmetry present. Obtaining training images about every 20 degrees is sufficient in the case of a hard hat [Selinger and Nelson 2001]. To cover the entire sphere at this sampling requires about 82 images since the hard hat is symmetrical in shape.

The grid line distribution of the sphere is shown in Figure 3. All the reference images are taken from a distance of 45cm away from the camera. In addition, each image populates another 18 sub-images with 20 degree rotations and 18 mirrored images from each rotated angle. Therefore, the full database consists of 2916 reference images per unit distance. Figure 4 shows six reference hard hat images.

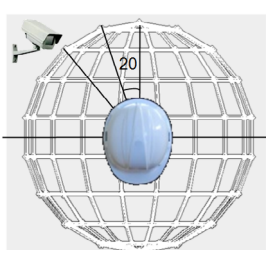


Figure 3: 20degree grid work of the object sphere

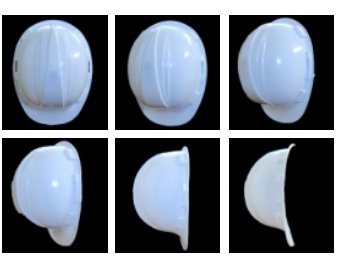


Figure 4: Reference images of the hard hat

Figure 5 shows the snap shot extracted from the digital video file. First, all the images are converted in to grey scale images. For every image obtained, the boundary extraction procedure is run. In order to obtain an edge/ boundary map, the Canny method is applied. After the original image is converted into an edge map, the similarity between the original image and the reference image is identified [Figure 6]. Correlation function can be used to separate a reference signal embedded in a noised signal from single dimension, two-dimensional or from any number of dimensional matrices (Proakis and Manolakis 1996). This method can be applied to detect the number of reference hardhat images embedded in the main video stream. If the video image matrix x has dimensions (N_1, N_2) and reference (hard hat) image matrix y has dimensions (N_1', N_2'), the 2-dimensional correlation v is;

$$v(K_1, K_2) = \sum_{N_1=1}^{N_1} \sum_{N_2=1}^{N_2} [x(N_1, N_2) \times y((N_1 - K_1 + 1), (N_2 - K_2 + 1))] \ldots\ldots (3)$$



Figure 5: snap shot from digital video file – *wall panel construction*

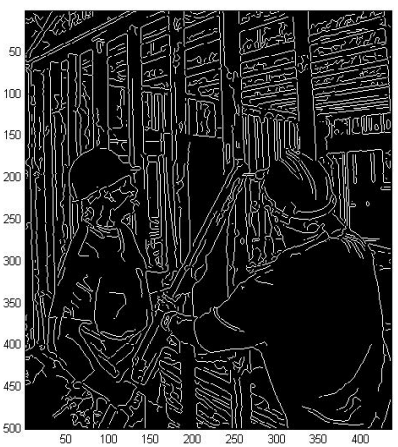


Figure 6: Edge map [Canny method] of Figure 5



(a) (b) (c) (d)

Figure 7: Reference images

Figure 7(a), 7(c): original reference images.
Figure 7(b): after 80 degree rotation of the image (a)
Figure 7(d): mirrored and rotated 260 degrees of the image (c)

A fixed distance of 45cm is maintained between the camera and the hard hat when taking reference images. The correlation starts from reference image scale factor 1.0 with the given video frame.
Then the reference image scale factor is gradually reduced with a fixed interval and matched for several times. The correlation between the reference image sizes and the distance from camera to the object (distance/size ratio) can be used to determine the location of the object along the z axis in the video frame.

It is recommended to use different coloured hard hats to differentiate the work force on site [e.g. white – Engineer, Yellow – Labourer, Red – Supervisor]. The average colour intensity in the region of the tracked hard hat shapes of the video image is checked. If it is linked with the above criteria, the system recognizes the type of the work group without identifying the personal information (Weerasinghe and Ruwanpura 2009). The proposed system is smart to tie the current work activity with each tracked worker. With an assumption of "Every tool generates a unique sound", it is proposed to track the sound pattern of the tool to support recognition of the current work activity.

Track Tool Sounds:
Four unidirectional microphones are installed at upper corners of the work space; real-time audio signal is transmitted to the central processing unit [see Figure 1]. The proposed system can recognize the sound pattern of the tools and measure the number of times the tool is used.

A database of reference wave signals for each construction activity is developed. Significant number of wave signals for a particular activity/equipment have been collected and populated in the database. This enables to determine the average wave pattern for each tool. Since the mono audio signal is considered as a single dimensional matrix, the following equation can be applied. If the real-time audio matrix x has dimension (N) and reference wave signal (nail gun) matrix y has dimension (N'), the single-dimensional correlation r is;

$$r(k) = \sum_{n=1}^{N} x(n) \times y(n - k + 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

An average nail gun reference audio signal is shown in Figure 8. Figure 9 shows the main audio stream that comes from a unidirectional microphone system with different tool sounds in a noisy background. The correlation function is applied on the main audio signal with the reference signal. The resultant correlation map is shown in Figure 10. A certain threshold level is selected according to the features to be extracted (four peaks rose beyond the threshold level as shown in Figure 10). Therefore, the figure interprets that four similar reference signals are embedded in the main audio stream at the relevant time locations.

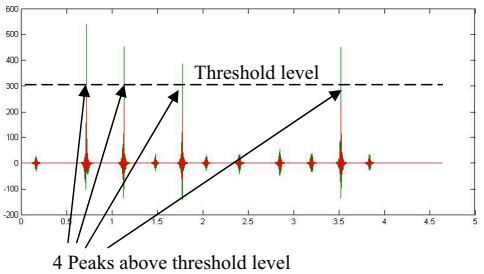


Figure 10: Resultant of correlation function.

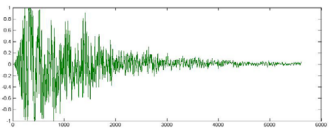


Figure 8: Reference audio signal [Nail Gun]

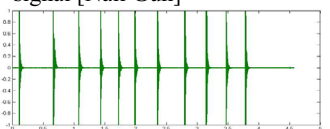


Figure 9: Main audio signal with different sounds patterns

Although human figures and tool sounds have been tracked, it appears as standalone information. Therefore the connectivity between tracked workers and the tool sounds are yet to be analysed. Determining location of the sound source and linking with the worker coordinates resolves the above problem.

Sound source tracking:

The sound triangulation scheme was influenced by the Global Positioning System (GPS), which triangulates the location of a receiver using satellites. The fundamentals of the triangulation idea are derived from the assumption that speed of sound is constant. Thus researcher was able to determine the distance between a microphone and the sound source using the speed of sound and the time it takes the sound wave to propagate to the microphone.

The equation below describes the relationship between the speed of sound, c, the location of the sound source (x,y,z), the location of the n^{th} microphone (x_n,y_n,z_n), the time of the sound source transmission (t), and the time of the sound source reception (t_n) .

$$f(x, y, z, t) = \sqrt{(x - x_n)^2 + (y - y_n)^2 + (z - z_n)^2} - c(t_n - t) \quad \ldots\ldots\ldots\ldots (5)$$

Following equation 6, Newton-Raphson method is used to solve the above non-linear equation. Given a function $f(x)$ and its derivative $f'(x)$, a first guess x_0, a better approximation x_1 is;

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)} \quad \ldots\ldots\ldots\ldots (6)$$

After solving this equation, the sound source coordinates and the operated time can be determined. Consequently, the performance/tool time of the worker is determined. As an example, if W1 generates 12 numbers of nail gun sounds in a one hour time frame, then the performance of that worker is 12nails/hour. Tables 1 to 3 show the sample results based on the algorithms developed.

Expected Results

Table 1: Summery of the results

Time	Video				Audio			
	Category	Coordinates			Tool Type	Coordinates		
		X	y	z		x	y	z
8:31:05	W1	45	65	32	Nail Gun	40	60	30
	W2	105	95	50	Hammer	100	90	40
8:35:05	W1	50	70	30	Nail Gun	48	68	31
	W2	115	90	52	Hammer	120	90	45

Table 2: Detailed description [Worker W1]

Time	Tool Type	Coordinates		
		X	y	z
8:31:05	Nail Gun	40	60	30
8:35:05	Nail Gun	48	68	31
8:40:22	Nail Gun	50	80	33
8:35:05	Nail Gun	60	78	35

Table 3: Tool Usage [Nail Gun]

Time	Worker	Coordinates		
		x	y	z
8:31:05	W1	40	60	30
9:25:05	W1	48	68	31
9:40:22	W2	50	80	33
9:50:05	W3	60	78	35

Conclusion

This study presented in the paper outlines the development of a real time and fully automated system to measure tool time of the workers using audio and video analysis techniques. High-end surveillance cameras are used to detect the humans and to differentiate different human categories in a construction site. Digital image correlation aids to recognize hard hats of the workers and to assess the worker movements. Work activity is recognized by analysing the tool sounds. The proposed four unidirectional microphone system aids to identify the tool sound and its generated location. The triangulation method runs as a supportive function to solve the coordinates of the tool sound location. The link between tracked worker and the tool sound is tied by analysing the coordinates of the worker and the tool sound. As a output of this system, it provides; (1) number of workers working at a given time period (2) worker movement path (3) tool time and performance of each worker (4) tool usage of each tool.

Although it is proposed to use different coloured hard hats to differentiate the work force, deviations for the above is often observed in practice. However it is stressed that in order to acquire the benefits arising from the study, the construction industry must be flexible to adhere to the prerequisites proposed by the study. In conclusion, the novel approach proposed in the study is expected to provide more precise inputs in the assessment of tool time and the worker productivity.

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Resource Performance Indicators in Controlling Industrial Steel Projects

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Abstract

Industrial steel construction deals with the design, fabrication, and site erection of steel elements and encompasses many activities, interactions, and potential resources. An effective project control system for such an environment, as well as issues concerning traditional control systems, are important. This has motivated the authors to propose an integrated and real-time monitoring and control system for steel projects. This paper discusses the application of the concept of resource performance indicators in major components of the proposed system that deal with measuring project performance and the simulation of different scenarios. An object model is utilized and a control object is defined for steel projects to ease the control process. The focus of this research is on labour performance indicators in the fabrication phase of industrial steel projects. To improve the accuracy of the outputs of the system, the Markov Chain method has been used to forecast the values of the resource performance indicators that are fed into the simulation model.

Introduction

Industrial steel construction deals with a variety of buildings, from heavy industrial buildings and petrochemical refineries to sheds, shelters, and roofs. Reduced construction times, efficiency, and cost-effectiveness can be considered as the major benefits of using industrial steel elements. Detailing (designing), procurement, steel fabrication, shipment, and site erection are five major phases in a typical industrial steel construction project.

The complex nature of steel construction (i.e., the large number of potential resources, activities, and interactions required, the industry's growth, and the adoption of new fabrication technologies and materials) requires advanced and effective tools to estimate, schedule, monitor, and control industrial steel projects. The authors (Azimi et al. 2009) proposed an automated and real-time monitoring and control system for steel projects. With the help of a collaborative steel company, the components of the framework are being implemented in the fabrication phase of steel construction. Steel fabrication refers to the manufacturing of steel pieces through a series of operations, including cutting, fitting, welding, sand blasting, and painting, in a fabrication shop according to the engineering design. Steel fabrication is one of the most complicated phases in industrial steel construction projects because of the unique of steel elements, the huge number of fabricated pieces, material handling and inspection activities, the large variety of steel pieces produced in terms of dimension and processing requirements, and the variety of equipment and labour disciplines involved.

The focus of the paper will be on the resource performance indicators used in the system for automated analysis purposes. Generally speaking, resource performance indicators are used for reasoning (Li et al. 2005) and this paper explains how these indicators can be used and forecasted to improve the reliability of the outputs of the automated control system.

Background

Monitoring and control refers to measuring the actual values of the basic variables of a project (such as the percent completed, the quality of work, and cost), analyzing these data, determining if the project is meeting the targets of the work plan, and taking necessary actions to meet project objectives if there are any deviations in project performance (Oberlender 2000). The construction industry is an enormous industry in North America and a huge amount of money is spent in this industry. As an example, in the first eleven months of 2007, US$12.82 trillion was spent in construction projects in the US (www.researchandmarkets.com/reports/656143). This highlights the importance of the role of monitoring and control systems in construction due to the fact that a small variance in the performance of the ongoing projects leads to the loss of billions of dollars. Thus, issues regarding current monitoring and control systems have developed into a major field of interest for researchers. In terms of monitoring, project managers and control systems require a high quality and real-time data to take timely and proper corrective actions after any deviation occurs. The emergence of new technologies, such as Radio Frequency Identification (RFID), has helped researchers to capture performance data for in-progress projects in real-time (Chin et al. 2008; Navon and Sacks 2007; Ghanem and Abdelrazig 2006; Cheng and Chen 2002; Ciesielski 2000). To be effective, there needs to be integration between monitoring and controlling. Gaps between monitoring and controlling components (e.g., evaluation, analysis, and taking corrective actions) may lead to delays and cost overruns. To deal with this issue, integrated monitoring and control systems are under development (Diekmann and Al-Tabtabai 1992; Kim et al. 2008; Moselhi et al. 2004; Nasr 2005; Nassar et al. 2003;

Po-Han Chen 2008). However, current systems are suffering from at least one of the following shortfalls (Azimi et al. 2009):

- Lack of some important components of an integrated project control system, such as forecasting performance, analyzing variances, and recommending corrective actions.
- Manual data entry, which is slow and error-prone.
- Inflexibility and lack of interoperability.
- Difficulties in terms of sharing data (centralized and office-based systems).

To address these issues, Azimi et al. (2009) proposed a project control framework in which real-time, as-built information from a monitoring system is integrated with a control system that includes different components and simulation models (Figure 1). The framework, which uses High Level Architecture (HLA) concepts (IEEE 1516), enables project managers to monitor the progress and performance of each project in a timely manner and to be notified automatically of any deviations; this notification includes complete information regarding the impacts of these problems.

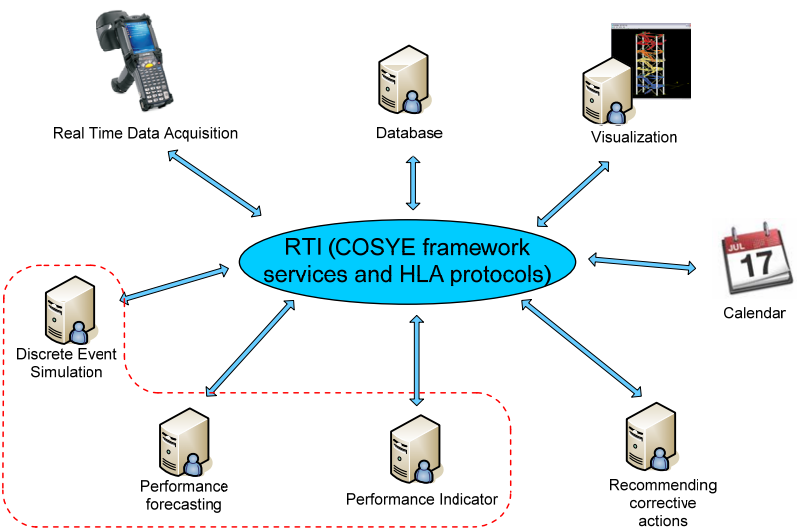


Figure 1. Proposed monitoring and control framework (Azimi et al 2009)

The infrastructure, the components, and the interactions between the components in the proposed framework have been discussed previously (see Azimi et al. 2009). This paper therefore deals specifically with the development and implementation aspects of the framework components marked with the red dashed line in Figure 1. A prototype of the framework has been implemented in the collaborative company. An automated data capturing system using RFID technology provides real-time information for other components of the system; evaluation and analysis regarding

project performance is carried out by other federates based on captured data. The following sections explain how current and predicted project performance are determined for controlling in the implementation phase of the framework.

Earned Value Analysis on Control-Objects

For control purposes, the level of detail for monitoring and analyzing project performance information needs to be determined. Figure 2 represents the Work Breakdown Structure (WBS) of a typical steel fabrication project.

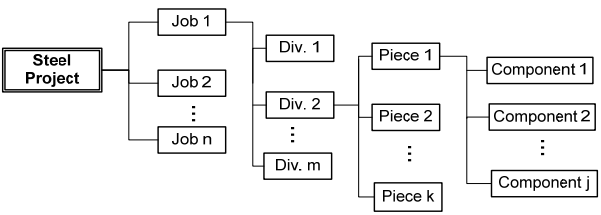


Figure 2. WBS of a typical steel fabrication project

In this research, division and project levels are monitored and controlled. Once progress and performance information at the division level is calculated with the bottom-up approach, project performance at the project level can be determined. A steel project is represented by a set of divisions, which are the control objects. Each division (control object) has its own resources (i.e., labour, material, equipment and, in rare cases, subcontractors) as well as as-planned and actual data, as shown in Figure 3.

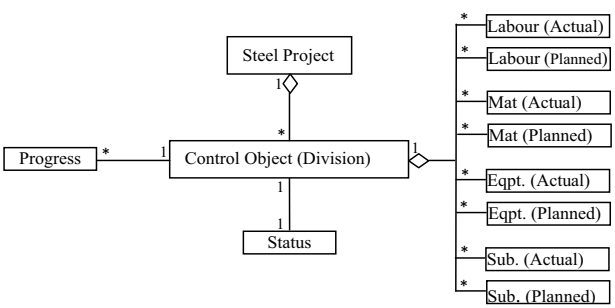


Figure 3. Proposed object model of a steel fabrication project

Status class refers to the actual start and finish time of a division. Additionally, progress of the division is considered as a class in the model.

To control project performance at the division level, the Earned Value Method (Li 2004) is used to disclose deviations in cost and time in project performance. This is done by calculating two indices: the Cost Performance Index (CPI) and the Schedule

Performance Index (SPI). The CPI determines if a budget is over or under run, while the SPI determines if a project is ahead of or behind schedule. To determine the performance indices at the division level, actual cost (man-hours spent in processing the division) and actual progress (percent completed) need to be calculated. Actual cost (man-hours) can be derived from the implemented actual data acquisition system by adding up the man-hours spent on processing pieces for the division. The implemented data acquisition system makes use of Radio Frequency Identification (RFID) technology to track labour and material in the fabrication shop (Azimi et al. 2009). The progress of each division is determined by dividing the weight of the fabricated pieces of that division (captured by the data acquisition system) by the weight of the division (recorded in the database). For performance variance at the division level, the cost and schedule performance indices (CPI and SPI) at the resource level are examined to determine the resource(s) that caused the deviation. A division with a variance in the CPI, for example, has reasonable cost performance indices (CPI≈1) for all resources except labour; labour then is considered to be the cause of the performance variance.

Resource Performance Indicators

Li (2004) introduced the concept of the resource performance indicators to identify the cause of variance in each performance index. Resource performance indicators therefore are used to detect problematic areas (Li et al. 2005). The monitoring and control system of this study is implemented in a collaborative company where labour is the major concern; this research thus takes into account three performance indicators suggested by Li et al. (2005) regarding labour performance in a control object (Table 1).

Table 1. Labour performance indicators used in the proposed control system.

Labor Performance Indicator	Indicator ratio
Division production	Qa / Qb
Unit productivity (fitting, welding & painting)	$\frac{Qa \times Mhrsb}{Qb \times Mhrsa}$
Crew attendance	$\frac{\sum_{t=1}^{n} N_t}{N_b \times n}$

Where:

Mhrsa : cumulative actual man-hours spent to process each steel division
Mhrsb : budgeted man-hours (cumulative)
Nb: planned number of crew members
Nt: actual number of crew members on the t^{th} day
Qa: actual number of processed divisions
Qb: number of divisions planned to be processed
n: the number of days that have been passed

The labour performance indicators are used for two purposes: reasoning and simulation. In terms of reasoning, a list of problem source factors is linked to a list of possible corrective actions and the best required action can be determined. For example, in the case of low unit productivity ratio (less than 1), inadequate skilled labor force or low work moral can be considered as two sources of problem. To deal with that, one can consider adding skilled workers and/or reallocating labour forces as possible corrective actions. Li et al. (2005) discusses in detail how the reasoning can be conducted using the resource performance indicators which is out of the scope of this paper.

Resource Performance Indicators in Simulating Steel Fab Shop

Simulation has been proved to be a powerful tool to analyze and evaluate complicated systems and processes such as steel fabrication process. The simulation in the proposed control system enables managers to experience and compare different scenarios in virtual reality and find the best solution for current or anticipated variances in a project(e.g. delays) as well as the fabrication shop (e.g. low utilization rate and long queues of steel pieces behind a station). To be reliable, the simulation model not only must be a good emulation of the operations and processes of a system in the real world, but the influencing factors as well. Given that in the collaborative company, the labour has the most contribution on the performance of projects, labour performance indicators have been involved in the simulation model.

While different scenarios (e.g. increasing active stations, overtime hours and etc.) can be tried, three scenarios are available for the simulation model regarding the labour performance indicators:

1. Fixed
2. User defined
3. Automatically forecasted

In the first scenario, the most recent value of each indicator captured by the data acquisition system is fed in to the simulation model and as the advances in the model, these variables don't change. Project managers can play with numbers regarding all the influencing factors and resource performance indicators in the second scenario to see the effects of changing each variable on the final results of the simulation. In the third scenario, the value of labour performance indicators at certain times in the future (e.g. on monthly basis) are automatically forecasted and are fed into the simulation model. In this case, the final simulation results are a better representation of the project performance and the fabrication shop in future.

Forecasting Labour Performance Indicators

A) Crew attendance indicator: Historical data has been used to predict the crew attendance indicator in this research. The database of a labour tracking system keeps records of timekeeping information on daily basis which forms the historical data. A preliminary analysis on the available data shows that on mondays and fridays or during certain months such as June, July and August crew attendance indicator is more likely deviating from its desired value which is one. Although crew attendance

indicator can be predicted on daily or weekly basis based on the past information, for the implemented system, this indicator is forecasted on monthly basis.

B&C) Unit productivity & Div. Production: Industrial steel projects typically have different stages and processes which are dynamic and complex. This makes it difficult to predict the labour Unit Productivity Indicator (UPI) and Division Production Indicator (DPI) and forecasting these indicators just based on historical data is not always accurate. There are many internal and external factors that can affect these indicators, and thus a system should be designed to model the dynamic nature of these indicators. A good forecasting embraces both historical data and reliable judgments based on construction experience and knowledge (Diekmann and Al-Tabtabai 1992). To address the stochastic nature of these two indicators, the concept of the Dynamic Markov Chain method introduced by Nassar (2005) is used in this research for predicting purposes. In this model, forecasting is based on current indicators as well as the influencing factors that affect the indicators. These influencing factors get involved in the model using the judgment of experts. Five states for UPI and DPI at time t, (i.e. A(t), B(t), C(t), D(t), & F(t)) are defined as in Table 2.

Table 2. List of states for the UPI & DPI

State	Indicator Rating	Ratio Range	Average Index (PI)
A	Outstanding	R>1.15	1.2
B	Exceeds Target	1.05<R<=1.15	1.1
C	Within Target	0.95<R<=1.05	1
D	Below Target	0.85<R<=0.95	0.9
F	Poor	R<=0.85	0.8

Once the states of the indicators are defined, probability transition matrices for each of the indicators can be established (Figure 4).

$$[P]_{UPI}= \begin{array}{c} State \\ A \\ B \\ C \\ D \\ F \end{array} \begin{array}{c} \begin{array}{ccccc} A & B & C & D & F \end{array} \\ \begin{bmatrix} P_{AA} & P_{AB} & P_{AC} & P_{AD} & P_{AF} \\ P_{BA} & P_{BB} & P_{BC} & P_{BD} & P_{BF} \\ P_{CA} & P_{CB} & P_{CC} & P_{CD} & P_{CF} \\ P_{DA} & P_{DB} & P_{DC} & P_{DD} & P_{DF} \\ P_{FA} & P_{FB} & P_{FC} & P_{FD} & P_{FF} \end{bmatrix} \end{array} \qquad [P]_{DPI}= \begin{array}{c} State \\ A \\ B \\ C \\ D \\ F \end{array} \begin{array}{c} \begin{array}{ccccc} A & B & C & D & F \end{array} \\ \begin{bmatrix} P'_{AA} & P'_{AB} & P'_{AC} & P'_{AD} & P'_{AF} \\ P'_{BA} & P'_{BB} & P'_{BC} & P'_{BD} & P'_{BF} \\ P'_{CA} & P'_{CB} & P'_{CC} & P'_{CD} & P'_{CF} \\ P'_{DA} & P'_{DB} & P'_{DC} & P'_{DD} & P'_{DF} \\ P'_{FA} & P'_{FB} & P'_{FC} & P'_{FD} & P'_{FF} \end{bmatrix} \end{array}$$

Figure 4- Probability Transition Matrices for UPI and DPI

Where,

P_{ij}= Transition probability of the indicators changing from state **i** at time **t** to state **j** at time **t+1** for i,j= A, B, C, D, and F.

For example, P_{CB} is the probability of unit productivity indicator changing from state **C**, (i.e. within target) at time ***t*** to state **B** (i.e. above target), at time ***t+1***.

Each P_{ij} and/or P'_{ij} can be defined by combining historical data and experts' judgments. The Analytic Hierarchy Process (AHP) is used to take into account judgment of the experts in terms of defining Probability Transition Matrices for UPI and DPI.

Since resource indicators with respect to UPI and /or DPI at any time *t* has to be one of the states (A, B, C, D, and F), so:

$$\sum_{j=A}^{F} P_{ij} = 1 \qquad \text{For i=A, B, C, D, and F} \qquad \text{Equation (1)}$$

A state probability vector for the proposed states for any indicator at any time *t* can be defined as follows:

$P(t) = [P_A(t), P_B(t), P_C(t), P_D(t), P_F(t)]$

Initial probability at the initial time t_0=0 can be defined by using the most recent data captured by the data acquisition system. For example if the actual UPI is equal to 0.97 we have:

$P_C(t_0)=1$ *and* $P_A(t_0)= P_B(t_0)=P_D(t_0)= P_F(t_0)=0$

In this method: $P(t+1)= P(t)*[P]^{t+1}$ Equation (2)

Where, $[P]^{t+1}$ represents the probability transition matrix, same as what is shown in figure 4 but at time (t+1). In current implementation, it's been assumed that the probability transition matrix does not change by time, in other words: $[P]^{t+1}=[P]$

Thus:

P_A(t+1)=Probability of outstanding performance in UPI at time *t+1*

$$=[\,P_A(t)*P_{AA}(t+1)+P_B(t)*P_{BA}(t+1)+P_C(t)*P_{CA}(t+1)+P_D(t)*P_{DA}(t+1)+P_F(t)*P_{FA}(t+1)]$$

$$=[\,P_A(t), P_B(t), P_C(t), P_D(t)\ P_F(t)] \times \begin{bmatrix} P_{AA}(t+1) \\ P_{BA}(t+1) \\ P_{CA}(t+1) \\ P_{DA}(t+1) \\ P_{FA}(t+1) \end{bmatrix} \qquad \text{Equation (3)}$$

The same calculation is carried out for determining other probabilities at time *t+1*. Based on the above, having the present value of the indicators (initial state), the forecasted indicator as at time *t* can be calculated as:

$$\text{UPI(t)}= \sum_{S=A}^{F} Ps(t) * PIs = P_A(t)*PI_A+P_B(t)*PI_B+P_C(t)*PI_C+P_D(t)*PI_D+P_F(t)*PI_F$$

$$= P_A(t)*1.2+P_B(t)*1.1+P_C(t)*1.0+P_D(t)*0.9+P_F(t)*0.8 \qquad \text{Equation (4)}$$

Where PI_A , PI_B , PI_C , PI_D ,and PI_F are the average PI values for different states as proposed in Table 2. As an example if current actual UPI(t_0)=0.92 (state D) then we have:

$P_D(t_0)=1$ *and* $P_A(t_0)= P_B(t_0)=P_C(t_0)= P_F(t_0)=0$

Assuming $[P]_{UPI}=\begin{bmatrix}0.5 & 0.2 & 0.1 & 0.1 & 0.1\\ 0.1 & 0.4 & 0.3 & 0.1 & 0.1\\ 0.1 & 0.2 & 0.5 & 0.1 & 0.1\\ 0.1 & 0.2 & 0.1 & 0.4 & 0.2\\ 0.1 & 0.1 & 0.1 & 0.3 & 0.4\end{bmatrix}$ & Eq. 3→ $P_A(t=1)=0.1$, $P_B(t=1)=0.2$, $P_C(t=1)=0.1$, $P_D(t=1)=0.4$ and $P_F(t=1)=0.1$.

Eq. 4→ UPI(t=1)= 0.88 (or state D)

According to the Probability Transition Matrix in this example, P_{DD} has the highest probability (i.e. 40%) and remaining in state D at time (t=1) is reasonable. The same approach can be followed to forecast DPI(t), the only difference is the transition matrix that should be involved (i.e. P'_{ij} instead of P_{ij}). It should be noted that different PI (average index) values can be used for each of the two labour performance indicators here. Project control philosophy of the company and the specific conditions of a project can also influence the PI values for the Unit productivity and Division Production indicators. Forecasting these indicators is on a daily basis due to the importance of them on the final results of the simulation model.

Conclusion

A monitoring and control system plays an important role in industrial steel construction owing to its complexity. The ability of the control system to accurately and reliably analyze the current and future situation regarding the project performance is a key to successful completion of the project. Project performance is so sensitive to the performance of the major resources involved. This paper proposes an approach in terms utilizing the resource performance indicators, which are originally defined as sensors for detecting troublesome areas, evaluating the current status as well as predicting the future status of the ongoing projects. Three labour performance indicators namely Crew attendance, Division production and Unit productivity that significantly influence the fabrication phase of the industrial steel projects were addressed and exploited in the paper. The Markov Chain method was deployed for forecasting the values of the performance indicators used in determining the future performance of projects. The project performance analysis discussed in this paper is a part of a comprehensive automated and integrated monitoring and control system which is under development and being implemented in the real world. Given the intricacy of the industrial steel projects, it is believed that this system can considerably help project managers to mitigate damages and loss in many projects.

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Application of Sensing Technology to Safety Management

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Abstract
In recent years, researchers have made considerable efforts to develop proximity sensing technologies that provide workers and equipment operators with an audible warning when predefined proximity thresholds have been breached. Examples of such technologies include RFID and Ultra-wideband sensors. Despite the practical applications of these technologies to safety management, implementation of such devices on active construction projects is very rare. In this paper, the authors identify the potential barriers and enablers associated with integrating sensing technologies within existing safety management strategies by interviewing safety managers throughout the United States. Using the findings from these interviews, the authors offer a framework for effective integration. It is expected that this framework can be used by construction practitioners to better understand how sensing technologies can complement existing efforts and by researchers who aim to better understand the potential role of such technologies in safety management.

Keywords: Human Error, Safety, Sensing, Technology, Management

1. INTRODUCTION

The construction industry accounts for an injury and illness rate that is nearly five time the all-industry average (NSC 2006). While conditions have improved since the Occupational Safety and Health (OSH) Act of 1970, the industry still accounts for over 1,200 deaths and 460,000 disabling injuries per year (Center for Construction Research and Training 2008). According to the National Safety Council (2006) the annual cost of construction injuries is estimated to be over $15 billion. Within the

construction industry, the highway construction and maintenance sector is one of the most dangerous (BLS 2008). The Federal Highway Administration (2004) estimated that a work zone fatality occurs once every ten hours and a work zone injury occurs every thirteen minutes (FHWA 2004). Additionally, the estimated direct cost of work zone fatalities is $6.2 billion per year (Mohan and Gautam 2002). Unfortunately, despite efforts to improve work zone safety, the injury rate continues to increase. In fact, between 1999 and 2003 the number of annual fatalities in the highway sector increased by 18 percent and the number of non-fatal work zone injuries increased by over 40,000 despite the fact that the volume of construction work remained relatively constant (FHWA 2004; BLS 2008).

This paper focuses on recently developed technologies that show great potential for reducing injuries on highway construction worksites through the reduction of unsafe actions. This study focuses on highway work zones because these projects generally involve dynamic work sites with workers-on-foot and heavy mobile equipment. Furthermore, due to the increased use of rapid renewal strategies, highway construction work is commonly performed at night under poor lighting conditions. Such harsh environments provide excellent opportunities to apply, study, and validate sensor technology and computer algorithms to extract relevant data for advanced decision making.

The study described in this paper had several objectives. The authors first attempted to identify and describe sensing technologies that have a theoretical potential to improve site safety. Subsequent objectives include identifying the level of awareness of these technologies in the construction industry, the perceived barriers to implementation, and potential benefits of technology integration. Finally, the authors attempt to create a framework for effective technology integration based upon input provided through multiple structured interviews.

2. Background and Literature Review

The salient literature was reviewed to establish a point of departure and to inform the data collection process. This literature review includes highway work zone injury statistics, causes of highway work zone injuries, and potentially useful sensing technologies. Social psychology and human error literature is also used to establish the theoretical impact of real-time warnings on safe work behavior. A comprehensive discussion of traditional safety management strategies is provided in Hinze (2006). Such a review has been omitted from this paper for brevity.

2.1 Highway Work Zone Injuries

Safety has historically been a problem in infrastructure construction due to the inherent dangers that exist in highway work zones. Highway construction sites can be differentiated because of the additional distractions attributed to high-speed passing vehicles, heavy equipment, and repetitive work tasks. Each year more than 200 workers are killed and over 20,000 are injured in the highway construction sector alone (Center for Construction Research and Training 2008).

Several studies have focused on the causes of highway construction injuries. In 1999, statistics for fatalities occurring on highway construction and maintenance projects between 1992 and 1998 were published by the Bureau of Labor Statistics

(BLS). Among the 492 work zone fatalities, the leading occupations affected were construction laborers (42%), truck drivers (9%), construction trades supervisors (8%), and operating engineers (8%). The most common primary sources of injury were trucks (45%), road grading and surfacing machinery (15%), and cars (15%). According to NIOSH (2007), nighttime work, contact with heavy equipment, and being struck by passing vehicles are the leading root causes of fatalities.

Nighttime work

Highway construction and maintenance is frequently performed throughout the night due to the pressure from the public to minimize traffic delays during high volume times. Nighttime highway construction has been established to be more hazardous for both passing drivers and construction personnel because of decreased visibility. Furthermore, there is a higher probability of drivers impaired by drugs, alcohol, fatigue, or age-related vision impairments during night-time, all of which contribute to the frequency of accidents (Arditi et al. 2005). According to this study, the factors that most contribute the nighttime fatalities on highway construction and maintenance sites include poor lighting conditions (43%), unfavorable weather conditions (8%), poor performance of safety garments (7%), workers not wearing safety garments (14%), conditions of vehicle operator (64%), and other causes (32%).

Workers struck-by mobile equipment

The majority of fatal injuries incurred by road construction workers are attributable to vehicle- and mobile heavy equipment-related incidents. When compared to workers on all other types of construction sites, workers of many differing occupations on road construction sites were found more likely to be killed by vehicles and heavy equipment. According to McCann and Cheng (2006) the majority of deaths involving vehicle and heavy equipment in traffic work zones include construction laborers (29%), heavy equipment operators (23%), and construction managers (14%). An analysis of 240 incidents involving serious injuries to workers on highway and bridge construction projects in New York State confirms that highway workers are at risk of severe nonfatal injuries from being struck by traffic vehicles or construction equipment (Bryden and Andrew 1999). This analysis revealed that traffic accounted for 22% of worker injuries and 43% of worker deaths in New York from 1993 - 1997.

2.2 Sensor Technologies

Multiple potential technologies are technically available to the construction industry for hazard sensing. However, the advantages and limitations of some of these technologies make them the preferred approach to collect data or preclude them from use (Bohn and Teizer 2009). Candidate sensors are: (a) Radio Detection and Ranging (RADAR), (b) Ultrasound, (c) Ultra Wideband (UWB), (d) Radio Frequency Identification (RFID), (e) Laser Detection and Ranging (LADAR), (f) Global Positioning Sensors (GPS), (g) Visual video (stereo or mono, wide field-of-view, pan-tilt-zoom), (h) Thermal video, (i) Digital imaging (visual and still, thermal, 3D range), (j) Range video, and (k) possibly others. Of these technologies, vision and wireless sensing technologies (video cameras, passive and active RFID proximity and alerts, and UWB positioning) offer particularly promising approaches for acquiring

the data set needed to enhance safety, because of a unique combination of technical capabilities, form factors, and economics (Teizer 2007). It should be noted that these technologies have many current limitations including positioning error. Positioning error of less than a half of a meter has been achieved in outdoor environments (Teizer et al. 2008).

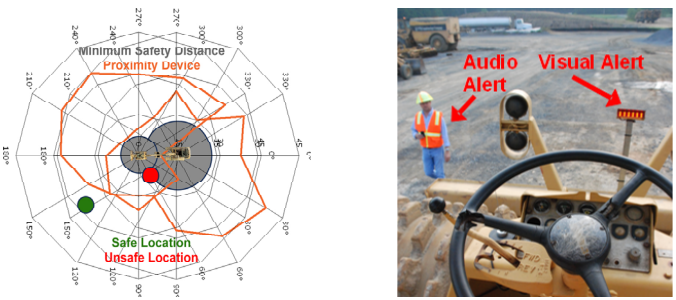


Figure 1: Implementation of active RFID alert device on worker/heavy equipment

Radio Frequency Technology

Safety in construction operations can be improved by utilizing embedded radio frequency technology and range imaging for real-time pro-active warning devices. Sensing technology has been developed that may assist ground personnel and equipment operators (trucks, forklifts) in detecting and recognizing hazardous environments. For example, the system may detect when workers are too close to equipment. In such an event of being too close, visual, acoustic, and vibration technology will activate alarms to the personnel through so called Personal Protective Unit and Equipment Protection Units (PPU and EPU), an active (battery powered) RFID device (see Figure 1). Since unsafe acts (e.g., mistaken entry into an unsafe work zone) are often not reported by workers or operators unless an incident occurs, the use of the proximity detection and recording technology will measure how often and how close construction workers are to heavy equipment. The current active RFID configuration allows to alert workers at average distances ranging from 2 to 50 meters, depending on the physical and ambient environment. Alert distances of more than several hundred meters can be achieved and were tested. A passive RFID configuration can achieve distances ranging from a few centimeters up to 10 meters.

Ultra Wideband (UWB) tagging and tracking is a relatively new field, particularly as applied to construction (Fontana 2004). Recent advances in miniature UWB tags and receivers have made it practical and economical to deploy UWB tags at a cost of $10-40 per tag. Teizer et al. (2008) compared in a series of experiments a UWB real time positioning system against a Robotic Total Station (RTS) surveying instrument. UWB tags offer precise positioning of tagged workers and objects. They can also exhibit long tracking range (up to 300m outdoors, max. 1,000m). The widespread use of real-time location tracking devices on individual workers (such as UWB tags) is not expected in everyday construction deployment scenarios until the tag cost decreases substantially and the battery life increases.

2.3 Theoretical Benefits of Technology Integration

Accident causation models provide strong and consistent evidence that accidents are the result of unsafe worker actions and uncontrolled hazardous exposures. The research aimed to improve decision making and prevent unsafe worker actions in hazardous work environments. Special attention was being paid to worksites that involve nighttime work, mobile heavy equipment, and workers belonging to minority groups that have shown statistically significant higher incident rates than the general workforce (Center for Construction Research and Training 2008)

Human error

Errors in judgment, decision making, and physical actions result in loss of productivity, the need for rework in industrial operations, and occupational injuries. In order to prevent human error organizations conduct training sessions, provide feedback to workers, and conduct inspections (Hinze 1996). These prevention activities rarely occur in real-time. That is, organizations rarely have the capability to systematically warn workers of their erroneous actions before negative consequences are realized. This is especially true in work environments where conditions continually change, mobile equipment is integrated within the workspace, and many distractions are present. Therefore, there is a clear need for a reliable real-time warning system that specifically targets the cessation of erroneous behavior.

According to Reason (1990), human error occurs in a limited number of forms. These forms include intentional erroneous actions (mistakes and violations) and unintentional erroneous actions (slips and lapses). The fundamental difference between these is that mistakes are planning errors (e.g., intentionally choosing an unsafe pathway through a worksite) while slips and lapses differ result in failures of execution (e.g., inattentiveness, distraction).

Mistakes are defined by Reason (1990) as, *"deficiencies or failures in the judgmental and/or inferential process involved in the selection of an objective or in the specification of the means to achieve it, irrespective of whether or not the actions directed by this decision scheme run according to plan*." According to Rasmussen et al. (1994), mistakes are relatively common and exist in two categories: Knowledge-based or rule-based. Rule-based mistakes involve the intentional application of a bad rule. These mistakes result from errors in standardized procedures and reflect and are caused by deficiencies in management. Unlike rule-based mistakes, skill-based mistakes are governed by stored patterns of pre-programmed instructions in the time-space domain. Errors in this domain are extremely common and occur when workers misjudge time or spatial characteristics of the worksite. Negative consequences resulting from skill-based mistakes are generally preventable when workers obtain feedback on their erroneous behavior before negative consequences occur.

Slips and lapses are defined by Reason (1990) as "*errors which result from some failure in the execution and/or storage stage of an action sequence, regardless of whether or not the plan which guided them was adequate to achieve its objective*." These errors occur when workers fail to make a cognitive attentional check because: (1) The process or behavior is not habitual (strong habitual intrusions), (2) A distraction prevents one from making required checks (omission); (3) Failures of prospective memory prevent safe work procedures (reduced intentionality), or (4)

Workers inadequately estimate durations within a sequence of actions (mistimed checks). These unintentional errors differentiated into two categories: (1) Those caused by distractions in a familiar work environment (slips), and (2) memory failures (lapses).

Detecting and preventing error

Typically, errors are detected through formal processes in the human body (i.e., self monitoring). Human beings constantly check their surroundings to ensure that our actions match our intent. These mental checks, however, are compromised by the cognitive errors discussed. The detection of errors must be supplemented by an external source. This is especially true in dynamic environments where time to make safe decisions is severely limited. According to Rasmussen et al. (1994) safe work practices are promoted when organizations establish effective safety feedback mechanisms that alert workers of deviations from prescribed practices, entry into unsafe work zones, and failure of standard controls.

Table 1: Relationship between human error, work environment, and prevention

Human Error	Definition	Environment	Technology-related Countermeasure
Mistakes	Intentional planning related error (e.g., skill-based errors)	Dynamic work environments are prevalent and standardized work processes do not ensure sufficient worker-hazard interactions	Prevents entry in unsafe work zones when ad hoc plans and work procedures cause entry into unsafe work areas
Slips	Unintended erroneous actions that result from mental distractions in familiar work environments	Typical work environments with one or more unusual external distractions	Provides workers with proximity warning when distractions prevent typical mental checks
Lapses	Unintended erroneous actions that result from temporary memory failure	Typical work environments	Provides a queue for workers who have temporarily forgotten safe work practices or tolerable distances

It has been shown that an adequate safety information feedback mechanism ranks second only to top management involvement in discriminating between safe and unsafe organizations (Kjellen 1983). However, safety feedback mechanisms are rarely implemented in construction and there is no technology or process currently used in construction that can provide feedback in real-time (Shell Safety Committee 1987). According to Reason (1990), attention can only be directed to a very small part of a total space in any given time and such attention must be focused on important problem spaces to prevent accidents. Table 1 provides simple definitions of the three human error modes, the environments in which they typically occur, and the countermeasures related to the implementation of the proposed technologies. This table was created based upon social psychology research conducted by Searle (1980), Norman (1981; 1983), and Mandler (1975). According to this literature, mistakes, slips, and lapses cause accidents because they result in a worker's failure to perceive that an event has occurred (e.g., that a bulldozer has begun to mobilize), failure to diagnose the nature of an event and to determine the necessary remedial actions (e.g., failure to recognize the need to change physical location when bulldozer's track has broken), and failure to implement those responses in a timely manner (e.g., duration

of time required to recognize a hazardous condition has exceed the time required to act safely) (Hall et al. 1982). In all such cases advanced warning of hazardous conditions would help to prevent failure in human actions (Wreathall 1982).

3. Research Methods

As previously indicated, some of the primary objectives of this study were to determine the perceived barriers and enablers associated with implementing sensing technologies, potential for injury prevention, and to establish a framework for integrating sensing technologies with traditional injury prevention strategies. To achieve these objectives the research team conducted a series of structured interviews with project managers and safety managers throughout the Unites States. Interviews were selected over surveys and expert opinion techniques for several reasons. First, interviews are an efficient means of collecting rich data with a high level of interaction between the interviewee and interviewer. Second, there are few individuals who would be qualified as 'experts' in the topic under investigation.

To ensure optimal external validity, interviews were conducted with safety managers and project managers of construction organizations throughout the Unites States and pattern matching was performed qualitatively by the researchers following data collection. It should be noted that the external validity is limited by the fact that the interviewees represented a convenience sample of contacts previously established by the research team. The internal validity of the study was enhanced by conducting multiple interviews with multiple interviewees. An important aspect of this study was to ensure consistent interpretations of the structure and application of the RFID and UWB sensing systems. Accordingly, a brief description of each technology and its application was provided to each interviewee prior to the interview date.

The interviewees were diverse in their positions and perceptions. In this pilot study interviews were conducted with five individuals who had an average of ten years of professional experience managing safety on highway construction projects in the US. While the interviewees were predominately located in Colorado, all had experience working outside of Colorado. Finally, interviewees included corporate safety managers, project safety managers, a Colorado Department of Transportation (CDOT) employee, and a project manager. During the interviews, the following questions were asked:

1. Are you aware of the potential application of RFID and UWB sensing technologies to prevent injuries in the construction industry?
2. Are there any reasons why RFID/UWB sensing systems would not work? Are there foreseeable logistical issues?
3. How might a real-time warning system prevent accidents? Could this warning system provide other benefits other than their intended use?
4. The tracking system can record the movement of workers throughout the site. How could this system prevent accidents? How could this be used to improve the effectiveness of the safety programs that you already have?
5. What are the potential limitations of the RFID/UWB systems?
6. How might these systems integrate with the existing Safety Program Elements (e.g., job hazard analyses, orientation, inspections)? Would the effectiveness of these, or some of these, improve with this technology? How?

4. Results

The results of this study are summarized below. Of the six interviewees, only one had heard of RFID or UWB technologies and no interviewees were aware of potential applications to construction. Therefore, the first step of each interview involved providing the interviewee with a description of the technologies. Additionally, a one page description of both technologies was created and distributed to the interviewees prior to the interview date.

The interview questions had three major themes: (1) potential logistical problems, (2) perceived benefits, and (3) specific framework for integration within existing injury prevention strategies. The first set of questions focused on the potential logistical problems associated with the technologies. These questions were asked to identify the perceived barriers to implementation in an effort to discover why the technologies have not seen widespread diffusion throughout the industry. The responses to the logistics questions indicate that the greatest perceived barriers to initial implementation are reliability of the technologies' warning systems (mentioned by 6/6 interviewees); technological complexity; lack of experts available to provide training (3/6); appropriate volume of warning systems (2/6); and potential overdependence of the workers (1/6).

The second set of questions focused on identifying the perceived benefits of the integration of the technological systems described. These questions were aimed to validate and supplement the theoretical benefits previously described in this paper. Interviewees identified many potential benefits of integration including minimization of unsafe worker actions near heavy mobile equipment, exposed edges, trenches, crane swing zones, and adjacent traffic. Simply, these interviewees believed that the technologies showed promise for increasing workers' and equipment operators' awareness of their proximity to an unsafe work zone or potentially dangerous interaction. The associated warning signals were believed to provide a sufficient warning to prevent unsafe actions that contribute greatly to severe injuries on highway construction sites.

There are some specific ways that the technologies may be integrated with existing injury prevention strategies. The UWB and RFID systems have the most potential to integrate with orientation and training, recordkeeping and accident analyses, activities performed by the site safety manager, and job hazard analyses. The technologies can integrate well with orientation/training, recordkeeping/accident analyses, and job hazard analyses in several ways. First, when UWB and RFID are used simultaneously, the technologies can be used to track workers throughout the site in an effort to determine the duration of time spent in unsafe work zones. Such data can be used to enhance recordkeeping/accident analyses by collecting unprecedented close-call information. Further, such information can be used to enhance orientation/training meetings by using actual tracking data and describing the potential risks associated with actual worker behavior.

The technologies also integrate well with the inspection, training, planning, and real-time management techniques used by effective safety managers. These systems could be integrated with a real-time alert system that provides the safety manager with a notification when unsafe interactions are occurring so that inspections

and monitoring can occur in regions of the worksite with the greatest potential for injury thereby optimizing his or her effectiveness. Additionally, the safety manager can use historical tracking data to enhance planning for subsequent phases or projects. For example, if workers spend time in unsafe zones due to lack of awareness, signage can be strategically located to proactively warn workers.

5. Conclusions and Recommendations

This study highlights several ways that RFID/UWB technologies can be employed to prevent injuries on construction worksites. Social psychology literature was used to create a theoretical basis for how the technologies could be used to prevent cognitive errors in dynamic and dangerous work environments. This theoretical foundation was validated and supplemented through interviews with a small sample of highly experienced safety managers in Colorado. The findings indicate that the technologies have particular application to real-time warnings of proximity to unsafe work zones, equipment, and materials. The technologies may also have potential for enhancing recordkeeping and accident analyses, job hazard analyses, orientation and planning, and enhancing management activities conducted by the safety manager. Despite these potential benefits, there are some significant barriers that may preclude the immediate use of these technologies including reliability, appropriate design for unique and dynamic work environments, and lack of expertise of typical safety and project managers.

The authors recommend future research that expands upon this study. Such research should involve case studies that produce recommendations for overcoming the perceived barriers. Research that produces empirical evidence of safety improvement would also be highly beneficial to the industry. Safety professionals and construction managers are encouraged to adopt the technologies and implement on a small sample population. It is expected that initial integration with a sample crew would involve a relatively low cost and have high short-term and long-term payback that could result in a safer worksite and a competitive business advantage.

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Automated Materials Tracking and Locating: Impact Modeling and Estimation

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Abstract

Successful, large scale field trials were conducted on two sites in Texas and Toronto using an integrated system of RFID tags, GPS technology, map software, and hand held computing to automatically track materials in the projects' respective lay down yards. This paper addressed the unresolved research question, that how will this technology impact projects if it is implemented upstream in the supply chain in an integrated and automated materials management system? This question is addressed by modeling the impact of automated materials tracking technology on increasing visibility within the construction supply chain. It is concluded that automated materials tracking has the potential to improve construction productivity, cost, and schedule performance.

Introduction

The Construction industry is characterized by the fact that every project is different from others in terms of planning, design, and execution. Likewise, the supply networks that fuel these projects with labour, equipment, and highly engineered materials are complex entities onto themselves. Improving the materials management process, particularly at the site level on large construction projects, has been identified as one area that can have a beneficial impact on the construction supply network and the construction process as a whole (Construction Industry Institute 1999; Kini 1999). The integration of Automated Materials Locating and

Tracking Technologies (AMLTT), namely Radio Frequency Identification (RFID) and the Global Positioning System (GPS), and the automation of part of the materials management process have been proposed and shown to be a viable means of process improvement. These technologies have thus far been shown to be well suited for application in the construction industry, especially with regards to accurately identifying, locating, and tracking material and equipment in a construction environment (Song et al. 2006; Ergen et al. 2007; Razavi et al. 2008).

However, what is currently lacking from the body of knowledge, on the application of AMLTT in construction, is an understanding of the impact that this technology could have on a project if implemented on a larger scale. Specifically, what impact(s) could AMLTT have if it were implemented within the construction supply network? The objective of the research presented in this paper is to investigate the theoretical impact that the application of AMLTT could have on the construction materials management process if implemented within different segments of the supply network. The specific area of the construction supply network that was chosen for investigation was the use of AMLTT to increase the level of visibility within the greater supply network. To examine the impact of AMLTT to increase the level of visibility within the supply chain, the process piping supply chain was modeled using EZStrobe, a commercially available modeling and simulation software package.

Background/Literature Review

The success of Supply Chain Management (SCM) in the manufacturing sector has lead to interest in its application in other industries, including the construction industry. The application of SCM principles, such as Just-In-Time (JIT) delivery, has seen some success in the construction industry. Tommelein (1998) was successful in demonstrating the theoretical ability of pull-driven scheduling to improve the performance of the pipe spool installation process by reducing on-site material buffers, decreasing the project duration, and identifying a means in which to increase crew productivity by altering their start date. Al-Sudairi et al (1999) simulated a steel erection process and concluded that a moderate material buffer on site could balance the impact of uncertainty in material delivery and productivity. Vrijhoef & Koskela (2000) went on to examine the supply chains of three construction projects (two residential projects and one office building). From their research it was determined that there exist significant problems (from a Lean perspective) in a typical construction supply chain, such as the inclusion of extra time in schedules to counteract uncertainties and the overall nearsighted management of the supply chain in general.

The difficulty in applying SCM to construction in all of the studies mentioned above can be recognized to originate from the fundamental differences between manufacturing and construction. The construction industry is dominated by ‘one-off’ projects; where ‘one-off’ refers to the lack of repetition in the construction of like facilities (Vrijhoef & Koskela 2000). Construction schedules vary considerably between projects, some schedules span years, while others span only a few months. Other constraints imposed on construction projects, such as weather, site conditions,

site fabrication, availability of resources (e.g. skilled and unskilled labour), and local laws and regulations can also be highly unpredictable and variable (Koskela 1992; Cox et al. 2006).

Materials management at the site level, in general, is focused on ensuring that the right materials are available for work crews at the right point in time. Common materials related issues that can arise include: lack of availability of required material, inaccurate warehouse records, damage of critical material or equipment due to improper storage, improperly sequenced deliveries, and large surpluses of material at project completion (Plemmons & Bell 1995; Thomas et al. 2005). The introduction of new technologies, which fall under the category of Automated Materials Locating and Tracking Technology (AMLTT) and the automation of specific aspects of the site materials management process have been proposed and shown to be a viable means of improving this process as a whole (Song et al. 2006; Ergen et al. 2007; Razavi et al. 2008).

Field Trials

Extensive field trials were conducted to investigate the possible impacts of AMLTT on construction productivity. The field trials were conducted at power plant construction projects in Rockdale, Texas and Toronto, Ontario, respectively. The Rockdale field trial was conducted at the Sandow Steam Electric Station Unit 5 project. The second field trial was conducted at the Portlands Energy Center (PEC) project, located in the port area of Toronto, Ontario.

RFID tags were attached to the construction materials. At the PEC, 224 pipe spools, 22 safety valves, and 100 globe valves were initially tagged with RFID transponders. In Rockdale, Texas, 400 structural steel components were tagged for one boiler. On both sites, data was collected on a daily basis to update and generate the positions of the tagged components. An individual carried a kit consisting of an integrated GPS unit, RFID reader, and a handheld computer. As the individual moved around the site, the GPS receiver determined its own position while the RFID reader identified the presence of the tagged components around that position at a rate of several thousand reads per second. The localization algorithms then processed the collected data to provide a more accurate estimate of the location of each tagged component. Details about these field trials and their results can be found in CII (2008).

Formulated Simulation Models

Simulation models were formulated for investigating the increase in visibility within the construction supply network due to the use of AMLTT. Models of the process piping supply chain, a typical component of industrial construction projects, were developed as the primary investigative tool for this research. Process piping, specifically the fabrication and installation of pipe spools, was chosen as the basis of the completed investigation due to the availability of literature which provided an understanding of its supply chain network and due to the authors' own field experience with this construction activity (Howell & Ballard 1996; Tommelein 1998;

Razavi et al. 2008). Two simulation models were developed. The first simulation model represents the existing process or situation as it typically exists in the construction industry today utilizing a material buffer. The subsequent model(s) represents a modified version of the existing process model in which AMLTT has been included thereby utilizing no material buffer. The EZStrobe: General-Purpose Simulation System (EZStrobe) was utilized to build the construction supply network models. EZStrobe is a discrete event simulation environment that is based on the STROBOSCOPE simulation platform.

Increasing Visibility within the Construction supply network

The series of models presented in this section were used to investigate the premise that an increased level of information transfer within the construction supply network, regarding the status of material and equipment, would subsequently reduce uncertainty at the site level. As a result, potential work opportunities would be created and taken advantage of. A work opportunity is defined as a task or series of tasks that could potentially be started and completed earlier in the construction schedule. These work tasks, however, are typically delayed due to uncertainty in the ability of the supply network to provide sufficient and/ or the required material to allow for an adequate and constant rate of production to be attained on site (i.e. the risk of delay is considered too great). Consequently, these work tasks are put on hold until a sufficient material buffer has been accumulated on site. For example, pipe spool installation is not typically started until a significant portion of the total pieces to be installed (60 to 80%) have been delivered to the site (Howell & Ballard 1996), thus utilizing a 60 to 80% material buffer.

Existing Supply Chain Model

The entire supply network for a typical construction project is composed of a complex system of elements. Modeling such a vast system was considered to be beyond the scale required to complete the intended investigation as part of this research. As such, only a single supply chain from within a greater construction supply network was modeled using EZStrobe. The chosen supply chain was that of a typical piping process on an industrial construction project. The piping supply chain model presented by Tommelein (1998) proved to be an essential resource. Industrial piping is also a segment of the construction supply network that is known to suffer from the effects of uncertainty as described by Howell and Ballard in their 1996 report entitled *Managing Uncertainty in the Piping Function*. The EZStrobe model developed to represent the existing piping supply chain was broken into two parts. The first part of the model depicts the segments of the piping supply chain which relate to the fabrication process. The second part of the EZStrobe model depicts the segments which relate to on-site installation. The first part of the model is composed of those activities which are directly related to the fabrication of pipe spools and associated activities which are based offsite. These activities include the generation of design specifications, the design process, the overall pipe spool fabrication process, and the transfer of material to the site. The second part of the developed model is composed of those activities that are directly related to the installation of the pipe spools and other associated on site activities. The activities in this part of the

model include the material receiving process, the completion of install area preparation, pre-installation work, and final installation. There is little to no supply network visibility assumed to exist within this model.

Modified Supply Chain Model

AMLTT, specifically RFID, employed in conjunction with a comprehensive data management system, offers the potential to drastically improve the ability to transfer information within the construction supply network. This in turn influences the potential to increase supply network visibility and subsequently decrease the level of uncertainty held at the site level concerning the status of material and equipment yet to be delivered. It is theorized that with decreased levels of uncertainty concerning material and equipment deliveries that site based project managers will be able to take advantage of work opportunities that would have otherwise been considered too risky. Accordingly, the requirement to build up costly stockpiles of material and equipment in project lay down yards and warehouses, prior to beginning specific construction tasks is expected to be mitigated. This theory is explored using the modified piping supply chain model presented in this section. In this model, however, it is assumed that AMLTT, in the form of RFID transponders, associated readers, and data management and communication systems, is incorporated into the piping supply chain at the earliest possibly phase. The start of the fabrication process was considered to be the earliest point in which AMLTT could be integrated into the piping supply chain, as this is the first point in which a physical entity exists that a RFID transponder can be affixed to. With the increased use of information technology based tools such as Building Information Models (BIM), the ability to automatically convey information regarding the status of specific items to a central project database may also be extended into the engineering and design phase in the future.

Figure 1 represents about a 10% sample of the complete model. We are sorry we could not present the full model which incorporated 40 “combi’s,” 32 normals, and dozens of probability branches and queues. These cannot be presented in this paper. The modified EZStrobe model is divided into three parts. Part 1 focuses on the segments of the supply chain related to the pipe spool fabrication process. Part 2, is focused on the pipe spool installation process. Part 3, is comprised of the majority of the additional modeling elements required to incorporate the conceptual flow of AMLTT derived information and the mechanism by which possible work opportunities are generated.

In the modified model, the install area preparation, pre-installation work, and installation activities are not constrained by the quantity of loads received on site; rather they depend on the availability of potential work opportunities that are generated as a result of information conveyed from various stages of the supply chain. It should be noted that a 50 day delay period to account for the completion of site work was applied to the install area preparation activity in this model. Dynamic based probabilities were assigned to the decision nodes associated with on site data collection points to account for the occasions when materials arrive on-site early or out of sequence with installation. The probability that a data signal originating from

one of these data collection points will be converted into a work opportunity is dependent on the number of occurrences of that activity up to that point in the simulation. The probability that a work opportunity will be generated increases as the number of occurrences of an activity increases. A feedback loop was also incorporated with these decision nodes to ensure that sufficient work opportunities are generated to eventually complete the specific work task in question. These work opportunities had the effect of reducing the need for a site stockpile. The stockpile was not in fact arbitrarily or directly reduced.

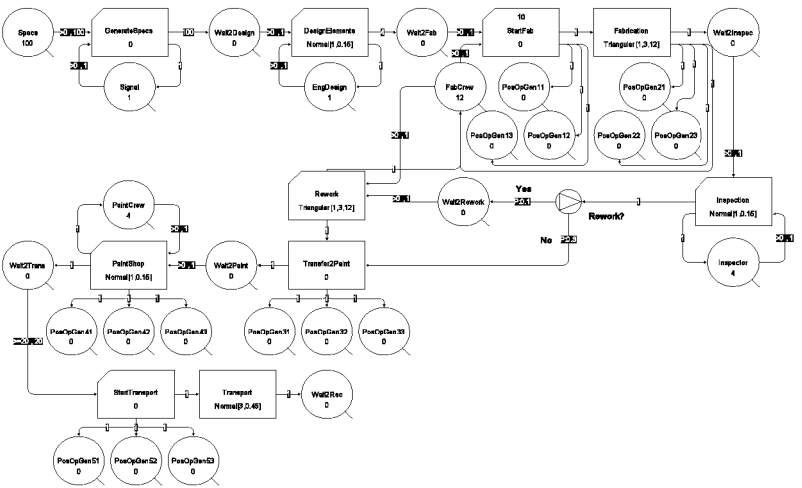


Figure 1: Modified Pipe Spool Supply Chain Model (Fabrication part only)

Simulation Results

The ability to meet or exceed a construction schedule is often a primary measure of project success in the construction industry. Accordingly, schedule performance was used as the gauge by which the theory that an increased level of supply network visibility via an AMLTT based system can beneficially impact site operations was tested. A baseline for comparison purposes was first established using the existing supply chain model. As stated earlier, piping constructors typically utilize a 60 to 80% material buffer (Howell & Ballard 1996). Therefore, the output generated using the existing model subjected to a 60% install buffer was used for comparison purposes. Subsequent analysis of the simulation output associated with other buffer sizes confirmed that the highest level of schedule performance, given other model parameters, was attained with a 60% install buffer in combination with a 55% buffer constraint on the remaining site based activities. For both the existing and modified supply chain models, the output associated with six principal activities has been reported. These activities are divided evenly between the off-site fabrication and on-site installation phases of the overall supply chain. The fabrication based activities

include the design of pipe spools, the overall fabrication of pipe spools, and the delivery of pipe spools to the site. The installation based activities include the install area preparation, pre-installation pipe spool work, and installation activities. A summary of the simulation results is provided in the next two sub-sections.

Summary of Existing Supply Chain Model Output

The existing model output for the case of a 60% install buffer is presented. Figure 2, shows the percent complete of each activity over time. The "Install Area Ready" and "Pipe Ready for Install" activities commence operations 124 days after the simulated project kick off. The last area is subsequently made ready for installation at day 222. This finish date corresponds to a rate of production of approximately 1 area prepared every 10 days. This rate of production is in line with the assumed overall rate for this activity. The final set of pipe spools is made ready for installation on approximately day 226. The corresponding rate of production is therefore 3.9 pipe spools per day. Installation is subsequently able to commence on day 131. Installation was recorded as being complete on day 246. This translates into a rate of production of approximately 0.9 areas per 10 days. This rate of production is slightly less than anticipated; however, it can most likely be attributed to the accumulation of incremental delays incurred in upstream activities. Overall, based on a combination of 60% install buffer and 55% precedent activity buffer, the estimated optimum schedule duration for the existing model was recorded to be 246 days. This is the result for which the corresponding output of the modified model will be compared to.

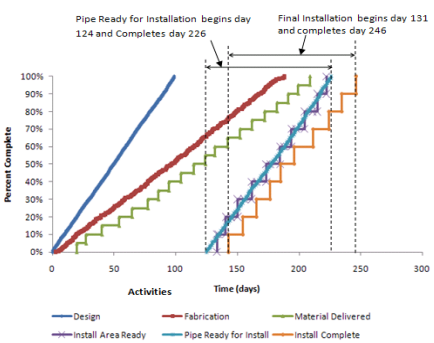


Figure 2: Percent Complete vs. Time (Existing Model)

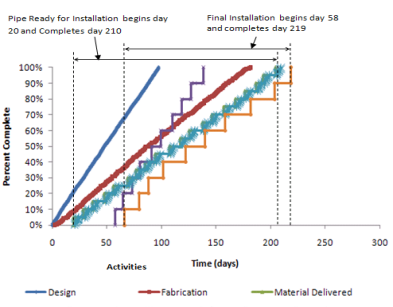


Figure 3: Percent Complete vs. Time Modified Model (Work Opportunities)

Summary of Modified Supply Chain Model Output

The simulation output for the modified model output is presented in the same format as the previous model. Figure 3 provides the percent complete profiles for each activity. Relatively constant rates of production are able to be achieved for each of the three on-site activities under the modified model. Sufficient work opportunities were generated to allow for the pipe spool pre-installation work activity to commence

immediately following the delivery of the first load of pipe spools on day 20. This activity reached 100% completion 190 days later on day 210. This corresponds to an overall rate of production of 2.1 pipe spools per day. Sufficient work opportunities were also generated to allow the preparation of install areas to commence immediately after the 50 day delay period to account for site work. This activity reached 100% completion on day 139. This translates into a rate of production of 1.1 areas every 10 days. Finally, installation was able to begin on day 58 and was subsequently completed on day 219. The resulting rate of production for this activity was calculated to be 0.6 areas completed every 10 days.

Comparison of Schedule Performance

To compare the performance of the modified model to that of the existing model in terms of schedule, three parameters were examined for each site based activity. The parameters examined include the start and end time of each activity and the ensuing rate of production. Each activity is compared separately in the following sub-sections.

Comparing the Rate of Install Area Preparation

The corresponding percent complete profiles for the install area preparation activity for both the existing and modified models from the previous sections are displayed together in Figure 4 (a) below. The transparent overlays correspond to the resource allocation profiles for each instance of this activity. The elimination of the material buffer and the subsequent change over to a reliance on work opportunities generated via AMLTT has the effect of moving ahead the start time of the install area preparation activity. The resulting difference between the start times is 73 days in favor of the modified model. The overall length of time to complete the preparation of all 10 install areas was also reduced from 99 to 89 days; however, this reduction can be attributed to randomness in the simulation engine and would not be expected to occur on average. The subsequent rate of production of each instance of this activity is relatively the same. Accordingly, the resource allocation profile is the same for each case at 1 full crew for 100% of the activity duration.

Comparing the Rate of Pre-Install Pipe Work

The percent complete profiles for the pre-install pipe work activity for both the existing and modified models are displayed together in Figure 4 (b). The resource allocation profiles for each instance of this activity are overlaid in the corresponding transparent colour. The effect of eliminating the reliance on material buffers as a primary constraint on operations is more evident when comparing the percent complete profile for the pre-install pipe work activity for each model. In the case of the existing model the pre-install work is completed over a relatively short period of time of 102 days as previously reported. In the case of the modified model, the start time of the pre-install work is able to be pushed forward by just over 100 days. The overall duration, however, is increased by a factor of two. This is caused in part due to increased crew idle time, which is manifested in the form of disjoints in the percent complete profile for the modified model. Accordingly, the rate of production between the existing and modified model is decreased by a factor of 2. However, this

can be compensated for by reducing the crew size by a half as indicated by the corresponding resource allocation profile. While the overall activity duration is increased, most project managers should appreciate the greater flexibility that this alternative provides and improved productivity.

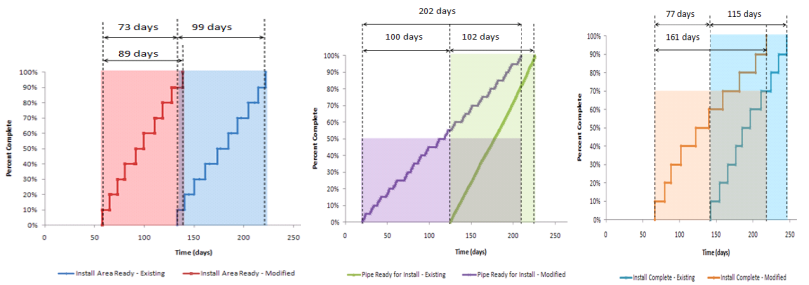


Figure 4 (a) **Figure 4 (b)** **Figure 4 (c)**

Figure 4: Comparing Rates of Productivity – (a) Install Area Preparation Activity; (b): Pre-Install Pipe Work Activity; (c): Installation Activity

Comparing the Rate of Installation

The percent complete profiles for the installation activity for both the existing and modified models are displayed together in Figure 4 (c). The resource allocation profiles for each instance of this activity are overlaid in the corresponding transparent colour. Similar differences in the percent complete profiles for the installation activity between the existing and modified models can be seen here as compared to the previous activity. The elimination of the material buffer allows for the start time of the activity to be shifted forward, in this case by 77 days. The overall activity duration under the modified model is increased by a factor of 1.4 from 115 to 161 days, which in turn decreases the overall rate of production. However, like the previous case, this can be compensated for by reducing the overall crew size by slightly less than 30%.

Conclusions

Based on the completed comparison it is evident that the integration of AMLTT into the construction supply chain has the potential to improve or at least maintain construction schedule performance, while reducing the dependency on costly material stockpiles. It is recognized that under the AMLTT based model the rate of production of two thirds of the site based activities was reduced significantly and crew idle time increased. However, as was shown, this can be compensated for by reducing the applicable crew size. The ability to start work tasks earlier in the construction schedule as a result of an increased state of knowledge of the supply situation should also provide project managers with a greater flexibility to account for other unexpected events that may hinder project performance. In addition, the overall duration of the theoretical piping operation was reduced from 246 to 219 days in favor of the AMLTT based model; a reduction in schedule duration of approximately

11%. An improvement in schedule performance of even 2 to 4% would translate into significant cost savings on any typical industrial construction project. While completely hypothetical, the results presented here serve to demonstrate the beneficial impact on schedule performance that could potentially be achieved via the integration of AMLTT within a single construction supply chain such as piping, let alone the greater construction supply network as a whole.

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Automated Model-based Recognition of Progress Using Daily Construction Photographs and IFC-based 4D Models

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Abstract

Accurate and efficient tracking, analysis and visualization of the as-built status of projects are critical components of a successful project monitoring. Such information directly supports control decision-making and if automated, can significantly impact management of a project. In this paper, we describe an innovative automated approach for recognition of physical progress from unordered daily construction photologs and Building Information Models (BIMs). First, we describe an automated approach to photo-realistically reconstruct the as-built in 4D and label scene for occupancy. The IFC-based BIM is subsequently fused into the as-built scene by a registration-step and is traversed and labeled for visibility. Finally a machine learning scheme built upon a Bayesian probabilistic model is introduced that automatically detects physical progress in presence of occlusions and demonstrates that progress tracking at schedule activity-level could be fully automated. We present results on automated tracking, analysis and visualization of two ongoing building projects.

Introduction

Accurate and efficient tracking of the as-built status of buildings under construction has been repeatedly reported as a critical factor for success of project monitoring (e.g., Bosché 2009, Bosché et al. 2009, Zhang et al. 2009 and Navon 2007). Such information directly supports progress control and if automated can significantly impact the management of a project. Current monitoring methods (1) require manual data collection and extensive as-planned and as-built data extraction from construction drawings and schedules; (2) and due to extensive workload are sometimes measured non-systematically and (3) are visually complex (Golparvar-Fard et al. 2009a, Navon and Sacks 2007). There is a need for effective techniques allowing data to be collected easily and at almost no cost, processing automatically and reporting back in a format useful for all project participants. In the meantime, cheap and high resolution digital cameras, low cost memory and increasing bandwidth capacity have enabled capturing and sharing of construction photographs

on a truly massive scale. For example, on a 200,000 SF building project an average of 500 photos/day is being collected by AEC professionals. Such a large and diverse set of imagery enables the as-built scene to be fully observed from almost every conceivable viewing position and angle during construction of a project. The availability of such rich imagery with minimal cost may enable reconstruction and visualization of as-built site geometry at high resolution. In the meantime, Building Information Models (BIMs) are also increasingly turning into binding components of AEC contracts. If linked with project schedules, BIM can form detailed chronological models that allow 4D clash detection and schedule quality control to be conducted. Furthermore they can serve as powerful baselines for progress tracking as well as visualization of discrepancies. Application of BIM during construction phase will be increased if further added-values from integrating BIM with as-built are investigated.

To date, application of unordered daily photologs for monitoring progress is unexploited by researchers. A major reason is such imagery has traditionally been in a form that is not easily adaptable for image processing; i.e., site photologs are usually unordered, un-calibrated, with widely uncontrolled lighting conditions. Developing computer vision techniques that can effectively work with such imagery to track as-built is a major challenge. In this paper, we introduce an innovative approach for tracking as-built elements from daily photographs based on *a priori* information (4D as-planned models). First using structure-from-motion (SfM) techniques, an as-built point cloud is generated and images are automatically registered. Subsequently the as-built point cloud is registered over the as-planned model. At this stage a combination of Multi-View Stereo (MVS) as well as voxel labeling-coloring algorithm is used to generate a volumetric reconstruction of the site, labeling different areas based on occupancy. Same labeling process is conducted on the as-planned model to identify occupied and visible areas for monitoring. Finally a Bayesian probabilistic model is introduced to automatically recognize progress by comparing it with dynamic thresholds learned through a Support Vector Machine (SVM) classifier. This makes our model to be the first *probabilistic model for progress tracking and visualization of deviations that incorporates both as-planned models and unordered daily photographs in a principled way.* Unlike other methods that focus on application of laser scanners or time-lapse photography (Bosché 2009, Bosché et al. 2009, Ibrahim et al. 2009, Zhang et al. 2009, Golparvar-Fard et al. 2009b, El-Omari and Moselhi 2008), our model is able to use existing information without adding burden of explicit data collection on project management and reports competitive accuracies compared to (Bosché 2009, Ibrahim et al. 2009) especially in presence of occlusions.

Overview on the D^{4}AR progress visualization and detection engine

As shown in Fig. 1 our work is based on the application of daily construction photographs, Industry Foundation Class (IFC) as-planned models as well as construction schedule to generate the D^{4}AR model and automatically measure progress. First we combine schedule with the IFC as-planned model to generate a 4D baseline for monitoring. Next using SfM, we generate an underlying 3D geometry for the as-built and set a baseline for visual navigation based on automatic registration of photographs in the scene. This is done by calculating camera pose (i.e., location, orientation, and field of view) and sparse 3D coordinate information of the as-built scene (Golparvar-Fard et al. 2009a). Subsequently the IFC model is superimposed

over the as-built point cloud. The Euclidean point cloud as well as the camera parameters is fed into MVS algorithm (Furukawa and Ponce 2009). The results are subsequently placed into an as-built voxel coloring and labeling algorithm developed in this research to get a dense reconstruction of the as-built and label scene for occupancy. Using a similarly structured algorithm, as-planned is also labeled for occupancy and visibility. The labeled scenes are fed into a novel Bayesian model and monitored by dynamically classifying the results through an SVM classifier. Finally, detected as-built, camera configurations, plus 4D as-planned model are fed into the D^4AR viewer to visualize as-built, as-planned and progress deviations in an integrated fashion. In the following, these steps are presented.

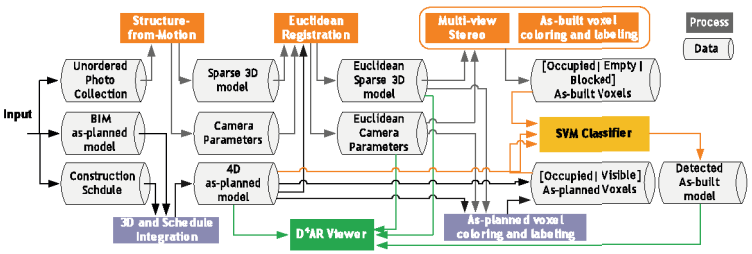


Figure 1. An overview of data and processes in our proposed system.

Reconstructing the underlying as-built representation

Recently Golparvar-Fard et al. (2009a) sparsely reconstructed and visualized the as-built scene from unordered daily photographs. The work is based on SfM similar to (Snavely et al. 2008) to fully automatically reconstruct an as-built point cloud from a set of images. This module consists of the following steps: (1) Analyzing and extracting SIFT feature points (Lowe 2004) from images; (2) Matching image features across image set; (3) Find an initial solution for the 3D locations of features points, calibrating cameras for an initial image pair and reconstructing the rest of the scene plus estimating motion of the cameras based on bundle adjustment (Nistér 2004; Triggs et al. 1999) and finally (4) Registering point clouds that are generated for each day to build a 4D as-built model (new concept in this paper). To present how these steps are formed, we choose two sets of 112 and 160 images that are taken on 8/20 and 8/272008 at Residence Hall (RH) project in Champaign, IL. In both cases, field engineer causally walked along the sidewalk of the project and took images within a few minutes.

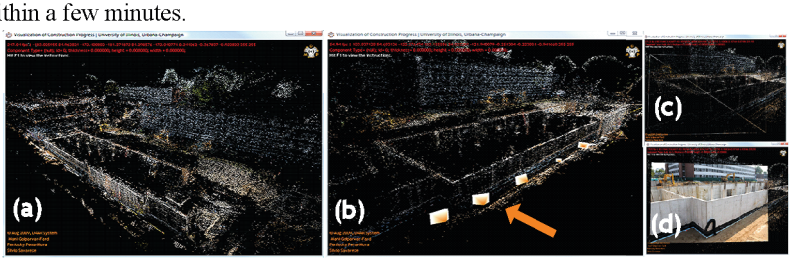


Figure 2. As-built point cloud reconstruction for RH project using 160 images taken on 8/27/2008.

Fig. 2a and b represents reconstructed scene from the same image subset and illustrate five registered cameras in the D^{4}AR environment. Once a camera is visited, the frustum is texture-mapped with a full resolution of the image so user can interactively zoom-in and visually acquire information on progress, quality, safety and productivity details as well as workspace logistics (Fig. 2c and d).

Aligning the as-built model to the as-planned model

To align the as-built point cloud with the as-planned model, transformation between these two Cartesian coordinate systems needs to be found. In this case, given an as-built point cloud that is reconstructed from photos collected at a time (t), we use the as-planned model that is updated up to time (t_0) ($t_0 < t$); i.e., the as-planned model shows progress up to time (t_0). The alignment transformation can be formed as a rigid-body motion and hence can be decomposed into rotation and translation. However in SfM, the scale may not be known. To solve this transformation with uniform scale (7 DOF) we need at least 3 corresponding points. These points could be surveying control points or a set of points that represent geospatial location of the foundation walls and columns as their detection and correspondence is visually easier. Let there be n corresponding points from as-planned and as-built models for registration. We denote the two coordinate system points by $r_{b,i}$ and $r_{p,i}$ respectively, where i is the number of corresponding points which ranges from 1 to n, $r_{b,i}$ and $r_{p,i}$ be the Cartesian coordinates of as-planned and as-built models respectively. We are looking for transformation of the form:

$$r_{b,i} = sR(r_{p,i}) + T \tag{1}$$

where s is a uniform scale factor, T is the translational offset and $R(r_p)$ is the rotated version of the as-planned model. This can be formulated as:

$$\sum_{i=1}^{n} \left\| e_i \right\|^2 = \sum_{i=1}^{n} \left\| r_{b,i} - sR(r_{p,i}) - T \right\|^2 \tag{2}$$

We follow Horn (1987) to get a closed-form solution to the least square problem of absolute orientation. In our system, this procedure needs to be done only once to have the initial point cloud registered to the 3D model. From then after, we only need to register the point clouds that are generated from new photographs to the underlying point cloud. For this purpose, we use a set of photographs that are showing part of the scene which is not significantly changed from one-day to another. For this dataset we use an Iterative Closest Point (ICP) algorithm that solves for scale as well (Du et al. 2007). This method automatically finds a random set of points from each point cloud and automatically aligns the new point cloud to the former one, in turn having the new point cloud registered with the as-planned model. This allows 4D as-built point clouds to be generated wherein user can navigate the as-built scene both spatially and chronologically. The 4D as-built registered with the 4D as-planned model allows expected and the actual schedule of the project to be compared as well. Fig. 3 shows 4 snapshots from the RH project. In Fig. 3a and b two separately reconstructed point clouds are shown while in Fig. 3c the two point clouds are registered and mutually visualized. In cases (a) and (b), reconstructions are based on 112 and 160 photographs collected from outside of the basement along the side-walk. In Fig 3d, registration of as-planned and as-built models is visualized. Table 1 reports the accuracy of registration. As observed high accuracies are achieved, though the accuracy is not

sensitive to how the control points are selected. Since usually more than the minimum number of control points (three) is selected, such error is minimized.

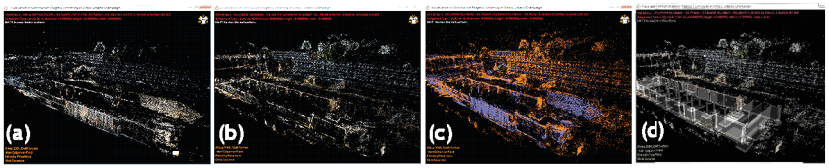


Figure 3. Registration of as-built point clouds for 112 and 160 images taken on 8/20 and 8/27.

Table 1. Registration error measured on reconstructions shown in Figure 3.

	IFC model + point cloud (a)	IFC model + point cloud (b)	Point clouds (a) and (b)
Image Size	2144×1424	2573×1709	--
# of corresp. Points	7	9	Randomly chosen by ICP
Δe_{mm}	0.20 *mm*	0.65 *mm*	0.43 *mm*

Automated progress monitoring problem setup and notation

In order to detect progress, we first discretize the integrated as-built and as-planned scene Ω into a finite set of opaque voxels (volume element in space) along dominant Euclidean axes wherein each voxel (v) occupies a finite homogeneous volume of the scene and has a consistent visual appearance. This approach allows us to reason about progress in small elements of space. In our model, voxels are equilateral; therefore resolution of the voxel grid is determined by δ. Given an image II_i, $proj_i(v)$ is used to denote the reprojection of the voxel over image i and is measured as:

$$\ni k = 1,2,...,8 \rightarrow [u,v,1]_k' = K_i[R_i \mid T_i][x,y,z,1]_k' \quad (3)$$

wherein k is the index of the voxel corners, K_i is the intrinsic camera parameters, R_i and T_i represent camera rotation and translation. Since we analyze all images within the SfM step, intrinsic and extrinsic camera parameters are known at this stage. The next step is to traverse the scene and assign as-built and as-planned labels as well as a color to each voxel. This step allows expected and actual progress in each voxel to be sensed. It is critical to traverse voxels in a certain order otherwise the reconstruction results will not be unique. In order to address this issue, we introduce an ordinal visibility constraint similar to that of Seitz and Dyer (1999) allowing certain invariant voxels whose colorings is uniquely defined to be found. Rather than only using this constraint to address uniqueness of the solution, in our approach we find areas within the space that are occupied and visible (progress). First we transform the integrated scene to a new coordinate system wherein the axes are aligned with the dominant axes of the as-planned site. This will minimize search space, since we can only reason about areas in which progress is expected to be observed. Then we start traversing the scene from the closest voxel to the convex hull of the cameras in a plane normal to the convex hull and in a front-to-back order (See Fig. 4- axis 1 to 3 directions). As we march through voxels, we verify visibility constraint and label scene as follows:

(1) *As-built labeling:* We first check if a voxel contains 3D SIFT or MVS points. In this case, we label that voxel as Occupied (O_b), have that voxel reprojected back on all images that observe it (3) and mask the reprojected pixels. Next, we keep depth of the voxel as another masking layer for each image. This allows us to automatically generate segmented images while accounting for complete and partial occlusions. If a voxel does not contain SIFT or MVS points (which is more often the case), we check

for visual consistency. In such cases if voxel reprojections on the image-set do not overlap with masked pixels i.e., is not fully occluded from all images, and it happens to contain part of the as-built scene (without considering noise or quantization effects), it needs to have equal radiance reprojections. In presence of these effects, we evaluate correlation of pixel colors to quantify voxel consistency:

$$\lambda_v = \frac{(n-1)SD^2}{\sigma^2} \leq thresh \qquad (4)$$

where SD is the standard deviation of color values, and σ^2 is the sensor color measurement error, and finally n is number of all images that observe the voxel. If λ_v is less than allowable correlation error ($thresh$), we label that voxel as visually consistent (O_b) and have that reprojected on all observing images and mark their reprojections. In our experiments there is a minimum allowable number of reprojected pixels for each voxel from all images (20 pixels). If consistency is not satisfied, we label the voxel as Empty (E_b) and finally if the minimum allowable number of pixels is not satisfied, the voxel is occluded from all views and we denote that voxel as Blocked (B_b). In our experiments we chose $thresh$ by analyzing completeness vs. accuracy for as-built reconstruction. This process has two significant outputs: (1) Labeling all as-built voxels [O_b| E_b| B_b], allowing reasoning to be made in presence of both static and dynamic occlusions; and (2) creating as-built range images.

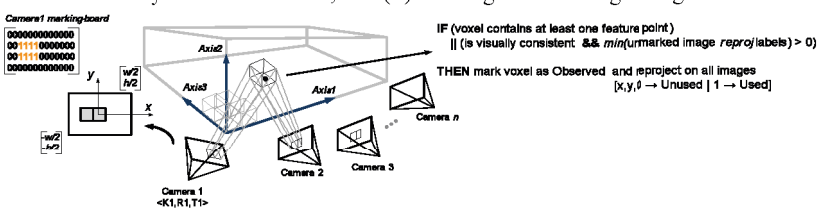


Figure 4. An illustration of coloring and labeling voxels and reprojecting labels on the image dataset.

(1) *As-planned labeling:* The as-planned model by itself accounts of static occlusions, though by placing the non overlapping areas of the as-built scene (e.g., reconstruction of excavators, temporary structures) over the as-planned, we induce dynamic occlusions. Now we march the scene in a similar fashion to that of the as-built. This time, if a voxel has at least one of its corners inside an as-planned element, we label that as Occupied [O_p]. Subsequently we reproject voxel on all images that observe it and mask reprojected pixels. In case of non-overlapping as-planned and as-built areas, we check the consistency from the as-built masking and have visually consistent voxels reprojected back on all images for masking pixels. This allows us to count for occlusions since if the reprojections contain the minimum unmasked pixels, we can label the voxel as Visible [V_p]. In our model, all labels are independent from one another and are marked with 1 or 0. Image pixels are also marked so that if a pixel is observed, the pixel is labeled with 1 and if not observed remains as 0 (See Fig. 4 left side). Such labeling allows us to reliably reason about progress in partial visible areas.

Probabilistic model for progress detection and discriminative learning

Once the scene is labeled, we can formulate progress as observation per expected as-planned element (i) with a binary value (E^i): E^i=1 if progress is detected and E^i = 0 if not. First we need to check for observation of expected columns attached to an

activity (all Elements i as E^i). Let's assume that each element E^i attached to the activity consists of n voxels. We introduce a set of probability events: Within a given volume in the scene (ω_i): Let η be the event of observing an occupied as-built element (any tangible physical element), θ_p be the event of observing as-planned element, θ_T be the event that an as-planned element is occupied and finally s the expected level of progress queried from the 4D as-planned model. We define probability of observing progress for element E^i associated with a given schedule activity (duration = n days) as a conditional probability of the form:

$$P(\eta^i \mid \theta_T^i) = \frac{P(\theta_T^i \mid \eta^i) P(\eta^i)}{P(\theta_T^i)} \tag{5}$$

Where $P(\theta^i_T|\eta^i)$ is the probability of observing as-planned element given evidence of occupancy; $P(\eta^i)$ probability of the expected as-built element observation and $P(\theta^i_T)$ probability of observing expected progress. Each element can be computed as:

For the as-built:
$$P(\theta^i{}_T \mid \eta^i) = [\frac{\sum O_b}{\sum O_b + \sum E_b}]_{\theta_p} \tag{6}$$

For the as-planned:
$$P(\theta^i{}_P) = [\frac{\sum V_p}{\sum O_p}]_{\theta^i{}_P} \tag{7}$$ and $$P(\theta_T^i) = (t/d)V \tag{8}$$

where $P(\theta^i_T)$ is the expectation of observable progress, d is the total duration of construction activity, and t represents the t_{th} day within d and finally V is the volume of expected as-built element. We use $P(\eta^i|\theta^i_T)$ to estimate progress with a threshold Γ^i. Choosing an optimal value for the threshold for each element is problematic. For example given a 10% visibility [$P(\theta^i_P)$] and 25% accuracy of reconstruction $P(\theta^i_T)$, the $P(\eta^i|\theta^i_T)$ may be susceptible to noise and inaccuracy in reconstruction. Therefore it may not be reported as detected. This selection is particularly difficult, because (1) to achieve a desired accuracy, for different element types with different materials, different *thresh* needs to be used; (2) Progress monitoring task with partial visibility is subjective by nature and needs a field expert's opinion as to whether it has taken place or not. Thus we use a machine learning model to estimate such dynamic thresholds in a principled way. We can express the threshold (Γ^i) as:

$$\Gamma^i = f(\theta_p(t), P(\eta \mid \theta_T), t/d, T, \Psi(t), \delta, thresh, \varepsilon) \tag{9}$$

Where t is construction activity duration from t=0 to d, T_i is element type (e.g., column, beam, foundation), $\Psi(t)$ is the surface visual appearance of the element i (e.g., concrete, formwork, steel), δ voxel resolution, *thresh* consistency threshold and finally ε is accuracy in registration and the underlying SfM and MVS algorithms. As shown in Table 1, we assume there is minimal error in registration and as-built reconstruction. Γ^i can be learned by casting the problem into linear classification problem. That is by learning the hyper-plane that separates the two classes in a multi-dimensional feature space, as shown in Eq.(9). The two classes are *progress*=1 and *no-progress*= 0. The optimal hyper-plane that separates the two classes can be learned in a supervised fashion using a linear support vector machine (SVM) (Fan et al. 2008). Once the classifier is learned given a new observation along with the measured features, we can establish whether progress has occurred or not by feeding observation into the classifier and retaining the output.

Experiments and results

In order to verify effectiveness and robustness of our proposed reconstruction pipeline as well as automated progress detection over arbitrary set of daily photographs and in presence of occlusions, we performed experiments on three different image datasets. These datasets were collected under different viewpoints and lighting conditions and were used for evaluating this task. These datasets are two photologs of 112 and 160 images from RH project and a 288 image dataset from a Student Dining (SD) construction project. The images are all taken at the basement level of project with significant amount of occlusion observed in both RH cases as the images were not taken from inside the basement area. Rather they were all taken along a side walk of the project (See locations of the camera frusta in Fig. 3-b). We synthetically reduced the resolution of these images to about 2MPixels and initially set voxel resolution to $0.06m$. Fig. 5 illustrates the dense reconstructions presented in Fig. 3b.

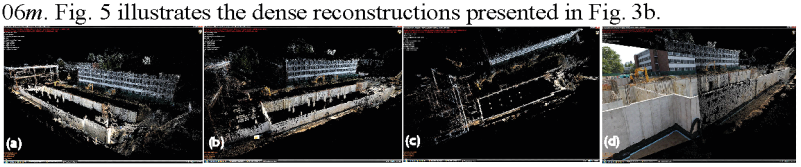


Figure 5. Illustration of dense as-built reconstruction for the same dataset presented in Fig. 3-b.

Comparison of detection accuracy

In our experiments, we analyze performance by (1) *Recall*: The fraction of truly recognized IFC-model elements relevant to the total number of model elements that are used for our SVM classifier. This will show *sensitivity* of our detection engine. (2) *Precision*: The fraction of truly recognized IFC-model elements relevant to the total number of elements that are recognized with progress in our detection engine. This will show the *accuracy* of our SVM classifier. In our approach, the SVM model classifies progress with a binary value (progress/ no progress). We train the SVM model over an initial set of categories that are fed into the machine (Cross-checked by two field engineers and a superintendant). The hyper-plane is dynamically learned though it can be roughly reported (from experiments) that if the expected observable area is less than 20% of the observable surfaces of the IFC element and the volumetric reconstruction has only been able to reconstruct the expected areas up to 50%, this element should not be recognized by the detection. The results of average accuracy for our experimental datasets are presented in Table 2. Although our approach is the first of its kind to take advantage of existing daily photographs, yet even in presence of sever occlusions, high accuracies are reported.

Table 2. Average accuracy of SVM binary detection for training and testing samples.

# of training elements	# of IFC elements	Training accuracy	Detection accuracy
112	152	87.50%	82.89%

To further examine accuracy and sensitivity of our detection engine, we studied precision-recall and true-positive/false-positive. Fig. 6 illustrates our experimental results. These graphs are only drawn for the elements that were expected to be detected and not for those elements that are fully occluded. Given the formation of this approach for the first time, the results seem very promising, yet it shows our approach is not sensitive to formation of the hyper-plane. Finally to represent progress, we use the D^4AR model platform reported and the color-coding scheme

presented in (Golparvar-Fard et al. 2009b). Fig. 7a to c show the result of our progress detection engine. In this case, IFC elements that are behind and on-schedule are color-coded with red and green accordingly. For those elements that progress is not reported, we color them in gray. Such color-coding scheme makes it easy to observe accuracy of progress detection, yet allows corrections to be made on a case-by-case basis. Fig. 7d to g illustrate examples of false positive and false negative in our detection. As observed, since our model does not contain operational details (e.g., forming stages), the formwork is falsely detected as finish of a concrete element construction. In Fig. 6d the wall highlighted should be detected, but due to occlusions it is not properly reconstructed and consequently not detected.

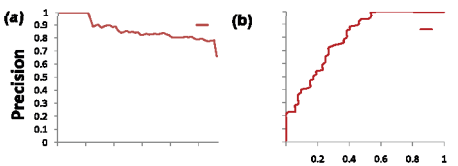


Figure 6. (a) Precision-Recall graph and (b) the TP/FP graph for our progress detection engine.

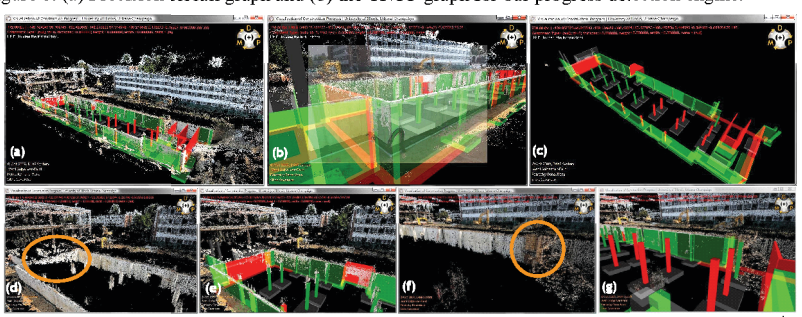


Figure 7. (a - c) Progress detection results color-coded over the IFC model and visualized in the D^4AR environment. (d, e) False Negative – the wall should be detected for progress although it is severely occluded (f, g) False Positive – the formwork should not be detected as evidence of progress.

Conclusions and summary

An automated approach for tracking, analysis and visualization of progress using daily site photographs and IFC-based 4D models is presented. In our approach, images can have low qualities, yet robustly generate dense point clouds. Subsequently the underlying point cloud is registered with other point clouds as well as the as-planned model, generating an integrated 4D as-built and as-planned model for progress visualization. Our as-built and as-planned voxel traversing demonstrates high accuracy in labeling for occupancy and visibility. The SVM model shows promising results in detecting progress. This overall marks our approach to be the first of its kind to fully take advantage of daily site photographs and IFC-based 4D models for progress tracking and analysis. Application of our system is perceived to minimize the time required for as-built data collection and as-planned data extraction; removing subjectivity of progress detection through an automated systematic detection; and finally interactive visualization to minimize the time required for coordination of

progress possibly leading to a better decision-making for project control. We need to conduct more conclusive experiments and research on reconstruction and progress detection especially at interiors and for MEP components, incorporating visual appearance detectors [$P(\eta^i)$] as well as introducing sequence knowledge to our system to enhance progress tracking and reporting abilities.

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Construction activity classification using accelerometers

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Abstract

Measuring and controlling productivity of critical activities will have a significant impact on the cost and time performance of a project. The current practice of acquiring productivity data is heavily dependant on manual collection and data entry; hence it is time consuming, costly and difficult. The objective of the present work is to investigate the automation of the activity sampling method for rapid and real time collection of productivity data. Activity recognition or classification is identified as the major challenge in activity sampling. The proposed method uses accelerometers for activity recognition and a framework was developed for construction activity classification using accelerometers. This paper discusses the preliminary investigation phase in lab environment with a single wired triaxial accelerometer attached to the body of the subject performing typical repetitive movements of a mason. The data patterns were distinct for different movements and hence the features extracted can be used in training for classifying various activity categories.

1 Introduction

The importance for measuring and controlling productivity is based strongly on the fact that construction labor costs are generally known to be 33-50% of the total project budget (Hanna 2001). The need to go back to the basics of measuring productivity at the project site level is strongly recommended as site is recognized as the defining locus of production for construction (Chan and Kaka 2004).The literature shows that there is inertia towards measuring productivity at the project level. Time and expertise needed in handling productivity data are identified as the major practical issues faced in the implementation of on-site productivity measurement system. The results of a survey indicated that 31% of the respondents stated that they did not have formal process to measure, monitor and

document construction productivity as it is time consuming, costly and was too difficult (Motwani et al. 1995).

The effectiveness of work sampling as a productivity indicator has been verified and work sampling information has shown close relationship to labor productivity (Liou and Borcherding 1986).Work sampling is a method that evaluates the amount of productive, supportive and non-productive time spent by the workers in performing the work activities. Time utilization studies are important as the meta-analysis study by Horman and Kenley (2005) reveals that 49.6% of time in construction is devoted to wasteful activity. Work sampling is a useful method for analyzing site productivity and helps in providing solutions for existing productivity problems (Orth et al. 2006). But one of the major constraints with activity sampling has been the amount of data that the observer can record and analyze during a sampling assignment. Manual methods of recording activity are both time consuming and pose difficulties in analysis. A computerized activity sampling tool, 'CALIBRE' as an application in Microsoft Access was developed (Winch and Carr 2001), but still it relies on onsite observations for monitoring the site.

Some studies have explored the benefits of image based techniques for activity classification. Peddi et al. (2009) developed an automated on-site productivity measurement system employing the concepts of computer vision and artificial intelligence where the system wirelessly acquires a sequence of images of construction activities. Gong and Caldas (2009) used intelligent video imaging method for analyzing productivity data for cyclic operations in construction. But vision based recognition has several disadvantages-computationally intensive, difficulty with moving backgrounds and varying light conditions. Gonsalves and Teizer (2009) attempted human motion analysis using range image cameras. Here a star skeleton structure was used for human activity recognition for application in health and safety. This method may be considered for automated activity recognition in activity sampling but the dynamic change in construction environment with higher levels of noise will severely affect the accuracy.

As activity recognition has been identified as the major challenge in activity sampling, a novel method, construction activity classification using accelerometers is investigated in this study. There has been research, utilizing accelerometers in health care and sports, and section 2 gives a review on both accelerometers and activity recognition using accelerometers. Section 3 discusses the frame work developed for activity classification in construction. The description of pilot study on classification in a labor intensive activity like masonry is presented in section 4, followed by conclusions in section 5.

2 Review on activity recognition using accelerometers

An accelerometer is a sensor that returns a real value of acceleration along the x, y or z-axis and so it can be any of the three types, uniaxial, biaxial or triaxial accelerometer. Accelerometers are objective and reliable for assessing physical activity levels as the signal magnitude area of acceleration signal gives very good correlation (r=0.89) with metabolic energy expenditure for various activities

(Bouten et al. 1997).The data from the accelerometer can be stored locally for offline processing or wirelessly transmitted to a data logging unit.

2.1 Advantages

The advances in micro electromechanical systems (MEMS) have greatly reduced the cost and size of these devices. These belong to the category of wearable sensors as easy attachment to the human body is possible with elastic straps. Accelerometers are currently among the most widely studied wearable sensor for activity recognition not only because of small size but also of accuracy and reasonable power consumption. They can be embedded in devices like wrist bands, cell phone, belts, etc. Sony-Ericson mobile phone with in-built 3D accelerometer (Prekopcsak 2008**),** EWatch multi sensor platform with a dual axes accelerometer (Maurer et al. 2006) and 3-axis accelerometer with embedded image sensor in a belt buckle (Cho et al. 2008) are some good instances showing integration of accelerometers with commonly used devices. Accelerometers have the advantage of being resilient and robust in trying conditions as opposed to image sensors.

2.2 Number of sensors and Position

Recognition accuracy increases with the number of sensors, but more sensors may be uncomfortable for the subject and could interfere with normal or spontaneous physical activity**.** So the main focus of research has been to recognize activity with one or two sensors. In general it is difficult to recognize activities using only one accelerometer, but the work by (Yang et al. 2008) reports an overall recognition of eight daily activities with an accuracy of 95% by keeping the sensor module on the dominant wrist. Comparing the classification accuracy with different configuration of accelerometer placements on human body helps in arriving at the optimum location. Positioning at the waist was chosen in many studies because this location provides the most useful information on the subject movements being close to the centre of the body. The waist is also a location that has been found to be comfortable to wear and convenient to the user.

2.3 Accelerometer specifications

Triaxial accelerometers are preferred as majority of activities performed involve movement in the three directions. Past studies have shown that the acceleration at body limbs and extremities can exhibit a 12g range, where as torso and hip experience 6g range in acceleration (Bouten et al. 1997). Hence the specification for ‘g’ range required for study depends on the location assigned for the accelerometer. The band width of mobility of interest of activities normally encountered lies below 20Hz and a sampling frequency of 40Hz is sufficient to meet the Nyquist criterion (Lyons et al. 2005).

2.4 Areas of application of activity recognition using accelerometers

A fertile domain for activity recognition is health care. Recent developments in communication and sensor technologies have paved the way for creating a smart health care environment. It is possible that patients can stay at home and their

movements can be remotely monitored using accelerometers. Assessing abnormal movements resulting from poor health is essential for monitoring patients' health status. Accelerometers also have been used for unsupervised home monitoring for house bound elderly and fall detection has been the primary subject for researchers in this area. Jonathan et al. (2006) have reported developing a cell-phone embedded activity recognition system for a variety of health-care related applications ranging from personal fitness to elder care. The field of sports is another area where it has found promising applications like recognition of movement patterns of a player. It helps in improvement to enhance skill and prevent injury. The prototype developed by Namal et al. (2006) can be used to select players based on their abilities and performance during the training. In another work triaxial wireless accelerometers were placed at chest and back to understand the stance and posture in lawn bowling (Gopalai et al. 2008). The study by Ermes et al. (2008) was aimed to assess the feasibility of activity recognition in out of laboratory settings that included cycling, rowing and playing football. But only a few works have been reported utilizing accelerometers in industrial settings. Uiterwal et al. (1998) have used accelerometers for measuring time utilization in various activities for assigning the right job for an injured worker under the rehabilitation program. In another work the accelerometer and acoustic data were used for indentifying different activities happening in a wood shop (Lukowicz et al. 2003). Zappi et al. (2007) have tried to recognize set of ten activities in the quality assurance checkpoint of a car assembly line.

2.5 Classification methods

Activity recognition is essentially a data analysis task in which the input accelerometer data is processed and analyzed to give output in the form of classification categories or labels. Hence activity recognition can be formulated as a classification problem. The real world activity recognition can rely on classifiers that are pre-trained on large activity data sets to recognize relevant activities as per Bao and Intille (2004). Human activity recognition traditionally has been performed by statistical methods like the Hidden Markov Model. Currently classifiers like Decision Trees, Artificial Neural Network and Support Vector Machines have become popular for delivering accurate results.

3. Construction activity classification frame work using accelerometers

Figure 1 shows the framework that was developed for activity classification in construction based on the available literature. This can be used for arriving at the best classifier and the best location of the accelerometer. Step wise explanation of the frame work is given below.

i. An activity is selected on the basis of its critical nature with regard to cost and timely completion of the project. .
ii. The activity categories of the workers can be obtained from the work sampling sheet if available or by conducting an observation study.
iii. The selection of the accelerometer depends on the range of measurement required and the sampling rate.
iv. The position of the accelerometer depends on the integration possibility and subject comfort. Initially more than one location may be chosen and the frame work helps in determining the best location.

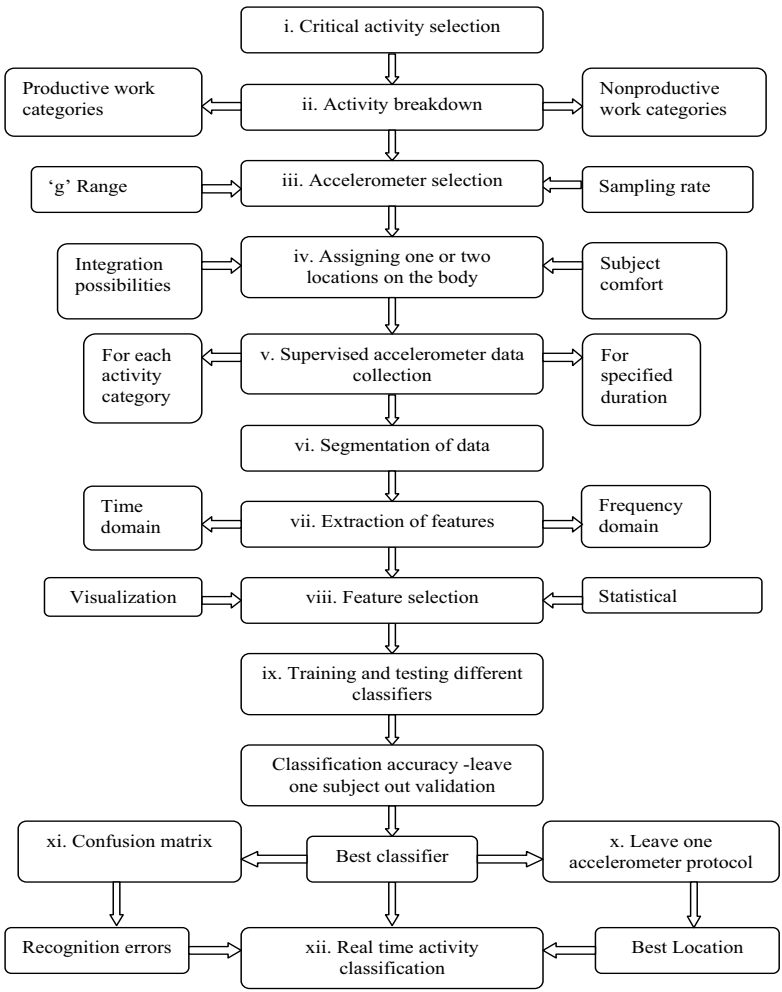


Figure 1 Construction activity classification framework

v. Data collection is taken for assigned tasks for fixed duration for different subjects in a supervised environment.
vi. The accelerometer data is broken into windows or segments. Human activity recognition employs typical overlapping window sizes of 1s or 2s.
vii. Time domain and frequency domain features are extracted from the segments.

viii. The highly discriminating features are selected using visual bar graphs or statistical techniques.
ix. Different classifiers are trained and tested , best classifier is identified
x. For the best classifier, the best location can be identified if more than one location was selected in the initial stage
xi. Confusion matrix helps in detecting the limitation of the accelerometer in recognizing any activity with the best classifier
xii. Real time classification is possible now using best classifier at the best location

4. Pilot study on activity recognition in masonry

Masonry or bricklaying is a critical labor intensive activity in building construction and the literature is rich with productivity studies in masonry.

4.1 Brief review on productivity studies in masonry

Sanders and Thomas (1991) have used data from multiple projects and have identified work type, building element, construction methods, design requirements and weather as the project related factors that significantly affect masonry productivity. As a continuation to this work they have used an additive regression model to forecast masonry productivity (Sanders and Thomas 1993). Sixteen field factors affecting masonry labor productivity were analyzed in a study by Ovararin and Popescu (2001). Enhassi et al. (2007) have used benchmarking approach to measure, analyze and compare masonry labor productivity across nine different projects. Olomolaiye et al. (1987) measured the amount of productive and unproductive times for masonry work in seven sites, using activity sampling. In another work, six critical productive activities were identified for bricklaying using step wise regression and these are fetch mortar, fetch brick, cut brick, lay brick, setting and checking, and measuring (Olomolaiye et al. 1996).

4.2 Selection of accelerometer

Low cost MEMS (micro electromechanical systems) inertial measurement unit Motion Node Accel was selected for the initial investigation. It provides measurement of linear acceleration along the three axes with USB interface output (2009, GLI Interactive LLC) and the Table 1 gives a few technical details.

Table 1 Technical details of Motion Node Accel

Weight	14 grams
Enclosure	ABS plastic
Sampling rate	50 to100Hz by 10 Hz
Physical size	59 mm x 36 mm x 15 mm
Power requirement	Powered by USB host
Range	Range ± 2g or ± 6g (user selectable)

The data acquisition is performed using Motion node software through a USB communication port, whose protocol is a GLI Interactive LLC proprietary format. A wired accelerometer was selected to ensure good quality of data for the initial investigation.

4.3 Position of the accelerometer

Activity recognition is investigated using single triaxial accelerometer at the mason's hip as it is a comfortable location and there is a possibility of integrating with belt and personal digital assistant. The sensor is firmly attached to the human body using velcro tape in order to avoid rotational noise caused by imperfect adherence. The 'g' range of ± 6g is appropriate for measurements at hip.

4.4 Data collection

Data was collected from one subject posing as a mason performing the repetitive movements like fetch brick, twist laying, fetch mortar, spread mortar and cut brick. These activities are typically cyclic, but for training the classifier, data need to be collected continuously for a particular movement for a specified time interval. Hence the data was taken continuously for five minutes for each activity and this corresponds to 18,000 samples as the sampling frequency selected was 60 Hz. The wired accelerometer is connected at the hip as shown in Figure 2 and the descriptions of each activity are given in Table 2

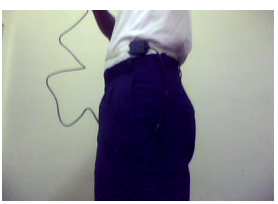


Figure 2 Location of sensor at hip

Table 2 Description of activities

Activity	Description
Fetch brick	Stooping down and fetch a brick with single hand by bending back
Twist laying	Turning towards the wall after a fetch with twisted action at the back for laying
Fetch mortar	Scooping mortar using trowel in one hand and placing on the wall with a bend and twisted action at the back
Spread mortar	Forward and backward action of arm and shoulder to spread mortar with trowel at a horizontal level
Cut brick	Performed with a trowel, to and fro motion of the arm along a vertical plane

4.5 Data analysis and Discussions

The acceleration data was stored in comma separated value format and then imported to Microsoft Excel for further analysis. The acceleration values for duration of one minute were then plotted. The acceleration values for all the activities follow a distinctive repetitive pattern. Figures 3a and 3b shows the patterns of acceleration for spread mortar and fetch brick respectively along the three axes. Hence the data segments are rich in information related to a particular

activity and this justifies the classification method utilizing the segments rather than instantaneous values. It can be also seen that the acceleration along the Z axis is more or less near to '-1g' value, due to the gravitational acceleration.

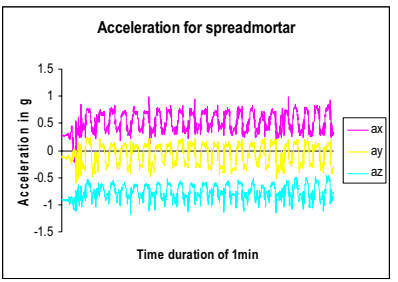


Figure 3a

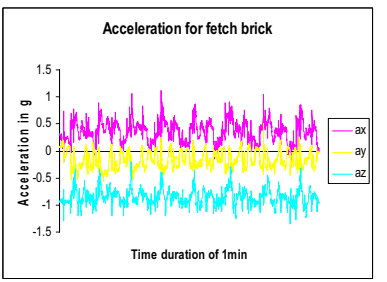


Figure 3b

A few popular time-domain features like arithmetic mean, median, mean absolute deviation, standard deviation and variance were calculated along the three directions. The features were obtained for the entire data set of 18000 samples for each activity category. Charts for mean and variance are shown in figures 4a and 4b respectively.

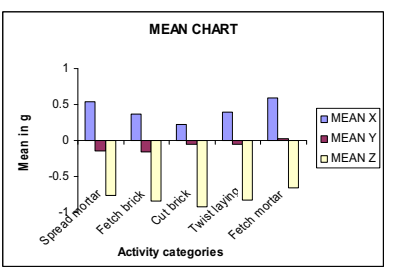


Figure 4a

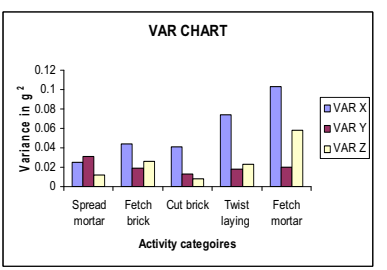


Figure 4b

It can be seen in figure 4b that the bar lengths are distinct for each activity. Hence 'variance' in prima facie is a discriminating feature and it may be used for training the classifier to recognize activities. However further statistical analysis and experiment based investigations are essential to evaluate the accuracy of the system to classify activities.

A few challenges of using wearable accelerometers in similar applications are discussed here in brief. It is difficult to ensure proper contact between the sensor and the body part for longer periods of time. The position of the accelerometer must be decided judiciously so that it will not interfere with the natural movements of the labor. Careful handling of wearable sensor with out damage can pose challenge in tough construction environment. Wireless accelerometers are necessary for real world application, but interference of other signals can affect the data quality. The labor must be educated regarding the objectives of the study to guarantee hearty cooperation.

5. Conclusions

A framework was developed for automating the activity classification process utilizing low cost accelerometers. A pilot study on activity classification in bricklaying was performed in lab environment and the preliminary results are highly encouraging. As discussed in the previous section, this framework relies on acceleration data segments and hence its optimum length and amount of overlap are decisive factors in correct classification. It was also shown how basic statistical parameters are relevant to select features for the training process. This work has opened an avenue for detailed studies with more subjects, different classifiers, out-of-lab settings and multiple sensor locations.

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Evaluating the Electric Consumption of Residential Buildings: Current Practices and Future Prospects

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Abstract

As the construction industry transitions towards green buildings, and the number of LEED certified facilities continues to increase, the question of how to evaluate as-built energy performance becomes more important. Most homeowners rely on a monthly bill to determine their electric consumption, which is not an effective way to understand the results of most energy-saving strategies. Real-time feedback and appliance-level information is necessary, but most solutions require extensive hardware sub-metering, with a high price due to the hardware and installation costs. We argue that, in order to achieve wide adoption, the solutions need to be simple, easy to install, inexpensive and be able to return the investment in a reasonable time.

In this paper we first analyze and compare the different types of technologies that are currently available for allowing homeowners to monitor their energy expenditure. Then we discuss new approaches that balance the trade-off between information and cost, and present preliminary results from a prototype Non-Intrusive Load Monitoring (NILM) system we have installed in a building.

1. Introduction

Conserving energy has become a pervasive goal across many different fields in recent years. The construction industry has been slowly embracing the concept of sustainability, partly through the application of certifications and standards for "green" buildings. It is rarely the case, however, that these sustainable buildings continue to be monitored after their construction, to assess their energy footprint. How do we know that these new facilities are in fact continuing to achieve the desired efficiency levels? How can building managers ensure this? For comparison, the

automotive industry, one whose products are hundreds of times less expensive than buildings, has been providing consumers with figures like instantaneous miles per gallon (MPG) for newer cars, helping the driver adjust their behavior accordingly.

The importance of buildings in the global energy consumption is hard to overestimate. Out of the 102 quadrillion BTU (quads) of total annual primary energy consumption in the United States, 40% is used to generate electricity. Of this number, 36% is consumed by commercial buildings and 37% by the residential sector (Energy Information Administration 2005). The remaining 27% is used, mainly, in manufacturing and transportation. Hence, reducing the consumption on any or both of these two types of facilities can have a significant effect on the total energy savings.

Facility managers (including residential homeowners), are interested in lowering their energy consumption, as it is becoming an increasingly expensive resource. But while there exist methods and tools for assessing the consumption of the various energy sources in a house, selecting the right approach in terms of costs and benefits, is not a simple task. Furthermore, most of the available solutions report static and/or aggregate information, such as monthly consumption, making it difficult to base energy-efficiency decisions on that type of data.

1.1 Motivation

As researchers in the intersecting field of information and building/construction technology, we believe it is our responsibility to shed some light on the different aspects of the problem of continuously evaluating the electric consumption of residential buildings. Specifically, we would like with this paper to (a) provide a brief summary of the different considerations that need to be taken when designing a measurement system for monitoring electricity consumption in residential buildings; (b) provide some insights into the type of data that homeowners may need in order to effectively reduce their electric consumption, based largely on literature findings; (c) survey some of the currently available solutions that exist in the market and analyze their similarities and differences; and (d) describe what some of the future technologies, currently being researched, could bring about.

A key motivation in the building industry is the Leadership in Energy and Environmental Design (LEED) family of certified facilities by the US Green Building Council. The LEED criteria have spawned a generation of high-performance buildings, yet they were devised for the design and construction of facilities. The bronze/silver/gold level achievements are awarded soon after buildings are occupied. In the future we expect that amendments to such standards will require life cycle monitoring of the facilities and/or require continuous energy improvements to maintain the ratings. To continuously improve energy use, significant improvements will need to be made in either user behavior and/or energy efficient technologies.

The behavioral impacts of providing users with real-time energy use feedback, even at the aggregate level (e.g., overall consumption of the building) can produce savings of up to 10-15% according to some studies (Fischer 2008; Parker et al. 2006). Larger savings are potentially achievable if more detailed data were available to the user, to automated building control systems or to electricity suppliers (allowing them to reward peak-shifting loads or subsidize equipment upgrades). We believe that if

decision makers had real-time access to the operational schedule and energy consumption of all the appliances in the building, better decisions could be made towards managing the building's electrical consumption. Furthermore, access to such fine-grained data would also benefit the building industry in many ways: informing designers about the effect of their choices on the energy consumption, supporting electricity audits and building commissioning processes, etc.

In principle, one way to obtain detailed appliance usage information would be through extensive hardware sub-metering. However, such an approach would have a high price due to the hardware and installation costs, as will be seen in later sections of this paper. Utilities provide their customers with monthly reports of their consumption, but automated meter reading (AMR) systems are starting to provide more frequent updates. Additionally, there are a growing number of commercially available power meters that can provide traditional power metrics in real-time at varying degrees of detail: the building's main electrical feed, circuit panels, individual circuits or individual outlets. These latter solutions range from hundreds to tens of thousands of dollars, their cost increasing with the level of detail obtained. The challenge, then, is to find a technology that balances this tradeoff.

In light of this, when discussing future technologies, we are going to give special attention to a technique called Non-Intrusive Load Monitoring (NILM), which attempts to deduce the energy consumption of each individual appliance in a building by matching their "*fingerprints*" on the overall voltage and current coming into the facility as measured by a single measurement system installed at the main electrical feed of the building.

1.2 Paper Organization

We will start by giving a brief overview of the different hardware and software considerations that we believe are important for effectively designing a system to continuously measure electricity consumption in buildings. These recommendations are based, primarily, on our past experience installing commercially available systems in different buildings around the city of Pittsburgh, PA. As an example, we have installed circuit-level power meters in two separate buildings in Carnegie Mellon University's (CMU) campus; collected data from 7 other previously installed panel-level meters; designed and built 3 custom panel-level systems for residential buildings; and evaluated a number of other commercial meters in our laboratory.

We then provide a brief survey of the currently available technologies, putting special attention to the average costs of installation and the information that can obtained from each of them. Following this, sections 4 and 5 are devoted to what we believe are possible future technologies. Section 5, in particular, focuses on NILM, and provides early results from a prototype system installed in a residential building in Pittsburgh. Finally, we present our conclusions and discuss possible future work.

2. Measuring Electricity Consumption in Buildings

To understand what, where and how we need to measure electricity consumption in residential buildings, it is important to first understand some basic principles of power systems. Energy, the physical quantity we are interested in, is computed by

integrating power over time. Electric power, in turn, is a function of voltage and current. Hence, by measuring these last two phenomena we can then use some basic mathematics to obtain energy measurements. The question then is: where should the voltage and current be measured? The electric distribution system in each housing unit can be thought of as having a tree-like structure where the leaves would be the individual loads (i.e. appliances), and the trunk would be the main feed coming from the utility. In between these two extremes, there are electrical circuits branching out of distribution panels. Thus, measuring energy at different points in this distribution system yields different levels of aggregation.

2.1 Hardware Considerations

As discussed earlier, there exist a wide variety of commercially available tools for measuring the electricity consumption of buildings. They can be differentiated, primarily, in two dimensions: (1) their time resolution (i.e., how frequently they sample the waveforms and compute measurements); and (2) what we will call their space resolution or, in other words, which points in the power distribution system they are measuring. Therefore, to properly select the appropriate hardware for the task, one needs to match these resolutions to the requirements of the application.

2.1.1 Time Resolution

The speed at which the voltage and current signals are sampled generally depends on the type of information that needs to be extracted from them, as well as the accuracy that is sought for the measurements. If the meters are designed for power quality analysis/control purposes, then higher sampling rates (in the kHz order) are necessary. This rate does not correspond to the rate at which the power-metrics are reported to the user.

2.1.2 Space Resolution

Meters are typically designed for measuring specific points in the distribution system: the main feed, the distribution/circuit panels, the individual circuits in those panels, in between the outlets and the appliances, etc. The choice of any of these depends mainly on the information that is being sought. If the user is simply interested in the overall energy consumption, then measuring the main feed would suffice.

As installing meters in the panel must be done by certified electricians, the cost for their installation scales with the number of circuits measured. The total installed cost, then, can be more than twice the price of the hardware. Such was the case for one of our installations in a 100-year old building at CMU.

3. Current Practices

Now that we have described some of the main considerations, we turn our attention to the different commercially available solutions. Table 1 shows the different devices that we considered in our analysis. Far from being a complete list of commercial products, this sample was obtained by making use of an on-line store specialized in power meters (www.powermeterstore.com), as well as a traditional web search engine (www.google.com). A more thorough review can be found in (EPRI 2009).

We needed to make some assumptions in order to perform an equitable comparison between devices of different types. To start, we did not consider those meters which did not have a data link for communicating with a computer and uploading the measurements. An asterisk is used in Table 1 to indicate such cases. Secondly, for circuit- and plug-level devices, we needed to assume the number of measurement points that would be required in order to provide an estimate of the whole-building consumption. For circuit-level meters the number we used was 18, which corresponded to the number of circuits of the device with the least number of inputs from our list. Similarly for plug-level devices, we chose 20 as the number of required measurement points since according to (Energy Information Administration 2005), that number of appliances accounts for approximately 85% of the electricity consumption of residential buildings in the U.S..

Table 1: List of commercially available residential power meters considered for this paper. An asterisk (*) is used to indicate that the meter does not provide a computer data port.

Type	Name	Model	Manufacturer
Whole-house	e2		Efergy
	Wattson	01	DIY KYOTO
	The Energy Detective	5000	Energy, Inc.
	Shark	100S	Electro-Industries/Gaugetech
	SIMEAS	P50	Siemens
	ELITEpro	DT EPB-VAL	DENT Instruments
	PowerScout	DT PS18-D	DENT Instruments
	Nexus	1250	Electro-Industries/Gaugetech
	OWL Wireless Elec. Monitor*	CM119	2 Save Energy Ltd
	Power Monitor*		Black & Decker
	PowerCost Monitor*	28000	Blueline Innovations
	Cent-a-meter*	ER CAM	Eco-Response
	EM*	2500	Energy Monitoring Tech.
	RFXMeter*		Cheapertronics
Circuit-level	PowerScout	DT PS18-D	DENT Instruments
	EnerSure		TrendPoint Systems LLC
	Smart	20	Elec. Educational Devices
Plug-level	Smart-Watt	SW25015	Smart Works, Inc.
	WattsUp?	PRO	Elec. Educational Devices
	Brand Meter	20-1850/CI	Brand Electronics
	Kill-A-Watt*	P4460 EZ	P3 International

As shown in Figure 1, the least expensive solutions we found for continuous monitoring of the overall consumption of a residential building were in the $50-150 (US Dollars) range without considering the installation costs. For more detailed data as can be obtained by measuring each individual circuit, the least expensive solutions were in the ten to twenty times more expensive. The price increases even more when considering the plug-level meters, which have a minimum cost of approximately

$3,000, without considering the networking costs and assuming that only 20 different loads in the house will be monitored.

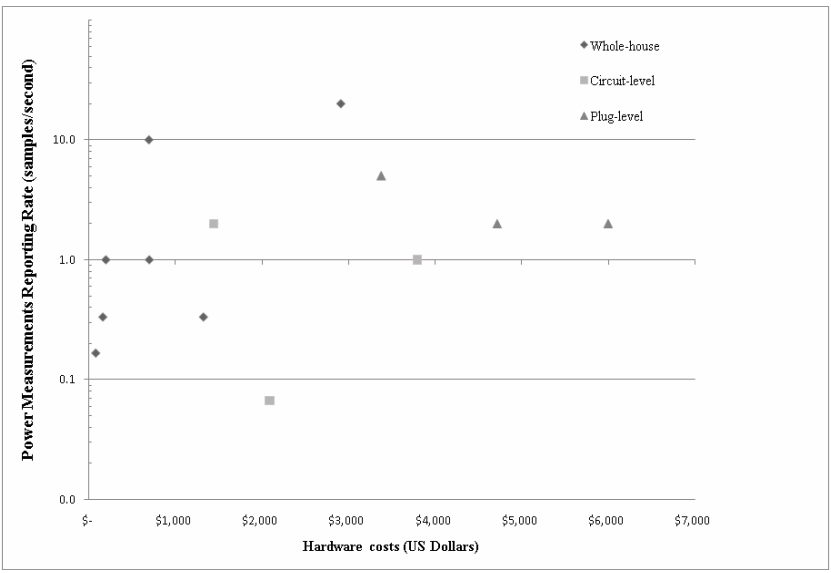


Figure 1: Cost of hardware versus update rate (logarithmic scale) for different types of power meters, all of which have a data port for uploading the measurements to a computer.

This last consideration is based on the idea that it is possible to limit the number of loads being continuously monitored in a house and still obtain valuable feedback that can guarantee savings. According to the Residential Energy Consumption Survey, just 5 end-uses account for roughly 50% of U.S. household electric consumption: refrigeration, air conditioning, space heating, water heating, and lighting (Energy Information Administration 2005). However, even if we know which appliances are responsible for the greatest portion of the energy consumption, many of these loads may offer very little room for modification. For example, besides changing the thermostat configuration in an old and inefficient refrigerator, the only other options left to reduce its consumption would be to repair it or replace it. This alternative may not be cost-efficient when compared to the energy savings it would bring about, even if it would greatly reduce the total consumption of the building.

Clearly, information has its price in this context. The more details homeowners want to know about their energy consumption, the more they would have to pay to obtain them. The real challenge, however, is that potential savings based on these different feedback mechanisms extend the payback period of these investments to unacceptable figures: decades in some cases.

3.1 Measuring green buildings

In the case of verifying the as-built energy performance of a residential building, the energy consumption of air conditioning, space heating, water heating, and lighting are

of particular interest. Since appliance choice and usage can be responsible for a great deal of variation in a home's total energy use, it is informative to separate these loads from the total consumption reflected by utility bills. Of course, not every home has all-electric space heating, cooling, and water heating, but according to the 2001 US census, approximately 40% of the space and water heaters in residential buildings are fueled by electricity (Energy Information Administration 2005). Table 2 notes some of the pros and cons of using different metering techniques to measure each type of load, with color shades indicating the difficulty, darker meaning more challenging. This analysis might suggest that a hybrid approach is best for achieving accurate measurements for each category.

4. Future Prospects

In recent years, there has been an increase in the number of product offerings that are targeting the residential and/or commercial building energy monitoring sectors. Many companies are focusing on creating better interfaces, specifically designed to appeal to the homeowner. Big names in the information technology industry, such as Google (Google) and Microsoft (Microsoft), have recently revealed their free products that make use of the energy-related data that is currently available, to manage and efficiently display electricity consumption information for building managers or owners. These products are implicitly assuming that more data will become available.

Table 2: Comparison of metering solutions for four major load-types. Shading indicates level of difficulty, with darker shades being more difficult.

	air conditioning	space heating	water heating	lighting
Whole-house	Measure spring/fall baseline and correlate cooling degree days (CDD) with elec. consumption.	Measure spring/fall baseline and correlate cooling degree days (CDD) with elec. consumption.	Measure watts of single off-on change and multiply by typical duty cycle.	Observe change in power when switching each light on or off.
Circuit-level	Central air conditioning can be easily measured; window units may share circuits with other plug loads.	Most likely isolated on one or more dedicated circuits.	Most likely isolated on a dedicated circuit.	Loads spread across many circuits; often on shared circuits and can even change circuits.
Plug-level	Central air inaccessible (hard-wired); window units usually require specialized outlets.	Central or baseboard is hard-wired (no plug). Portable space heaters overload some plug-load meters.	Hard-wired; impossible to metter.	Plug-in fixtures are easily measured. Hard-wired fixtures cannot be measured.
NILM	Easily recognized, but power varies during cycle, complicating energy calculation.	Easily recognized; if heat pump, power varies during cycle, complicating energy calculation.	Easily recognized, but hard to train on sample transitions without user controls.	Lights are often confused with other lights. Category-level recognition may help.

However, even though hardware costs may decrease with time due to technological improvements and economies of scale, labor costs for installing these solutions in

homes will likely not, thus maintaining the total price for intensive sub-metering solutions at a high level. It follows, then, that many of the near future prospects for residential energy monitoring will likely be utilizing easy-to-obtain aggregate consumption data. The advent of the so-called "Smart Meters" (meters that establish a two-way communication with the utility company) could also support this vision by providing energy readings that are closer to real-time.

Of particular importance is one technology that tries to extract as much valuable information as possible from these aggregate data streams: Non-Intrusive Load Monitoring. First investigated more than twenty years ago (Hart 1992), this approach aims at identifying patterns in the total voltage and current signals which it can relate to the operation of individual appliances in the building. The technology has yet to reach the consumer market, probably due to hardware costs and the challenges posed by having to train the system (Smith, Leslie Norford, and Steven Leeb 2003). We believe that technological improvements in recent years have decreased the costs of hardware enough to overcome the first barrier, and ongoing research is now tackling the human-computer interaction problems posed by training.

Given the promising outcomes that NILM could provide, we devote the following section of this paper to share our experience implementing a simple prototype system based largely on the techniques described in the literature.

5. The Case for Non-Intrusive Load Monitoring

To test the effectiveness and analyze the potential of NILM, we developed a prototype system and installed it in an apartment unit. The system measured voltage and current on the two voltage sources (phases) coming into the apartment from the utility's transformer. A computer with a data acquisition card sampled these signals at a rate of 10kHz, and computed estimates of the spectral envelope as described in (S.R. Shaw et al. 2008). Using an event detection algorithm inspired by (Luo et al. 2002), the system could identify the precise moments when an appliance in the house had changed its state. Following this, we applied kernel regression on a fixed window of samples of the power signals around the event, and used the coefficients of this regression as a "signature" for the given state-transition. These signatures were stored during the training phase, and used during regular operation to compare new, unknown state-transitions against them and provide proper labels. More details on the system can be found in (Berges et al. 2009).

Our tests in the laboratory, before deploying the system in the apartment unit, showed that after events were detected, it was capable of assigning the correct label, out of 34 possible ones (e.g. toaster turning on, fan going from low to high, etc.) with an average 10-fold cross validation accuracy of approximately 80%. Additionally the detector gave very few false positives in our lab tests, and virtually no false negatives.

The situation proved to be different in the apartment unit. Because we did not implement the multi-resolution techniques for the event detector described in (Luo et al. 2002), some slow start-up transients triggered many false positive predictions. The electric heating system of the building especially contributed to this type of error. Nonetheless, these start-up transients did not occur very frequently, and we were able to reduce the number of false positives by fine-tuning the parameters of the detector.

Validating the NILM system requires hardware sub-metering (either plug-level or circuit-level if on a dedicated circuit). To test the accuracy of the energy estimates, we installed a plug-through power meter in the top-consuming appliance: the refrigerator. Using these isolated measurements we could compare the estimates of the NILM system and evaluate the performance. Figure 2 shows the result of this experiment. The difference between the energy usage as computed by NILM and the plug-meter was less than 0.5 kW-h (15%) for a 1 day period partly shown in Figure 2.

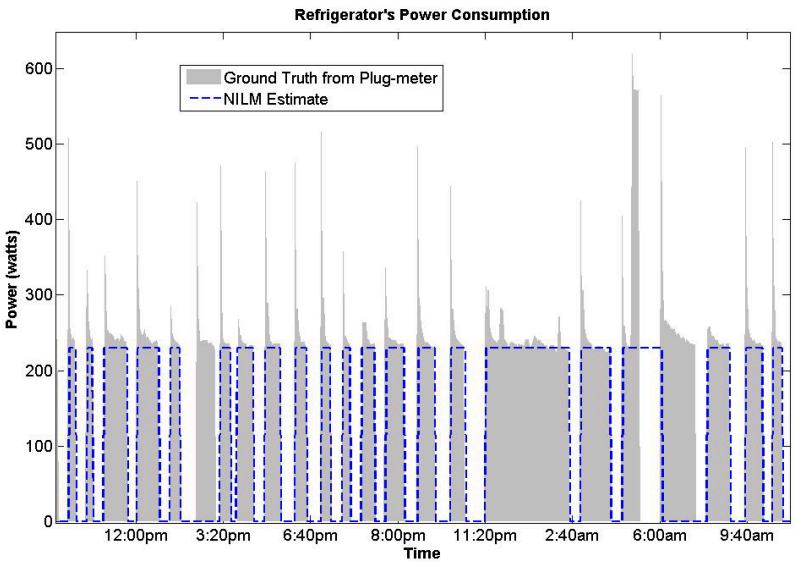


Figure 2: Power consumption of the refrigerator during a 12 hour period as estimated by NILM (dashed line) and the plug-meter attached to the appliance (solid line).

6. Conclusions and Discussion

Future technologies for continuous, detailed measurement of the electricity consumption of buildings will likely rely on a hybrid approach combining advanced techniques for extracting useful information out of low-cost data sources present in buildings, as well as direct measurements of the consumption of individual appliances. We have shown some examples of currently available technologies and provided a brief comparison which indicated that the level of information provided by them is proportional to their cost.

Detailed feedback on electricity consumption can benefit many facets of the building industry. It may facilitate the implementation of LEED standards that go beyond the design and construction of facilities, inform building designers on how buildings really operate, and provide support for building commissioning and energy audits.

NILM techniques show promising results to provide detailed information at a low cost. However, more research is needed to bring this technology to market. We believe that ways of achieving this include a combination of better training processes and interfaces, more generalized appliance signatures that can be shared across buildings, and the integration of other sources of information (e.g., motion sensors, temperature sensors, etc.) into the framework. As lower-cost sources of detailed consumption data become available, we anticipate the growth of more sophisticated software for analyzing those data, as well as more reliance on such analysis for investment planning and verification.

7. Acknowledgements

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Automatically Tracking and Guiding Underground Tunnel Boring Machines during Microtunneling and Pipe Jacking Operations

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Abstract:

Tunnel Boring Machine (TBM) has been extensively implemented in microtunneling and pipe jacking projects for constructing subsurface pipeline infrastructure. Commonly used laser systems for TBM guidance tend to suffer from instable performance and low accuracy, while the high complexity in the system design of some advanced solutions compromises the system reliability while driving up the technology's cost. This paper presents an in-house developed automated and cost-effective TBM guidance system. The TBM's positions are automatically surveyed by a robotic total station and real-time line and level deviations from as-designed tunnel alignment are derived instantaneously. Given the coordinates of three observation points on the TBM, the TBM's three rotation angles in the underground space are determined by a "point-to-angle" computing algorithm. The automated system was assembled in house and tested at a pipe jacking site in Hong Kong. Practical constraints and considerations associated with the system setup and field testing are discussed. The performances of the automated system are evaluated in terms of accuracy and timeliness by comparing the testing results against data sourced from current control practices.

Introduction

Microtunneling and pipe jacking are commonly employed in urban areas for the installation of small to medium diameter underground pipelines, such as sewers, drains and water mains (Mok et al. 2007). In contrast with the conventional open-trench method, microtunneling provides an environmentally friendly and sustainable urbanization technology thanks to its "trenchless" nature. Tunnel boring machine (TBM) is a steerable and remotely controlled tunneling machine

that has been extensively applied in microtunneling to excavate subsurface tunnels (Kramer et al. 1992). How to steer the advancement of a TBM along the as-designed tunnel alignment is a crucial factor to the success of every microtunneling project (Thomson 1993). Tolerances of deviations on line and level are generally specified in orders of ± 50 mm and ± 75 mm respectively for pipe jacking projects (PJA 1995). However, unforeseen underground obstacles and variable geological conditions present uncertainties and challenges to tunnel alignment control.

An effective TBM guidance system plays a significant role for closely controlling the subsurface tunnel alignment. At present, laser targeting systems predominate in straight drive microtunneling and pipe jacking applications (Geoffrey 2004). However, problems in practical applications include (1) the displacement of the laser beam due mainly to the theodolite standpoint being destabilized during the pipe jacking process; (2) the dispersion and refraction of the laser beam over a long travel distance in the tunnel; and (3) the difficulty in receiving laser's projection over a long distance on target boards having restricted screen size (Thomson 1993). Additionally, some sophisticated gyro-compass systems or motorized laser targeting systems have been developed for TBM guidance, especially for installing pipeline along curved alignments (Seilert and Nod 2007; Tacs 2009; VMT 2003). On the other hand, the high complexity in the system design compromises system's reliability while driving up technology's cost, including system maintenance and technical service. In practice, many operators are guided by conventional laser systems while heavily counting on experiences to steer the TBM. It is not unusual that TBM operators and site managers are caught by surprise with out-of-tolerance tunnel alignment errors (Mok et al. 2007).

The research aims to investigate automated and cost-effective alternatives to guide TBM's advance during microtunneling and pipe jacking operations. We proposed a simplified TBM guidance system through integrating automated TBM tracking with on-line computing (Shen et al. 2009a; Shen et al. 2009b). A robotic total station is remotely controlled to automatically survey the TBM's position in terms of point coordinates. The coordinates are then processed to derive the line and level deviations from as-designed tunnel alignment. Further, based on the coordinates of three observation points on the TBM, the TBM's three rotation angles, namely yawing (TBM's head turning "left-right"), pitching (TBM's head turning "up-down") and rolling (TBM's body rotating around its own central axis), can be determined by innovative "point-to-angle" computing algorithms, without the use of instrumentation (inclinometers and gyro-compasses). As a continuous effort, the present research focuses on the evaluation of the system performance in practical settings by conducting field testing. A local pipe jacking site for constructing one cross-river tunnel with a length of 220 m and an inner diameter of 1200 mm was selected as the test bed. In this paper, practical constraints and considerations associated with the system setup are discussed. The performances of the automated system are evaluated by comparing the testing results against data sourced from current practices in terms of accuracy and

timeliness.

The remainder of this paper is organized as follows: first, the design and the functionality of the proposed automated TBM guidance system are described. Next presented is the implementation and field testing of the system in a pipe jacking site, followed by analysis of testing results. Discussions on practical performances and applicability of the research are made before drawing conclusions.

Automated and Simplified Solution to TBM Guidance

To address the limitations identified in current TBM guidance systems, we developed an automated and cost-effective TBM guidance system based on robotic total station and on-line computing. Figure 1 gives a depiction of the system design. A robotic total station is linked with a control laptop computer to automatically fix three tracking points on the TBM. Thus, the TBM position in the underground space can be accurately mapped and line and level deviations derived in real time. In addition, with the coordinates of three tracking points known at two consecutive time events, three rotation angles of the TBM (yaw, pitch, and roll) can be deduced through on-line computing by a "point-to-angle" algorithm. To counter the likely destabilization of the total station by ground vibration during the tunneling and pipe jacking operations, a reference benchmark, which is a fixed point in the shaft or above the ground, serves as the fourth tracking point for periodically calibrating the offsets of the total station's standpoint.

TBM Positioning and Deviations Calculation

Suppose the coordinates of the total station are $[x_0, y_0, z_0]$. The total station automatically surveys one specific tracking point i by measuring three parameters relative to the total station: (1) the slope distance d; (2) the horizontal angle α; and (3) the vertical angle β. Note, all the coordinates are given in the local geodetic frame (East-North-Zenith). The coordinates of point i is calculated by

$$\begin{cases} x_i = d \times \cos\beta \times \sin\alpha + x_0 \\ y_i = d \times \cos\beta \times \cos\alpha + y_0 \\ z_i = d \times \sin\beta + z_0 \end{cases} \quad (1)$$

Given the ideal coordinates for point i are $[x_i', y_i', z_i']$ as per the as-designed

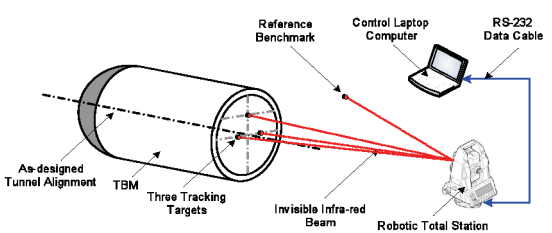


Figure 1. System design of the automated TBM guidance system

tunnel alignment, the deviations in line and level can be determined by

$$\begin{cases} DevLine = \pm\sqrt{(x_i - x_i')^2 + (y_i - y_i')^2} \\ DevLevel = z_i - z_i' \end{cases} \quad (2)$$

Computation of Three Rotation Angles

The majority of currently available TBM guidance systems utilize inertial instrumentation, such as gravity-referenced inclinometers and magnetic compasses, to gauge rotation angles of the TBM. By contrast, this research implements an innovative "point-to-angle" computing algorithm to calculate the TBM's orientations. It provides a cost-effective alternative to current methods by eliminating the use of any inertial instrument.

Theoretically, two non-zero and non-collinear vectors form a unique rigid plane to describe the position and orientation of a solid object in space. In the proposed TBM guidance system, three tracking points mounted on the TBM form the two vectors. Shown in Figure 2, the TBM together with the three tracking points (P1, P2 and P3) undergo orientation changes from t1 to t2. Mathematically, the changes can be represented by three sequential rotations, namely (1) a yawing angle $\Delta\psi$ about the z-axis; (2) a pitching angle $\Delta\theta$ about the x-axis; and (3) a rolling angle $\Delta\Phi$ about the y-axis, as illustrated in Figure 2.

The coordinates of P1, P2 and P3 are determined at two consecutive time events t1 to t2, and further processed to form two vectors V_{t1} and V_{t2}. The TBM's three rotation angles can be calculated by solving

$$\begin{bmatrix} \Delta\psi \\ \Delta\theta \\ \Delta\phi \end{bmatrix} = f\begin{bmatrix} V_{t2} & V_{t1} \end{bmatrix} = f\begin{bmatrix} P1_{t2} & P1_{t1} \\ P2_{t2} & P2_{t1} \\ P3_{t2} & P3_{t1} \end{bmatrix} \quad (3)$$

The "point-to-angle" computation has been comprehensively investigated in aeronautics and astronautics disciplines in the past four decades. In order to maintain a balance between computing time, accuracy and minimal tracking points, the classic TRIAD (Tri-Axial Attitude Determination) algorithm was implemented in this research (Black 1964; Wertz 1978; Shuster and Oh 1981).

Monte Carlo simulations have been conducted to assess the errors in point positioning and angular measurement by the proposed solution. The resulting

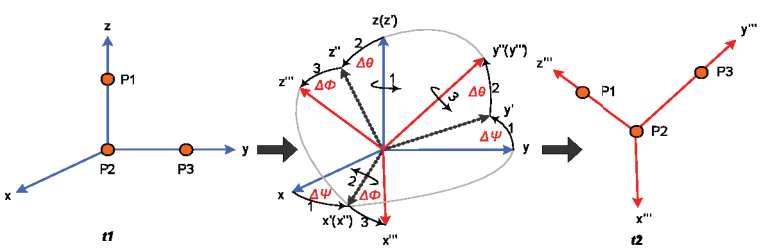


Figure 2. Rotations of a solid frame represented by three sequential rotations

position errors were found to be in the order of 3-4 mm, while the angular errors in the three rotation angles in the order of 0.8-0.9 degree in terms of the standard deviations (Shen et al 2009b). The performance of the system is validated through field testing in the following section.

Field Testing Validation

The proposed TBM guidance system was assembled in house and underwent extensive lab testing from October 2008 to August 2009 at the Hong Kong Polytechnic University. The prototype system mainly consists of a robotic total station linked with a laptop computer via a RS232 serial cable. A computer program was coded by graphic user interface (GUI) programming in MATLAB (Marchand and Holland 2003), to enable total station control, automated data collection and on-line computing. The field testing commenced in late August 2009 at a pipe jacking site in Hong Kong with close collaboration with local industry partners. The project constructed a concrete tunnel with a length of 220 m and an inner diameter of 1200 mm across a 40 m-wide river situated in the New Territories of Hong Kong. Site operations commenced in October 2008 and were completed by December 2009. Figure 3 shows the layout of the jacking shaft. A laser theodolite was deployed for guiding TBM steering, complemented with periodic independent surveying for cross-checking the deviations of the as-built tunnel.

System Setup and Practical Constraints

Before conducting the field testing, system setup at the site was deliberately designed, in order to ensure the functionality of the automated system while minimizing disruptions to ongoing site operations. In particular, practical spatial constraints presented challenges to the installation of (1) three tracking targets on the TBM and (2) one robotic total station in the jacking shaft. After coordination with site engineers, three tracking targets were finally mounted around the laser target board on the TBM, while a custom-built stand of the total station was firmly attached to the stand of the laser theodolite, as shown in Figure 4 and Figure 5 respectively. Notably, the length and height of the total station's stand were well considered so as to maintain the line of sight to the three tracking

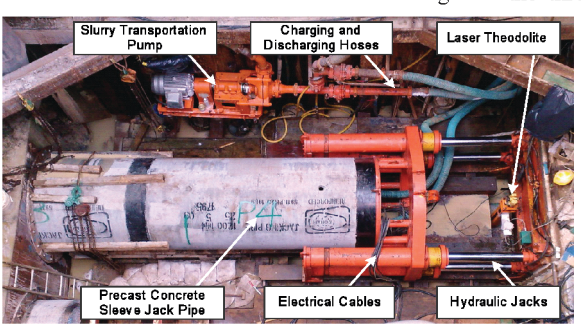


Figure 3. Layout of the jacking shaft with pipe jacking equipment

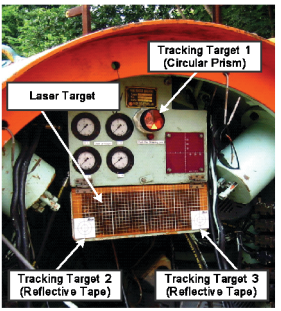


Figure 4. Three tracking targets mounted on the TBM

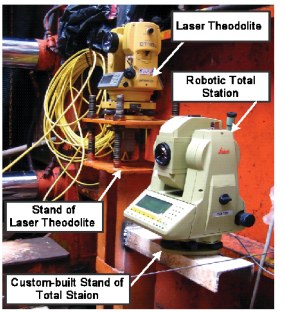


Figure 5. Installation of the total station on a custom-built stand

targets on the TBM.

Evaluation of On-Site Performance

After all instruments were properly initialized on site, the robotic total station was controlled by the program running on the laptop computer, shown in Figure 6. Coordinates of three target points on the TBM were automatically tracked and surveyed. Three rotation angles of the TBM were determined by on-line computing in real time. The resulting surveying and computing data were recorded in a database for further analysis.

The automated system functioned well for continuous tracking and real-time computation of the TBM positions in the 3D underground space. With the well-thought system setup on site, the line of sight between the total station and tracking targets proved to be available, even with the intermediate jacking stations and intermediate pumps installed within the pipe strings. The frequency for updating the TBM position and the rotation angles was once per minute. Table 1 gives the automated surveying results recorded in the database, including target point surveying results and calculated coordinates with time stamped. In addition, two different types of tracking targets were tested under practical settings: the glass prism functioned well to track the working TBM in the dark underground



Figure 6. On-site testing of the automated TBM guidance system

Table 1. Automated surveying results: data samples

Pt.	Date	Time	Hz.Angle	V.Angle	Dist.	Northing	Easting	Level
	yy-mm-dd	hh:mm:ss	(deg)	(deg)	(m)	(m)	(m)	(m)
1	2009-9-10	17:20:00	199.648	89.211	41.305	825826.676	817626.146	-3.978
2	2009-9-10	17:20:09	199.367	89.658	41.314	825826.596	817626.333	-4.3
3	2009-9-10	17:20:17	199.884	89.661	41.321	825826.715	817625.979	-4.303
1	2009-9-10	17:21:05	199.647	89.213	41.311	825826.67	817626.145	-3.98
2	2009-9-10	17:21:14	199.37	89.655	41.319	825826.592	817626.329	-4.298
3	2009-9-10	17:21:23	199.882	89.663	41.328	825826.708	817625.978	-4.304

tunnel over the entire drive length (220 m); while two reflective tape stickers could be automatically recognized and tracked within 55m. In the following section, the minute-by-minute positions and orientations of TBM over the first 55 m are checked against on-site manual records and independent surveying results provided by the contractor.

Data Analysis and Comparison

Site trials were carried out during the course of microtunneling operations. Figure 7-11 illustrate continuous two-hour testing results on September 10, 2009 with the tunnel chainages (or jacking distances) ranging from 36.68 m to 37.44 m. Figure 7 and Figure 8 present the line and level deviations of the TBM alignment determined by the automated system. It was found that the alignment was well controlled during the testing period. In particular, the line deviations varied between ± 10 mm while the level deviations were less than 35 mm. Besides, Figure 9, 10 and 11 give the resulting three rotation angles in the testing. As the TBM operator adjusted TBM's orientations cautiously and infrequently, the rotation angles were found to be relatively steady. For instance, the majority of yawing data lay between 198 deg and 199 deg.

The testing results were further compared against actual site records. The TBM operator recorded the TBM's deviations and inclinations upon the start and completion of the jacking process of every pipe section. In addition, the alignment and deviations of the as-built tunnel were checked by independent surveyors hired by the contractor on a weekly basis. Table 2 compares the alignment results by different methods on three tunnel locations (with close chainages). Data obtained from the automated system were found to closely match manual records resulting from the other two methods. The differences in deviations from the three methods are less than 18 mm, while the differences of the pitching and rolling angles are less than 1.7 deg. Note the yawing angles are unavailable by use of the current laser system and the independent surveyors only check line and level deviations. The automated system, therefore, provides real time TBM positioning and tunnel alignment surveying with reasonable accuracy while significantly increasing the frequency of data updating.

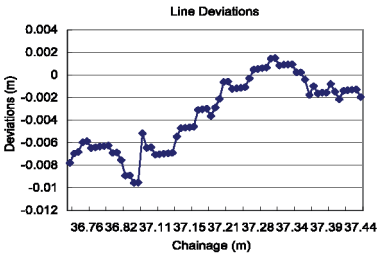


Figure 7. Line deviations determined by the automated system

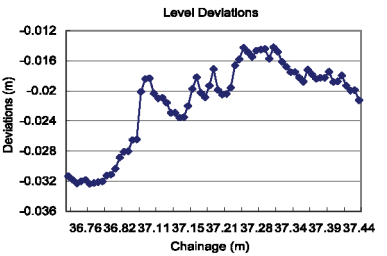


Figure 8. Level deviations determined by the automated system

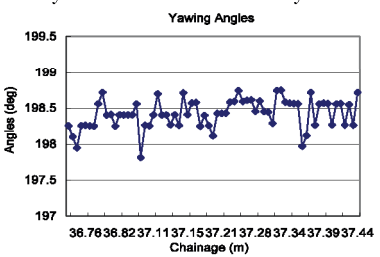


Figure 9. Yawing angles determined by the automated system

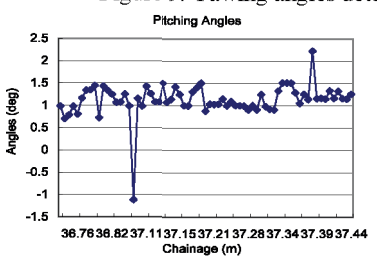


Figure 10. Pitching angles determined by the automated system

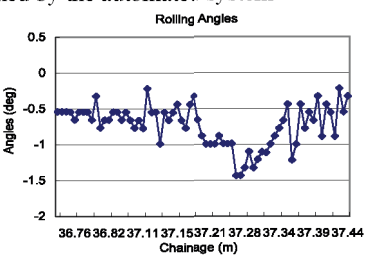


Figure 11. Rolling angles determined by the automated system

Table 2. Comparison of selected data collected by three methods

No.	Data Collection Methods	Chainage (m)	Deviations (mm)		Rotation Angles (Deg)		
			Line	Level	Yaw	Pitch	Roll
1	Operator's Record	17.74	20	-35	/	0.7	2
	Independent Surveying	22.688	13	-22	/	/	/
	Automated System	18.487	9	-27	198.1	2.4	1.2
2	Operator's Record	35.8	0	-30	/	0.5	0
	Independent Surveying	33.31	9	-30	/	/	/
	Automated System	36.639	-8.1	-31.1	197.1	-0.7	-0.4
3	Operator's Record	49.65	5	-20	/	0.6	0
	Independent Surveying	51.938	14	-16	/	/	/
	Automated System	49.609	7.3	-12.8	198.5	1.6	-0.9

Conclusions

A TBM is the leading resource employed in microtunneling and pipe jacking operations for constructing underground utility pipeline. Accurate TBM positioning in the underground space is crucial to guiding the TBM's advance and controlling the subsurface tunnel alignment. To address the limitations identified in current TBM guidance systems, we propose a simplified TBM guidance system: accurate TBM positions can be automatically measured by a robotic total station so as to derive the line and level deviations in real time; Additionally, with the coordinates of three fixed points on the TBM tracked, three rotation angles of the TBM are computed by a "point-to-angle" algorithm, without the need of instrumentation such as inclinometers and compasses.

Field testing of the prototype automated TBM guidance system was conducted at a pipe jacking site in Hong Kong. The system was deliberately set up at the site against practical challenges, especially the tight spatial constraints for mounting three tracking targets on the TBM and installing the total station in the jacking shaft. As a result, the automated system functioned well for continuous and real-time tracking and computation of the TBM positions and its three axes orientations. The frequency for updating TBM's position was once per minute. The tunnel alignment deviations and the rotation angles of TBM over the first 55 m were collected by the automated system, and further compared against TBM operator's manual records and independent surveyors' results, indicating a close match.

In short, the research has contributed to the state of the practice in TBM guidance and tunnel alignment control for microtunneling and pipe jacking operations through integrating automated data collection and on-line computing. By deploying an off-the-shelf robotic total station and eliminating the use of inclinometers and gyro-compasses, the resulting TBM guidance solution can potentially provide a quick, cost-effective alternative to tackling a critical engineering task.

Acknowledgments

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Geospatial Databases and Augmented Reality Visualization for Improving Safety in Urban Excavation Operations

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Automated/Real-Time Systems
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Abstract: The U.S. has more than 14 million miles of buried pipelines and utilities, many of which are in congested urban environments where several lines share the underground space. Errors in locating excavations for new installation or for repair/rehabilitation of existing utilities can result in significant costs, delays, loss of life, and damage to property (Sterling 2000). There is thus a clear need for new solutions to accurately locate buried infrastructure and improve excavation safety. This paper presents ongoing research being collaboratively conducted by the University of Michigan and DTE Energy (Michigan's largest electric and gas utility company) that is investigating the use of Real-Time Kinematic GPS, combined with Geospatial Databases of subsurface utilities to design a new visual excavator-utility collision avoidance technology. 3D models of buried utilities are created from available geospatial data, and then superimposed over an excavator's work space using geo-referenced Augmented Reality (AR) to provide the operator and the spotter(s) with visual information on the location and type of utilities that exist in the excavator's vicinity. This paper describes the overall methodology and the first results of the research.

1. Introduction: The underground space in urban environments is a spider's web of electric lines, gas lines, cable TV lines, fiber optics, telephone cables, traffic signals, street lighting circuits, drainage and flood control facilities, water mains and waste water pipes. In some locations, major oil and gas pipelines, national defense communication lines and mass transit rail/road tunnels, all compete for place underground (Sterling 2000). The U.S. has more than 14 million miles of buried pipelines and utilities, many of which are in congested urban environments where several lines share the underground space. Hits to utility lines cause interruption to daily life and commerce, and physical danger to workers, bystanders and nearby buildings. These costs are borne by the Contractor, Locating Company, Utility

Providers, Insurance Companies, Affected Public and Business Owners. Thus it is a cost borne by all parties, including tax payers and society at large either directly or indirectly.

The period from 2004 to 2007 saw a total of 52 fatalities, 132 injuries and over 600 million dollars loss in damage to property. Additionally, of all incidents related to buried utilities, excavation related accidents accounted for nearly one-third (PHMSA 2009). Thus it is apparent that increased attention needs to be paid to utility locating technologies that aid in accurate and safe excavation. A Federal study on buried utility detection technology identified the following two goals: firstly, avoiding third-party damage to existing underground utilities that is caused by the presence of unknown or mislocated utilities; and secondly, developing utility location capabilities independent of size, depth and utility materials, that can detect even in presence of utility congestion. The overarching goal of our ongoing research project is to address this critical state of affairs and propose new integrated technological solutions to prevent excavator-utility hits, and thereby improve safety and accuracy in urban excavation projects.

2. Problem Description: Locating underground pipes and other infrastructure prior to excavation has long been a problem area due to complexity involved and the large number of variables over which accurate control is not possible. This section deals with the current state of affairs in terms of locating utility lines and limitations in them.

2.1 Current Locating Technologies: Geophysical technologies are those technologies that assist in investigating the earth's sub-surface. While tremendous development has taken place in the field of locating technologies over the past decade, no one method has emerged as being complete and without flaws. The following is a brief description of the most commonly used methods in locating underground utilities.

Ground Penetrating Radar (GPR): Ground Penetrating Radar (also known as Ground Probing Radar) is a technique that uses short duration, high frequency electromagnetic wave pulses. These pulses are transmitted from an antenna into the ground. Materials such as rocks, water, or pipes buried below the surface reflect the waves which are returned as an echo. While GPR is widely used with good results, when used with conductive soils (clays, saturated soils, etc.) and in congested environments (presence of rocks etc), it gives below par results. (Read and Vickridge 1997)

Electromagnetic Techniques: Electromagnetic methods detect the field generated by the buried network and not the buried pipe itself. Electromagnetic techniques can be Active or Passive. Active systems depend on current being applied to the pipe and detecting the field thus generated. While in passive systems, the location is based on receiving natural signals transmitted from the underground assets themselves as would be the case of an electric conduit that has current flowing through it naturally.

Electromagnetic methods are low cost, simple and quick but cannot locate non-metallic pipes except if tracer wires or Sondes are used (Read and Vickridge 1997).

Magnetometer Technique: This method works on the fact that the earth's magnetic field varies over a particular distance which is caused by underground features such as metallic pipes, large voids and ore bodies. The setup uses two coils to evaluate the difference in intensity and/or direction of the vertical component of magnetic flux which maybe caused by a ferromagnetic object. The advantage of this method is that it is relatively cheap. However, presence of buildings, cables, fences, etc affect the output considerably and thus this method cannot be relied upon entirely (Read and Vickridge 1997).

Resistivity Methods: The setup for this method uses 4 electrode probes placed in a line in the ground and a current passed through the outer pair. The inner pair measures the potential drop between them, giving an estimate of ground resistivity. However this method is quite slow. The electrodes need to be coupled very well with the ground making surveying beneath roads for buried assets difficult (Read and Vickridge 1997).

Acoustic Detection Systems: Although acoustic detection methods are primarily used for locating leaks in water mains, they can also be employed for detecting and mapping water distribution pipe networks. However the system requires easy access to the pipelines like a hydrant or a water meter. Passing traffic can also lead to sources of errors. Thus it is limited to small and shallow networks. No depth value can be obtained as well. (Read and Vickridge 1997)

Infrared Thermography: This method is based on measuring very slight variations in temperature, and producing a thermographic image, where objects are represented by their thermal rather than their optical values. An infra-red scanner head and detector are used to capture the thermal data. The equipment is relatively expensive. Ground moisture content drastically affects the readings and depth values cannot be measured. Thus it needs a supplementary system to measure depth values (Read and Vickridge 1997)

Subsurface Utility Tracing: In this method a signal is induced in a subsurface utility and the signal's position is tracked as it moves along the utility. It is also referred to as Direct Induced Signal Emission as the electric field formed as a result of the signal passed is used to detect the buried pipe.

Vacuum Extraction: Another method often used is Vacuum Extraction (Vacuum Excavation) or Potholing. This method offers the option of safely and economically excavating in areas inaccessible to conventional digging equipment. The air excavation method however cannot be used on hard surfaces like pavements and has a higher initial cost. The water vacuum excavation systems can cut pipes or electrical conduits due to the force of the water (Read and Vickridge 1997).

Each of the described techniques is effective in certain scenarios and less effective in others. However given the wide range of variables that one has to deal with in underground utility location, no single technology emerges as being comprehensive in locating underground utilities of all types in a range of soil conditions. Thus it is generally accepted in the industry that a multi-sensory approach that would utilize a combination of such technologies is likely to give more accurate results.

2.2 One-Call Utility Notification Organizations: A study of various One-Call Utility pre-marking systems/organizations reveal that most states within USA require by law for excavators to have the utilities pre-marked by the identification service before actual excavation is carried out. Michigan's statute, Act 53 of Public Act 1974, requires anyone who engages in or is responsible for the planning or performance of any type of excavation e.g.; grading, demolition, cultivating, auguring, blasting, or boring to provide advance notice of at least three full working days to MISS DIG (MISS DIG Systems Inc. 2009). In the state of Michigan, MISS DIG SYSTEMS is the One-Call Utility Notification Organization. The MISS DIG system and other similar One-Call systems have reduced utility line hits to a great extent. However such systems still have 2 limitations in their current form (DTE Energy 2009, Personal Communication). The first being that location of a buried utility is marked approximately on the surface within a 3 feet wide band rather than its exact location, and once the excavator has removed the top soil/surface, the operator once again depends more on judgment than on visible information. Secondly, MISS DIG system does not provide any information regarding depth of a buried utility (MISS DIG Systems Inc 2009). Furthermore, as noted above, the markings are made as a strip of potential area which is 18 inches wide on either side of the utility line's expected location. This equates to a zone that is 3 feet wide. Thus it is not as exact as an excavator operator would like and current One-Call systems would need additional improvements to make them more useful for excavators.

2.3 As Built versus Actual: The single largest cause for utility line hits is the discrepancy between as-built drawings and actual location of utility lines and incomplete as-built drawings (Hammond and Weintraut 2001). This issue leads to negating the positive effect of the MISS DIG System. Most utility owners including our collaborator DTE Energy concede that often times the as-built drawings show a completely different picture from what actually exists beneath (DTE Energy 2009, Personal Communication). Part of the problem lies in the method of laying utility lines. In extremely crowded urban environments, contractors are left with no choice but to shift utility alignments by a few inches to a few feet to account for existing utility lines occupying the same space. As-Built drawings thus do not actually represent the reality of what lies beneath (Hill 2006). Since existing As-Built data solely does not accurately serve the purpose of underground utility locations, an alternate method of location, based on a combination of recorded as-built data, and active real-time sensing is proposed in the following section.

3. Importance of the Research: The importance of research in the area of underground utility location can be exemplified by incidents of stray hits to utility

lines that look innocuous at first but have consequences that are dire. An example of such a hit was a case in January 1995 when a construction crew driving piles for a new garage accidently crushed a high voltage underground electric cable serving Newark International Airport's three passenger terminals. As a result, hundreds of flights were cancelled and thousands of passengers were left stranded (Minneapolis Star Tribune 1995). Also with utility companies spending millions of dollars every year on locating their buried assets and accident recovery (Sterling 2000), it is clear that the area is in need of urgent attention.

3.1 Federal Interest in Utility Locating Technologies: A Federal Study on Utility Locating Technologies suggested that that multi-sensor technology (GPR, Acoustic plus Electromagnetic) and multi-frequency approaches offer the greatest potential for stand-alone utility location in the future (Sterling 2000). The use of this multi-sensor technology together with a 3D model view of the buried infrastructure is one of the responses to the Statement of Need. The view would be of such quality so as to allow identification of material of pipe and other essential details. Section 15 of the Pipeline Safety Improvement Act of 2002 discusses the National Pipeline Mapping System which requires operators of pipeline facilities to provide to the Secretary of Transportation geospatial data appropriate for use in the National Mapping System, the name and address of the person with primary operational control, and a means for a member of the public to contact the operator for additional information about the facilities. There is a requirement to update the information as necessary. Such information can then be used by a system to create 3D models of the buried pipes and be projected onto the real world view. Thus there is all-round effort, guided by a federal agenda, to convert buried utility data into a format that is interoperable, accessible, and always current.

3.2 Introduction to the Proposed Collision Avoidance Framework: It is evident that all the existing techniques in the field of underground utility detection have limitations. A consequence of these limitations is the hits to underground utility lines that lead to large values of loss to surrounding facilities, residents and other utilities in the network. Thus an approach that combines these existing technologies by building upon their capabilities offers the most promise to help mitigate the extent of the accidental damage caused.

In particular, a technology that gives the excavator the location of the pipes at all times (i.e. even after the top surface has been excavated away) as well as the depth and other attribute information of the pipes can help alleviate most of the problems not addressed by using current technologies. To achieve this, our proposed approach involves the creation of 3D models of the buried pipes from existing databases owned by utility companies and superimposing these models over the normal real-world view (captured in Real Time) of an excavator or backhoe operator using Augmented Reality (AR). This can be better understood by referring to the Figure 1 below.

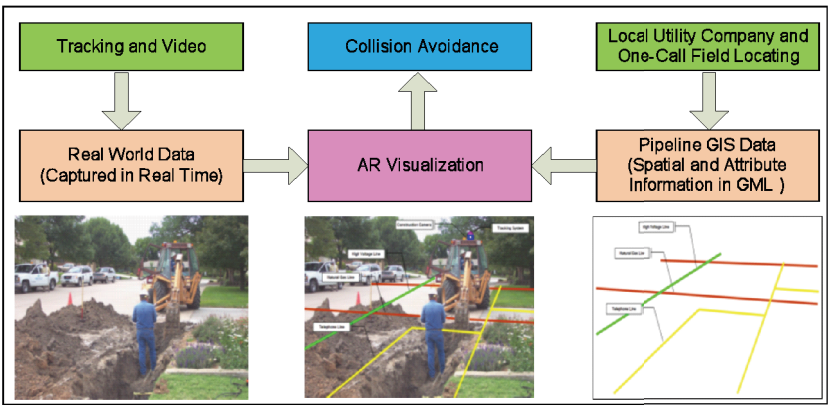


Figure 1: Data Flow for Collision Avoidance System Using Augmented Reality

The advantage of such a technology over using spray paint, stakes or flags to mark the approximate location of the utility is that unlike the existing methods, the location indicators remain in the operator's view even after the top layer has been excavated away. Furthermore, the superimposed 3D pipe models can be color coded allowing the operator to easily identify the pipe(s) the crew is interested in. As can be seen in Figure 1 above, other attribute information such as depth, material of pipes, etc. can be annotated over the pipes thus giving the excavator additional information. The following section describes our Technical Approach in detail.

4. Technical Approach: The excavator-utility collision avoidance framework being developed by our group is based on the use of Augmented Reality (AR) visualization technology. Data on the underground pipes is obtained from the databases of utility companies. The data from these databases can be transported and encoded in an XML based format called Geography Markup Language (GML). A combination of GML and wireless fidelity make such an operation of transporting data over the internet extremely feasible today unlike a few years ago. Such a view of 3D pipe models on the real world view of a user has been attempted in the past (e.g., Mendez et al. 2008). Utility information has also been visualized as vector based graphics in AR before (e.g., Roberts et al. 2002). In each of these cases, the goal of the study has been to demonstrate the feasibility of AR technology to visualize GIS information. This research builds upon the success of these prior studies and incorporates AR visualization as a key component into a multi-sensory excavator-utility collision avoidance framework.

Figure 2 graphically depicts the major components of the developed framework. The major components of the framework are: 1) Accessibility and conversion of accurate as-built graphical information on buried utilities; 2) Visualization of annotated graphical information in excavator operator's view in georeferenced AR; 3) Real-time tracking of excavator's kinematic articulation and position of digging implement; 4) Proximity querying and interference detection between digging implement's current location and buried utilities; and 5) Rapid reality capture of buried utilities using

geophysical technologies to supplement accuracy achieved by geometric interference analysis.

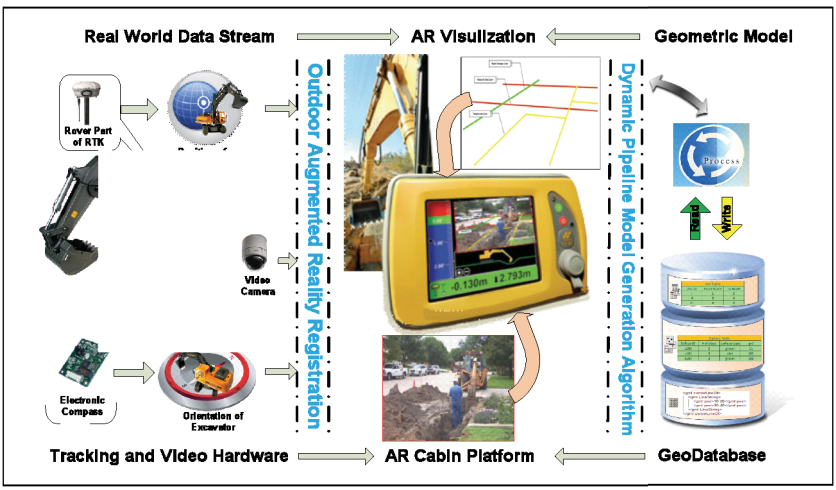


Figure 2: The architecture of visual excavator-utility collision avoidance framework

4.1 Underground Utility Data Classification: The research team has first begun addressing challenges in the utility data accessibility and conversion component of the proposed framework. We have classified the data into 4 cases such that every owner of utilities whether public or private would fit into one of these 4 cases. A flowchart of this classification is shown in Figure 3.

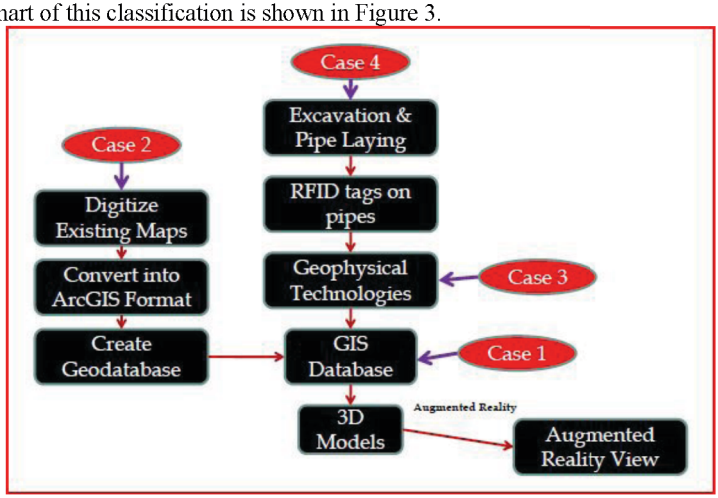


Figure 3: Buried infrastructure data classification cases 1- 4.

Case 1 is the best case scenario where utility owners have all their assets stored in a GIS database. Case 2 refers to those owners who have the asset information stored in the form of maps and drawings either in paper or digital form but not in the form of an intelligent database. These maps then need to be converted into GIS format from which a database can be built. When utility owners already have pipes buried underground but are unsure about their exact location, it is classified as Case 3 in our classification. This case will require the use of Geophysical Technologies to get the exact location of the underground utilities. After the location is obtained, a database would be constructed using the geophysical test results. These steps would then bring the data up to the level of Case 1. Case 4 refers to the case when new pipes need to be laid and thus along with documenting the location of pipelines, the use of new technologies such as Radio Frequency Identification (RFID) tags and Sensors mounted on pipes is also envisaged. Thus Case 4 is the all encompassing case. The eventual goal for any case is to produce 3D models of the underground pipes and project them in AR (framework component 2).

As a test case, our group worked on a sample dataset provided to us by the University of Michigan Architecture, Engineering & Construction (AEC) division. The data provided to us was in the form of a digital AutoCAD drawing (.dwg file). Thus it was a Case 2 classification. We performed a series of operations to convert this AutoCAD drawing into a GIS shapefile. Our group used ArcGIS 9.3 for this initial test case. The ESRI Shapefile or simply a Shapefile is a popular geospatial vector data format for geographic information systems software. It is developed and regulated by ESRI as a (mostly) open specification for data interoperability among ESRI and other software products. We created 3D models of the pipes in Google SketchUp. Even though this algorithm involved several manual steps, our overall goal is to create 3D models for AR visualization in real-time. Figure 4 below shows the conversion of data from the initial AutoCAD drawing to a Google SketchUp 3D model. The middle drawing has selected utility lines highlighted in red as a feature of being converted into GIS shapefile unlike an AutoCAD drawing.

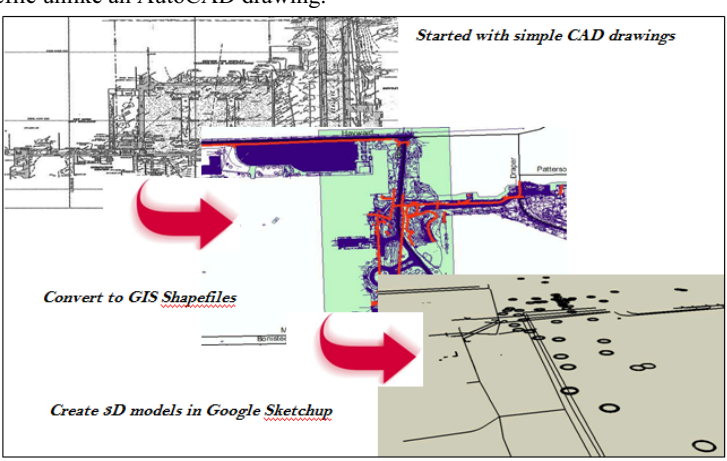


Figure 4: Conversion of data from one format to the other.

4.2 Augmented Reality (AR): As Figure 1 shows, to implement the AR view of pipelines on the excavation site, two data resources are needed: the pipeline GIS data and the real world data. The two data resources are retrieved independently and integrated by AR software in real time to render the augmented view. Many local utility companies establish Geodatabases (GIS Databases) for their underground assets. The GIS data is transported via GML. In the GML schema, geographical coordinates, geometric characteristics and other attribute information of the pipelines are represented. At the same time, the real world data contains the real time tracking data and video stream of the real excavation scene. The tracking data supplies the AR system with position and orientation of backhoe, which is used for establishing the camera reference coordinate system with the origin at the video camera. The CAD models of pipelines, which are originally represented under the geographical coordinate system, can thus be aligned with the new camera reference system, calibrated and superimposed on the video sequence representing the real world.

4.3 Working of the System: The framework is based on the data flow chart in Figure 2, . Mounted on the rear of the backhoe is the rover component of a RTK (Real Time Kinematic) GPS system, which transmits the geographical coordinate at the frequency of 1Hz. Considering the chassis of backhoe is stationary at a short time slot during operation, The frequency of 1Hz is enough for updating the position of backhoe. Also the electronic compass is attached to the front of the backhoe close to the boom, and transmits the orientation of boom in the form of yaw, pitch and roll with the maximum sampling speed of 30 times per second. Since the boom of backhoe swinging continuously during excavation, high frequency of orientation sampling is necessary for updating the gaze direction of video camera so as to maintain the correctness of the viewing frustum (Khoury and Kamat 2009). Video stream captured by video camera is put at the background of the augmented view. Eventually, the mixed view of pipelines and real excavation site can be displayed to the excavator operator through a cabin monitor. A prototype simulation of such a system was created in the virtual environment of Google Earth. This prototype simulation is shown in Figure 5 below. Figure 5.a shows the third-person view of the excavation site. Figure 5.b is the augmented view which is displayed on the cabin monitor. Straight colored lines indicate the location of underground utilities, the strip buffer warns the excavator of the uncertainty in the location displayed. The pop-up annotations let the excavator be aware of the attribute information of the buried pipelines.

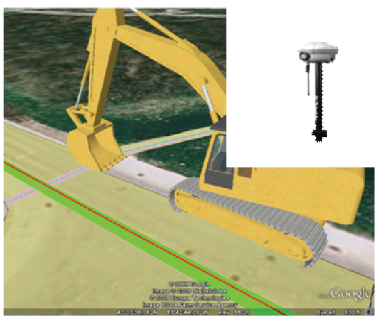


Figure 5.a

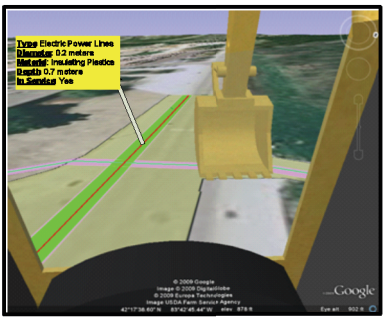


Figure 5.b

Figure 5: Interface for the collision avoidance augmented reality system

5. Conclusions and Future Research: The framework described in this paper, by building upon the existing technologies has the potential to transform underground utility locating methods. The simulation in the virtual world of Google Earth shows that having the utility lines pre-marked using AR would be an extremely useful aid to excavators. As mentioned above, the registration process of superimposing pipeline models on the real scene can be divided into two steps: First using the location and orientation of the backhoe to set up the camera reference system; second aligning the pipeline's geographic coordinate with the camera reference system. Therefore obtaining the accurate location of the excavator and the pipelines are the deciding elements for the registration accuracy.

The American Society of Civil Engineers (ASCE) estimates that a total of nearly $2.2 trillion is needed to overhaul the entire United States infrastructure over the next several years. Water and waste water pipelines were given a grade D- in the 2009 ASCE report (ASCE 2009). Laying new pipelines and replacing decades old sewer lines would all be required as part of the expected rehabilitation work. The presented research is thus very timely and critical, as the proposed framework would allow excavating teams to observe buried utilities while on the surface, and could help reduce time and cost over-runs while significantly improving safety. As noted earlier, viewing 3D models of pipes in AR is an initial step of our research. Our eventual goals are to develop an integrated collision avoidance system and a comprehensive utility maintenance system. Ongoing research is addressing technical challenges defined by this overall technical agenda.

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Real Time Information Integration via "*i- Booth*©"

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ABSTRACT
Information has the best value when it is delivered to the correct place at the correct time in the required format. Many scholars have noted information and communication chaos in the construction industry. The "*i - Booth*©" is a real time information management system, which functions as the hub of the real time information integration system, is a novel technology developed at the University of Calgary in 2006. The concept was tested in commercial building construction settings with positive improvements in terms of tool time, productivity, and worker satisfaction. The content of this paper includes the conceptual framework, Graphical User Interface (GUI) development, and system building & verification process of the "*i - Booth*©*."* The challenges under worker, management, technological, automation, and external issues during the development of the interface of the "i-Booth" are also explained in the paper. The multi-point capability of the system is expected to enhance the integration of the design office, the construction office, and the site staff as well as improve tool time, construction productivity, worker satisfaction, and communication.

Introduction

The present status of the technology usage in the construction industry and current communication practices were recently investigated in Alberta, Canada to develop innovative solutions to improve communication and productivity (Hewage and

Ruwanpura, 2009). One of the main findings in this investigation was the justification of "inadequate communication" between the various parties involved in construction projects. Almost all workers blamed the managers for the insufficient "information flow" from the site/main office to the operational (site) levels (Hewage and Ruwanpura, 2006a). Wachira (2001) too mentioned that 50% of construction workers usually complain about inadequacy in communication. Bowden et al. (2006) and Mohamed and Stewart (2003) found that only 20% of the information passed down to the operational (worker) level in a construction site. This also confirms FIATECH (2008)'s remarks on the field-level automation and the wireless and display technologies by comparing lack of use in the construction industry compared to manufacturing and transportation industries in terms.

Further, Hewage and Ruwanpura (2006b) found that the "inadequate communication" between the stakeholders in construction projects; especially at the site level leads to productivity losses and inefficiencies. This was validated by interviewing 101 workers from four construction sites of four general contractors. Hewage and Ruwanpura (2006a) also proposed and pilot tested a novel concept called "Information Booth" to address communication issues in the construction site environment. "Information Booth" is an automated information outpost designed to aid lead workers and foremen during the daily tool box meeting and site operations. The key information elements stored in the 'Information Booth" were daily and weekly targets, technical specifications, 2D or 3D drawings, 3D construction details, and safety information (Hewage and Ruwanpura, 2009).

Communication involves the flow of material, information, perceptions, and understanding through a variety of sources. To be able to contribute to the success of a project, a worker must be told exactly what tasks are expected of him (Dozzi and Abourizk, 1993). Clear explanations of tasks and expectations are required to achieve optimum productivity levels. Employees must also know where their instructions come from: there must be a visible communication chain on the job. It is likely that the instructions from an unknown source will be disregarded by most of the people. Moreover, to be totally successful, the communications should flow both ways. The "bottom-up" management system practiced in Japan improved productivity substantially; the system works because it nurtures the idea of communicating ideas both upward and downward (Dozzi and AbouRizk, 1993).

The main purpose of this paper is to discuss the real-time information integration using the latest version of the Information Booth called "*i-Booth*" to improve communication between various entities in a project. The challenges faced during the development of the interface of the "*i-Booth*" are also explained in the paper.

Present Status of Information Integration in Commercial Construction

The construction industry has an increased recognition of the need to implement innovative information and communication technologies and its potential benefits on projects (Weippert et al. 2003). Magdic et al. (2002) concluded that some important experience has already been gained and the main building blocks for mobile computing in the construction industry are already available in the market. Their final test showed that the efficiency of information interchanged with and at a building site can be improved significantly even by using current mobile computing components

unmodified (PDA's, mobile phones and web services). Despite the barriers to implement IT at site level, Daito Trust Construction Company, a Japanese construction firm, developed a large-scale mobile computing system called the DK Network. The company reports that the system made the process of construction easier and greatly increased productivity (Daito, 2003).

As projects become more complex, the amount and detail of the information required increases. This increase in turn makes the process of storing, retrieving and analyzing the control information more complicated. One commonly cited means to overcome labor shortages and improving productivity, cost effectiveness, and competitiveness is through the use of advanced technologies (Tatum, 1986, Johnson and Tatum, 1993).

It has been reported that the tool time of the construction projects is approximately 45 to 60 % with a mode of approximately 50% (Ruwanpura et al. 2006, Hewage and Ruwanpura, 2006a, Hewage and Ruwanpura 2009). The inefficiency in materials management, equipment management and communication issues lead to non-tool time (Hewage and Ruwanpura, 2006a). The researchers have found that the morning tool box meeting in which foremen communicate the day's planned activities to workers lacks effectiveness and enthusiasm. It was also noted that supervisors do not deliver the information in a format that is easily understood by the workers. As a solution, the researchers have come up with a novel communication tool that may serve many purposes. A computerized information kiosk equipped with important jobsite information called the "Information Booth". The "Information Booth" was successfully tested in an active hospital construction project in Calgary by using it in the toolbox meeting on a daily basis. The focus was to improve communication between the foreman and workers. Foreman used the "Information Booth" to explain the work targets, expectations and work assignments while showing other additional information such as the technical information and safety to improve communication. Hewage and Ruwanpura (2009) explained in detail the use of the "Information Booth" in the hospital project, which increased the tool time by 10% and productivity by 17%.The "Information Booth" was further developed as the "*i-Booth*©" (Figure 1) with several additional functions. The additional functions include Short Message Service (SMS) alerts for communicating new uploads (drawings, approved change orders) to the system by linking remotely accessed camera system for "Virtual Supervision" (Silva et. al., 2009) and integrating handheld electronics for information transfer between site and office. These updates were included in the *i-Booth* based on the input received from workers and the managers of the construction sites documented in Hewage et al (2009).

Real-Time Information Integration System using *i- Booth*©

Construction companies use several internal systems for information management between the head and site offices; however, the systems used for on-site information management are relatively fragile (Hewage and Ruwanpura 2006a). Integration of existing company systems with the proposed system is a critical factor for success. The link between these systems must be integrated and automated so that the current data from the company system can be retrieved from the "*i-Booth*©". At the same time, the company system can access the data from the site level in real time. Construction companies utilize various web portals for document management.



Figure 1. "*i-Booth*©" and Graphical User Interface (GUI)

These systems fall in to two categories i.e.; in house systems and commercial systems such as "e-Builder" (trademark of e-Builder Corporation). The main challenge researchers encountered during development stage is to find a uniform data structure to facilitate the integration process. FIATECH (2008) has developed an ISO standard (ISO 15926) for process plant information exchange, though such a standard has not been developed for commercial construction until now.

Research team designed a link between the "*i-Booth*©" and in-house document management system to facilitate integration process. This linkage prevents information double handling and increase user acceptance of the proposed system. The primary reason behind the selection of in-house document management system was the accessibility to the information (software architecture).

Research team has identified three main data types i.e.: primary data, secondary data and supporting data for "*i-Booth*©". The main focus of the primary information category is drawings and its related documents such as specifications and change orders. The design and engineering staff at the engineers' office has the ability to edit the contents of the drawings whereas the site staff can only read/view the drawings. Site staff (end users) with editing privileges could add additional details for each category such as description, index, and version. Timely delivery and notification of approved change orders is a critical to ensure smooth operations in construction sites. When a change order is issued from the system (through architect's office or engineer's office) the end-users (construction manager, superintendent) in site level will be notified with a SMS message.

The secondary information of the "*i-Booth*©" system consists of technical information, safety, 3D-views, schedule and productivity toolbox. Information/data loaded in this section consists of technical documents, training/safety videos, site manuals, Material Safety Data (MSD) sheets, 3D or isometric drawings and training handouts. The schedule section includes the master schedule, look-ahead schedule (2 or 3 week), marked working drawings and handheld synchronization. Site supervision and management personnel have the ability to upload working or marked drawings to working drawings sub sections. Schedule sub-section contains the construction master schedule, look-ahead schedule, and work assignments. Project

manager/construction managers have the ability to export MS-Project and Primavera schedule directly to the system to share with site personnel (supervision staff and lead workers).

The supporting information provides valuable inputs to better plan and manage construction projects. Supporting data section consists of "Virtual Supervision" and weather information. Remotely accessible wireless cameras enhanced the potential of site supervisory capabilities; emerge the term "Virtual Supervision" (Silva et. al., 2009). "Virtual Supervision" is added to the "*i-Booth©*" system to enhance the supervision quality of building construction. Weather information will be useful for the workers in the workface to prepare for weather variations throughout the day as the researchers found that the workers spent significant amount of time moving between the site trailers and the workface (Hewage and Ruwanpura, 2006b, Hewage and Ruwanpura 2009). The weather variations can also be used to proactively plan the work of the day if the prediction shows negative impacts to the projected plan of the day.

Figure 2 illustrates the fundamental relationship between main data types and construction process. Arrow styles represent the importance of the data (solid; high priority, dash; medium priority and dots; low priority) and arrow heads mark the information flow. The network diagrams in the right side of figure 2 represent the conceptual information flow in the proposed system. System data management processes make use of hybrid (server and local terminal) solution. Primary data will be handled by a server solution. Primary data will be stored in Network Attached Storage (NAS) or Storage Area Network (SAN). Servers and the network were designed with redundancy to improve data reliability. Server loads will be managed by a special system administration team (initially University of Calgary IT administration will provide assistance) to maintain the speed and accessibility of the system. Secondary data in the system will be managed similarly. However large capacity files associated with safety and 3D-views is an exception and majority of these files are static. These files will be manually uploaded to the system in the job site. This synchronisation process will be carryout though high speed USB port of the local "*i-Booth©"* terminal. Supporting data management is relatively simple since two external websites were embedded to the proposed system.

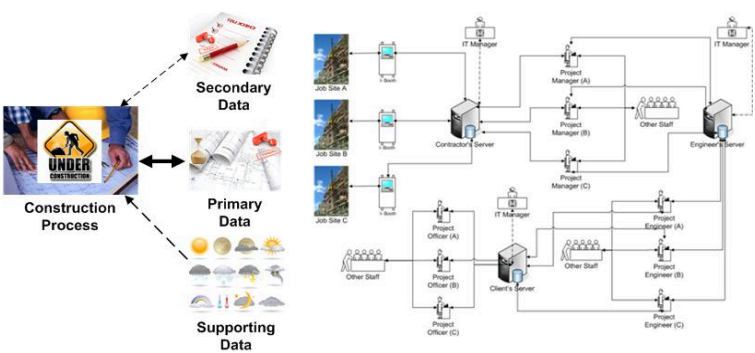


Figure 2. Relationship between the Data Types and Construction Process

System Design and User Behavior

Graphical User Interface (GUI) and Human Interface Device (HID) selection was an important issue encountered by the research team during system design stage. The main screen of the system was designed to enable touch screen functions. As work force in Alberta commercial construction include significant number of foreign workers with limited English literacy, icons were selected to enhance the identification without much difficulty. The data structure and browsing mechanisms were kept uniform and simple to improve usability. Construction personnel's' behavior modification (manage the resistance to change) and adult education were important factors considered when deciding on GUI and HID's.

HID's were selected carefully based on the results from Hewage and Ruwanpura (2008). Initially, the research team identified mechanisms such as trackballs, joysticks, pointing devices, keyboards, and touch screen for interaction between the system and site personals. After many interviews and discussions with construction professionals, touch screen was selected as the main interactive media. Construction workers were more comfortable with touch screen rather than keyboard and pointing device (Hewage and Ruwanpura, 2008). Screen selection was based on factors such as screen size, anti-reflective (sunlight readability without back light enhancement) (Vartech, 2009), resistance to dust, resistance to construction chemicals and weather resistance. 32" and 42" LCD screens were selected for the system based on opinion from construction professionals.

When the system is idling, screensaver function is utilized to convey safety tips and proper work practices to educate the operational level (workers). Research team is developing safety and work practice screen savers with the aid of industrial research partners. Screen savers will be changed every two weeks based on the work activities carried out in job site (research team and site staff will decide the suitable screen savers). Every 10min screen saver will change based on identified main activities (in two weeks time frame discuss above).

Expected Problems and Intended Solutions

Problems may be encountered in the early stages of implementation of the real time information integration process in construction projects. The researcher team expects problems in five major categories: worker, management, technological, automation and external issues. The researchers carried out a brainstorming session with the construction professionals and project team to mitigate the impact of the following issues.

Worker Issues: Worker issues have been identified as the most influential area. Human issues will be the most influential factor in the success of the integration system. The majority of human issues are expected to be with the "*i - Booth*©" and integration system. Issues related to the "*i - Booth*©" will be coping with the technology, any changes in workload, and the associated benefits. The problems related to the "*i - Booth*©" are being tackled by the researchers from its inception because of the knowledge gain during the actual test of the Information Booth (Hewage and Ruwanpura 2009). The "*i - Booth*©" is designed in such a way that anybody with a general understanding of a computer or an automated teller machine

(ATM) will be able to operate this device. Site management may raise concerns about the using system as a toy by the workforce in the workface. Research team has introduced user authentication protocol to prevent this. In the workface foremen and lead workers will have the full access information (according to the trade) such as drawings, change orders, etc. The workers do not have direct access to the "*i-Booth*" without the assistance of the foreman or the assigned lead workers (in the absence of the foreman).

Management Issues: In general, the construction sector offers stiff resistance to IT solutions (Mak, 2001). The majority of these problems are initiated by management. Researchers may encounter strong resistance from management with the proposal to change internal systems with IT for better efficiency. The success of the integration system will depend on management comfort and trust to the system. Researchers will carry out awareness sessions with management to convince and educate them on IT tools, which are available to assist, and not intended to replace the human brain. The other main challenge will be to convince construction industry to use e-format instead of paper version. Both electronic version and paper format will be used during the early stages of the implementation to measure the effectiveness of both versions. The construction sector is slow moving towards to e-format from paper version but there are positive signs of emerging such as e-bidding (Coolnet, 2009).

Technological Issues: Researchers encountered a few technological difficulties in the inspection of the project to provide connectivity and power for the "*i-Booth*©". In site level getting a hardwire connection to workface will lead to many other problems (such as wiring and disturbance). Therefore connectivity issue was settled by cellular modem and portable internet connection. In site level getting a hardwire connection to workface will lead to many other problems (such as wiring and disturbance).

Automation Issues: Automation issues will arise during the early stages of the implementation of the integration system. An internal IT department (of construction companies) should be able to handle these issues. If not, the research team and the IT division of the University of Calgary will have to resolve the issues with the internal IT department of the contractor (research partners). The main issue will be managing the loads in the file servers. Finding a uniform data structure to integrate in-house/commercial document manage system with proposed system (this aspect was explain in detail in real time information integration section) is another concern. Solution to this concern is explained in details in the real time information integration section.

External Issues: Weather conditions in Alberta can be critical during both late Fall and winter seasons. The system is designed to withstand up to -40C temperature. In case of unidentified problems, the researchers have been advised to follow a four step procedure to resolve the problems (Silva et al. 2008). The four step procedure is (figure 3.):

- The worker or identifier of the problem should immediately inform their supervisor.

- The supervisor should inform the issue to the information manager (IT Manager), which a new position suggested by the Information Booth, or his assistant on the construction project.
- The information manager will discuss the issue and its resolution with the researchers/developers.
- Changes will be made, and a pilot test will be conducted by the researchers/developers in the actual site environment.

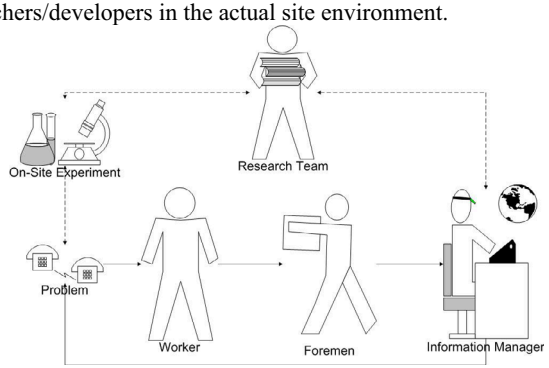


Figure 3. Resolution Mechanism of Unidentified Problems at the Front-end

Conclusion

"*i-Booth*©" system is a novel concept currently being implemented in Alberta, Canada. The main contribution expected from this system is to enhance efficiency and effectiveness of the work force in the site environment through improved communication between site management and workers. The authors strongly believe that the worker and supervisory staff satisfaction will be increased due to the real time information integration and improved communication, as in the case of the actual test of the first version of the Information Booth documented in Hewage and Ruwanpura (2009). It is noted that the sustainability of the system depends on the worker and supervisory staff satisfaction, increase in efficiency and communication, and the significant savings to project schedule and cost.

Accuracy of construction planning and estimation may improve considerably due to the real-time connectivity between construction site and head office (Silva et al. 2008). On site implementation of "*i-Booth*©" may revolutionize 3D and 4D CAD application such as BIM in field level because of the simplicity in implementation and utilization. These 3D visualizations will aid foreign/local workforce in Alberta to better understand the work to be performed. "i-Booth©" system is easily applicable to Oil and Gas industry to disseminate information at workface. Tool such as SMART Plant 2010 can be effortlessly integrated with the propose system to enhance the productivity and effectiveness of the workforce. Authors strongly believe "i-Booth©" may persuade positive outcomes in construction industry such as improvement in direct tool time, productivity, improvement in worker satisfaction and better information integration and information management. The comments made by the industry professionals after seeing the features of the i-Booth and the results of the first version of the Information Booth have increased the opportunity to test it in few

construction projects from the end of 2009 until mid of 2010. According to Constructor 2010 Magazine "i-Booth©" will revolutionize the construction industry in Alberta (Contractor, 2010). It is noted as a limitation that the proposed frame work will focus the issues and necessities of the participated research companies in building construction in Alberta, Canada.

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Real-time Spatial Location Tracking of Construction Resources in Lay Down Yards

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Abstract

Emerging wireless remote sensing technologies offer significant potential to improve the management of construction resources in lay down yards by tracking the location of personnel, yard vehicles, and materials in real-time. This paper presents a theoretical concept for real-time lay down yard asset management. A field trial using Ultra Wideband (UWB) positioning technology is presented to track spatial and temporal location of resources (workforce, equipment, material) that are present in lay down yards. The benefits and limitations of the technological approach which were applied in this research will be explained in detail and recommendations for its use in field tracking applications in large and open construction environments will be given. A particular focus of the paper is on the comparison of the accuracy of real-time location data from a commercial UWB system with ground truth measurements from a robotic total station.

Keywords: Automation, Data collection, Sensors, Tracking, Ultra Wideband.

1. Introduction

Compared to manufacturing and production, the dynamic environment in which construction activities take place presents a challenge in automating its work tasks. Nevertheless, sensing technologies and automated data collection techniques promise to have large benefits compared to the current materials management and control procedures in construction industry, which are mostly manual, labor intensive and

error prone (Navon and Berkovich 2006). They often are not applied in the field for various reasons, e.g. due to the high implementation cost and risk of failure during the initial implementation phase. Recent developments in the field of asset location and tracking may represent an opportunity for research in the construction industry. These include technologies designed to help workers and managers to locate equipment, hazard areas or tools anywhere on the construction premises. Among other advancements, wireless, non-destructive, and reflector-less construction technologies have been identified as key breakthroughs for both practitioners and researchers in the construction industry. Such envisioned technologies focus on reducing non-value-added activities while monitoring and tracking the position of a particular resource on site from a remote and safe location. A combination of the advantages of several technologies formulates a system that ultimately operates near real-time (1Hz or higher) and will expedite material delivery, track the location of workers, equipment and hazardous areas, and increase process, productivity, and facility quality.

Measuring the aggregate productivity is a difficult task in construction. A number of studies point towards a possible decline in onsite construction productivity (Eastman and Sacks 2008). By using technology during the construction and life cycle of the built environment, it is beneficial to track resources to improve the efficiency and effectiveness of the supply chain in construction. Moreover, as the construction industry has been moving towards prefabrication and preassembly in recent times, the industry and society as a whole can benefit by studying the improvements made in manufacturing and other industries and by tracking, locating, finding, and distributing the right material to the right location at the right time (Haas et al. 2000). Supply chain management involves all the activities associated with the transportation of goods from the raw material to the end user. In a construction industry supply chain, lay down yards play an important role to facilitate both quick information and material flow (Barriga et al. 2005), thereby transforming the control from a “push” system to a “pull” system.

This paper focuses on material handling in construction lay down yards, which forms an integral part in this “pull” system and on technology that has the potential to speed up processes, saving cost and time. In addition, this paper explains the concept of using technology to pro-actively monitor workers and operators in real-time which could be used in the near future to reduce incidents rates and idle times in lay down yards. Potential applications are elsewhere on a construction site.

2. Current State of Knowledge

There is immense interest and potential in systems that provide users the location of project critical resources (workforce, equipment, material), which is also called “context awareness” in robotics and telecommunications. Localization is the technique that is used to achieve such measurements and is mostly solved by proximity, angle, or distance to a reference location (time of flight or signal strength of transmitted and received signals). Knowing the location of construction resources (workers, equipment and material) and identifying and measuring the status of work tasks helps to improve the project performance. Sensors and sensing technology can be used in construction and infrastructure projects (Akinci and Anumba 2008) to achieve automated tracking ability. Selection of a particular technology for tracking

depends on the principle of localization techniques such as line-of-sight (LOS), required signal strength and calibration required for implementing the technology. The prevailing legal framework regarding the permitted bandwidth and associated availability and implementation costs also adds constraints in the selection of technology (Khoury and Kamat 2009). Radio Frequency Identification (RFID) technology has found uses in identification and localization in various industries including the retail and medical industry. In the construction industry, RFID was successfully used to automate the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects (Song et al. 2006a). Results showed that RFID technology can function effectively in a construction environment involving large metal objects, but at the same time issues regarding the optimum speeds at which the reader can be moved (<2 mph) so that tags can be read with 100% accuracy remain a concern. Global Positioning Systems (GPS) are capable of providing position information but the high cost of equipment makes it unfeasible for tracking every piece of material in a construction lay down yard. Combining RFID with GPS technology, where mobile RFID readers are equipped with GPS (Song et al. 2006b) reduce the implementation cost, but concerns with read range and the number of passes required to identify the location are still present (Grau and Caldas 2009). Other approaches focus on RFID in combination with ultrasound signals in a wireless sensor network (Skibniewski and Jang 2009). However, low power ultrasound devices with a measuring range of up to 100 m and multi-path effects limit the application of this methodology to smaller work areas. Existing technologies like RFID, RFID +GPS, RFID+ultrasound are found to have limitations in terms of reliability, scalability, and interoperability. Hence a low cost sensor system, which is robust in cluttered environment and provides real-time location information is desired.

3. Construction Resource Location Tracking Using Ultra Wideband Technology

Ultra-wideband (UWB) was initially developed for military use in the 1960's. FCC approval lead to UWB being explored for monitoring of construction site activities (Teizer et al. 2007b). Use of UWB for target imaging and identification was explained by Taylor in his studies of Ultra Wideband radar (Taylor 1991). UWB is a short pulse radio frequency (RF) waveform which is based on the time-domain principles of electromagnetic theory (Fontana et al. 2002). Compared to other technologies like RFID or ultrasound, UWB has shown to possess unique advantages like high temporal resolution along with a high bandwidth, which are ideal for precision localization applications. Higher range, measurement accuracy and immunity to interference from rain, fog or clutter makes it ideal for use in construction environments. Research has shown the feasibility of a commercial UWB system for precision asset location for tracking of high valued assets in hospitals and military facilities (Fontana et al. 2003). Unlike GPS, UWB provides a means for indoor positioning systems which are helpful in the case of emergencies (Ingram et al. 2004). UWB signals are considered to be immune to multipath interference, and hence have an edge over other technologies in a cluttered and dense communication environment. Testing is underway to use UWB localization in mining environments and several challenges like presence of physical obstacles,

communications constraints and other environmental factors have been identified (Chehri et al. 2009).

Personnel, equipment, and materials inside a lay down yard can be tagged with UWB tags to track the location of each of these resources in real-time. A typical UWB localization system comprises of (i) a central hub processor and computer interface with (ii) receivers that are capable of instantaneous ultra wideband field detection while being connected to the hub using CAT-5e shielded cables, and (iii) tags that are attached to the resources which are to be tracked. The location of each tag is calculated based on synchronizing the arrival signal using the time-of-flight principle. Signals between receiver and a tag can then generate real-time two-dimensional positioning data if at least three receivers are used. Real-time 3D location sensing requires at least four receivers, preferably at locations with significant difference in elevation. The accuracy of the distance measurements will depend on the geometric configuration of the reference point and the receivers on the field. Studies are being done to determine if a larger overlapping region is advantageous in terms of accuracy as compared to a smaller overlapping region or vice-versa. The materials and equipment operators are tagged and the operators are provided with a visual display of their own location and the location of the material to be picked up in a plan layout.

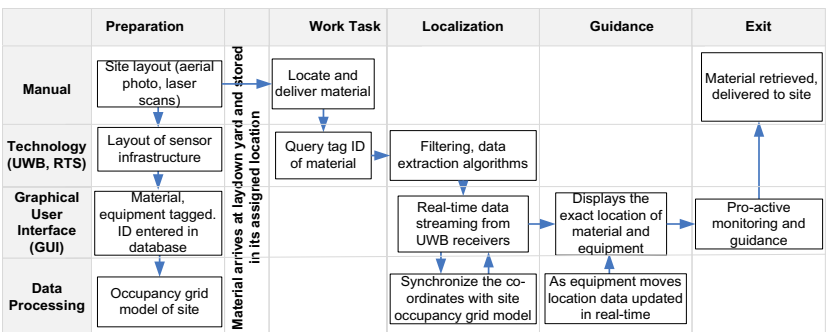


FIGURE 1 A methodology of lay down yard tracking using Ultra Wideband technology

4. Methodology for Real-time Location Tracking using Ultra Wideband

This paper explores the possibilities of UWB technology to locate the precise co-ordinates of resources and the application in a construction lay down yard for real-time tracking and proactive monitoring to guide equipment operators to the exact location with high accuracy. This paper extends the laboratory work already conducted at RAPIDS Lab at Georgia Tech for real-time three dimensional location sensing for workforce, equipment, and material positioning and tracking and provides a methodology for on-site implementation on the basis of field trials (see Figure 1).

The methodology involved tagging each material that arrives at the lay down yard gate and entering the data into an inventory management system database (see Figure 2). The key here is to match the piece mark of the material with the ID (identification) of the UWB tag. Pieces of equipment in operation and in motion in the yard are also tagged. Once an operator receives the instructions to pick-up and deliver a particular item(s), the corresponding tag ID can be looked up in the computer interface. A data

processing and graphical user interface (GUI) is developed that analyzes the RF signals inside the hub and displays the location of receivers and UWB tags in real-time. The data can be filtered to display only the locations of the equipment and the required items for pick-up in a plan layout. Additional data processing algorithms and visualization tools were developed to display the position data in a MATLAB environment and to predict the shortest path, using path-planning algorithms. This can be used for pro-actively guiding the equipment operators. More details about the GUI is given in next section.

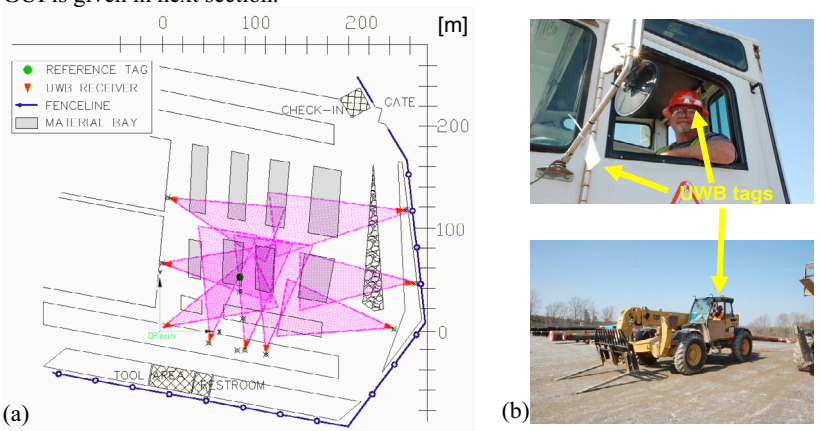


FIGURE 2 (a) Triangulation of UWB tags using receivers that overlap the area of coverage, and (b) UWB tags applied to construction resources inside the lay down yard.

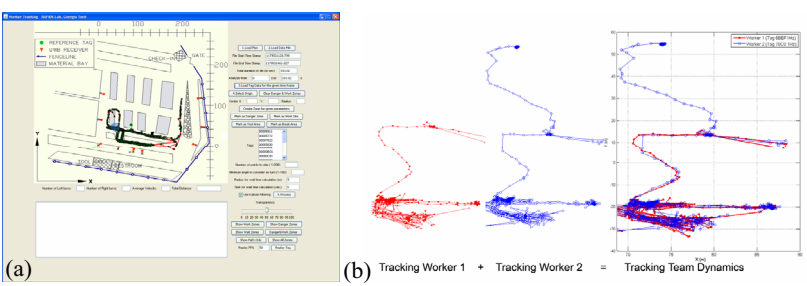


FIGURE 3 (a) Visualization of a resource trajectory inside the graphical user interface (GUI), and (b) paths of two workers on the same work task assignment.

5. Developing a Graphical User Interface (GUI) for Pro-active Guidance

A graphical user interface was developed which uses the CAD model or site layout plan to provide the information of current site conditions. Robotic Total Station (RTS), laser scan, or GIS information can be integrated to provide the spatial characteristics of the lay down yard. Sensing data is geospatially registered with these models to provide a rich data set as input for planning and execution of activities. These models can be fully utilized by including the schedule information for resource

monitoring and allocation and also measurement of work hour utilization of activities. Such a model is envisioned for the construction site and was experimentally tested in lay down yards.

A data fusion model based plan layout of the laydown yard and path planning algorithms like modified Dikjstra's algorithms were used for pro-active resource monitoring and equipment and worker guidance. A RTS was used to locate the maximum co-ordinates of the laydown yard. These are plotted onto a CAD drawing and divided into suitable sized grids, usually 1m x 1m. The occupancy grid model, which is used in robot navigation (Moravec and Elfes 1984), has been adapted for detection and tracking of construction resources (Teizer 2008; Teizer et al. 2007a). The principle of occupancy grid model is to represent a multidimensional tessellation of space into cells, where each cell stores a probabilistic estimate of its state (Elfes 1989). The methodology to embed 3-dimensional construction sites into a 2-dimensional surface and to decompose it into cells are explained in the literature (Lee and Adams 2004).

In this research, these cells have two sets of information for static and dynamic objects. The static objects such as the boundaries of the lay down yard, the approximate alignment of all the materials, the tool area and break and rest rooms are located by RTS, laser scans, camera or a combination of any of these technologies. They are then integrated in the CAD drawing. Developing this static model completes the first step, which is followed by locating dynamic objects. All dynamic objects in the lay down yard were tagged. The initial locations of materials are also marked in the model and were again tagged and whenever moved, their location was updated automatically and in real-time. The static and dynamic models are then combined to obtain a complete data fusion model, which has all the details of the lay down yard.

6. Field Experiments and Data Collection

Experiments were conducted at the lay down yard site for new coal power plant near Cliffside, SC. The lay down yard under consideration had an overall area of 16 acres, which provided ample opportunity to test the maximum ranges and feasibility of employing an UWB system over a large area. The major material bays comprised mostly of custom fabricated steel pieces, which were well laid out for workers and equipment to move around. There was only one entry point to the yard, which was guarded, and a tool and restroom area for workers. All experiments were conducted under the supervision of a safety manager at all times and with consent of the workers and equipment operators. The site layout and sensor infrastructure deployed is illustrated using Figure 2a.and 3a.

UWB receivers were set-up at the boundaries of the lay down yard at suitable locations based on prior experiences. These receivers were connected to the central hub using shielded cables. The cables were buried in soil whenever crossing the vehicle paths to avoid damage. A reference tag was placed, which was in the line of sight of all the receivers. Laser scan data of the environment was not available for this experiment. The plan view of the lay down yard that can be seen in Figure 2a was established through the data collected from a robotic total station.

The location of important control points such as material bays, fence, road and other installments on the field were recorded. These were used to develop a plan of the lay down yard. The lay down yard, access and work areas, the tool area and other facilities, and sensor locations can be identified. Real-time x, y, and z data from the UWB sensors were then merged with readings from the RTS. Both data sources were calibrated to have the same Cartesian coordinate system.
The origin was set to be one of the UWB receivers and the y-axis was oriented to be in line with another receiver. The red triangles in Figure 2a represent the location and orientation of UWB mid gain receivers (60 degree field of view) and the green circle show the location of the reference tag that is necessary to triangulate the radio frequency signals of the UWB system based on time-of-flight (TOF). The shaded areas are the bays that were tracked for material pick-up and delivery. Figure 3a shows the plan with the experimental layout of receivers and the material bays.

6.1 Tracking equipment and material in lay down yard
An UWB tag of 1Hz frequency was attached to a yard dog (the truck without the trailer) as shown in figure 2b. The driver was instructed to drive around the yard to simulate the process of picking up material and delivery. Data in this preliminary experiment was collected for duration of 45 minutes and the position of the equipment was tracked successfully in real-time. Figure 3a shows the path followed by the equipment during the test. The figure shows the movement of the equipment and features such as the exact location for a given time, turning radius, start and end points of the path etc. can be extracted. The plan layout was embedded in the GUI and the UWB data was analyzed in this background. Figure 3a also shows the GUI with this test data. The GUI can be used to analyze the data within a particular time range and the path of the equipment can also be simulated (replayed). Based on these simulations, it was possible to conclude that the equipment data collected stayed within the actual paths on the plan. The experiment was repeated with different pieces of equipment to ensure that the type, size and functionality of the equipment do not affect the data collection.

6.2 Tracking Workers and Team Dynamics in Lay Down Yard
UWB tags of different frequencies were used for a second experiment. This test included 60Hz, 30Hz and 1Hz UWB tags. These tags were attached to the hard-hats of workers. Data was collected while the workers were involved in their daily activities. Figure 3b shows the paths of the workers tracked during a particular work tasks (searching for a material piece). The visualized trajectory data shows that it is possible to pro-actively monitor the workers and their location in a very large lay down yard using UWB technology.
Figure 3b shows the path of a worker who had a 1 Hz tag attached to his hard-hat. The path runs from the material bay towards the tool area. The tool area was outside the experimental set-up and hence, was not very well captured by UWB receivers thus causing some considerable noise measurements. However, within the experimental area, all UWB paths were very well defined. The experiment shows the feasibility of using UWB in tracking and that UWB technology can be used to study the productivity of construction resources, including workers. For example, it can be

measured how much time workers spent to get tools from a tool box (a task that is considered to be non-value adding task by many field practioners). The paths of two different workers on a same task were monitored using 1Hz UWB tags (IDs: 6BEF, 70C0). From the data log that was recorded at the same time, it was evident that both of workers were riggers and consequently need to work together to hoist steel members. This is evident from the UWB data as well.

6.3 Comparing UWB data with RTS data to Validate Error Measurements

Data was collected simultaneously using RTS and UWB technologies. A 1 Hz tag was attached to a special hard-hat developed for measuring the error rate of UWB technology. The top of the helmet carries a miniature RTS prism. The RTS was calibrated to follow the prism and collect highly accurate data (less than 3 mm per data point). This was compared with the data received from UWB for the same duration. Initial results show almost negligible differences (see Figure 4a). Plotting the error measurements (deviation between RTS and UWB) on a time based scale resulted in Figure 4b. Overall error measurements can include instrument reading error, field observation and recording errors. Another reason for larger deviations is the data output of UWB and RTS as they were collected in two different time scales (up to 60Hz vs. 4Hz, respectively).

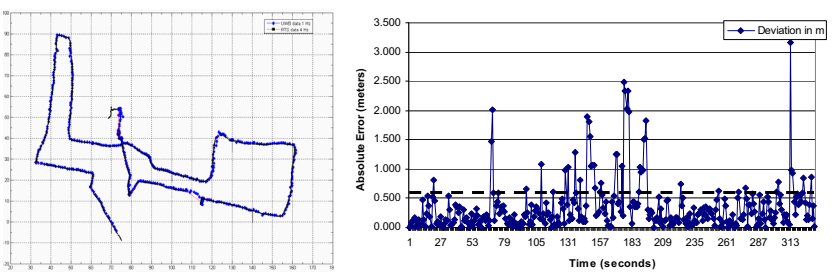


FIGURE 4 (a) Comparison of paths measured by UWB and RTS (Distance in meters) and (b) error rate of UWB data in comparison to ground truth measured with RTS

An algorithm was developed to synchronize the frequency using interpolation of data points. The absolute deviation of the data points was computed. After analyzing the data, a suitable range for the deviations are fixed and the results were plotted. Figure 4b shows preliminary results of comparing UWB to RTS data for the duration of about 300 seconds using a 1Hz UWB tag which equates to roughly 300 data points. It is observed that nearly 95% of all recorded points show a deviation of less than 0.6 m, which is suitable for construction activities.

7. Results and Discussion

Application of lean principles in material management and delivery in a lay down yard can help optimize the entire process by avoiding or reducing the time spent in performing activities. All tasks in work processes can be classified as value-adding or non-value-adding activities. Some examples of non-value-adding activities that are common in lay down yards are redundant search functions and unnecessary

transportation. Inefficient means used in identification the location of material and errors in retrieving the correct material are the major reasons for loss of time and resources. Use of an automated localization system based on UWB can minimize this loss and thereby help streamline the operational processes in lay down yards. In addition to tracking, proactive monitoring has immense potential to reduce the incidents and near-misses that occur on construction sites. The application for safety purposes needs to be explored in more detail as part of future research.

Moreover, a detailed study on cost vs. benefit, in particular on cost saving by using UWB technology may provide construction practitioners with enough confidence to embrace this technology. Along with improved data acquisition techniques, UWB may provides easy integration with other management and scheduling systems providing prompt updates to changing field information and to any kind of project stakeholders that are interested in such data.

The ease of use coupled with enhanced information sharing will increase the responsibility of ownership within a group of practitioners. These, along with an improved resource utilization and cost savings on document handling and storage space, are some of the major advantages of UWB tracking systems. UWB's main limitation at this point is a necessary measurement infrastructure, which once set in place can be effective for at least the project duration.

8. Conclusions

Rapid technological advances have made it possible to implement cost-effective UWB radar and UWB communication and tracking systems in construction tracking applications. As demonstrated in a field trial, UWB system can provide robust real-time tracking of multiple construction resources at the same time giving decision makers tools in their hands that were not available before. Preliminary experimental results to locate and track materials and pieces of equipment were presented. In addition to some successful field trials that tested a commercially available UWB system, some limitations and benefits of the technology applied were highlighted. Technological challenges remain and are on the side multipath interference. Additional research was identified to investigate UWB systems and its applicability in construction further.

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Semi-Automated As-Built Modeling of Light Rail System Guide Beams

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Abstract

For a light rail system, smooth contact between the vehicle and the guide beam is critical for reducing the friction and the vibration of an operating vehicle. Therefore, the shape of guide beams needs to be controlled with mm-level accuracy during the construction. Currently, most methods for detecting shape defects of guide beams, such as experimental run of vehicles, are costly and tedious, and can only identify defects after the completion of the construction, causing reworks and delays.

From dense point clouds collected by laser scanners, inspectors can manually extract geometric features and conduct virtual inspections of guide beams. However, the manual geometric feature extraction process impedes effective utilization of point clouds for the shape analysis of guide beams. This research developed a semi-automatic approach for simultaneously extracting the axis parameters (e.g., radius) and cross-section features (e.g., width) of a guide beam using a Hough-Transform based approach, and discusses factors (e.g., data density) influencing the performance of this approach.

Keywords: Laser Scanning; Geometric Feature Extraction; Information Retrieval; Quality Control; Surveying; 3D Modeling;

Introduction

The precise installation of a guide beam for a light rail system is critical for both the riding quality and the maintenance costs. Smooth contact between the guide wheels of a vehicle and the guide beam are important for reducing the vehicle frictions and hence reducing the vibration of an operating vehicle and the maintenance costs of the vehicle and the guide beam. Therefore, the quality control of the shape of a guide beam is important for the performance of a light rail system and the cash flow of the project. Currently, two approaches for detecting shape defects of guide beams are mainly used: 1) Visual inspection; 2) Experimental run of vehicles. The former requires inspectors to walk along the track and manually identify shape defects (e.g., distortions of the flanges). This method requires highly-skilled

inspectors to make decisions based on their experiences, and is subjective and time-consuming. Experimental runs of vehicles expose a constructed light rail system to real working conditions. During experimental runs, engineers can observe the vibrations of the vehicle to identify sections of problematic guide beams. Such real-scale experiments could be expensive. Moreover, both the visual inspection and the experimental run methods are conducted after the construction, when it might be too late or too expensive to fix those detected defects.

Laser scanning is a promising method for capturing geometric details of guide beams during the construction. A laser scanner can densely sample the surfaces of a guide beam in minutes (1 cm step size within 50 m for the scanner used in this research), and generate dense point clouds. With such dense data, inspectors can reconstruct 3D as-built models of guide beams using commercial 3D modeling tools, and manually conduct virtual inspections on these models. One major issue is that this manual approach requires inspectors to manually extract axis (e.g., radius) and cross section features (e.g., width) from point clouds. This becomes a tedious approach considering the fact that guide beams can run for miles resulting in a very large amount of 3D data.

For improving the efficiency of utilizing laser scanners for more effective quality control of guide beams, this paper presents a semi-automated approach for simultaneously extracting the axis and cross-section features of an I-beam.

Related Studies

Previous research studies have investigated various methods for extracting geometric features and object poses from 3D data. Kwon *et al.* developed algorithms for extracting parameters of cuboids and cylinders from flash LADAR scanned point clouds (Kwon et al. 2004). Vosselman *et. al* showed the effectiveness of a set of Hough transform-Based algorithms for extracting planes, cylinders and spheres from laser-scanned data (Vosselman *et al.* 2004). Based on Gauss-Newton least square fitting method, Barker developed a MATLAB library for extracting 2D and 3D lines, circles, planes, cylinders, cones and spheres (Barker 2004). Using the Generalized Gauss-Markoff model, Gruen and Akca proposed a framework for extracting arbitrarily posed parametric surfaces by comparing data patches against a library of predefined surface templates and determining the most probable surface model for a given data patch (Gruen and Akca 2005). Gilsinn *et al.* used Principal Component Analysis (PCA) to estimate the pose of an I-beam (Gilsinn *et al.* 2005). Results of these research studies show the feasibility of automatic extraction the geometric features of light rail guide beams from dense point clouds.

One major difficulty of applying these previously developed geometric feature extraction algorithms for automatic extraction of guide beam features is that most algorithms can only handle simple 3D scenes (e.g., horizontal beam on flat ground in an open space). Many construction sites have more complicated geometric conditions (e.g., moving objects, and occlusions) than those in these simplified scenarios. To overcome this issue, we decided to develop a semi-automated approach, which requires inspectors to manually localize a number of axis points of the guide beam, and then the algorithm can refine such rough axis information to obtain accurate geometric features of the guide beam.

Guide Beam Features

Generally, a guide beam has two categories of geometric features to be inspected for their shape quality control. The first category of features includes the parameters of the axis curve (axis curve features), while the second category of features are the features of the guide beam's cross sections (cross section features).

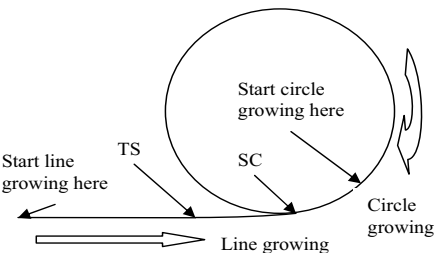


Figure 1 Line and circle fitting and growing for finding TS and SC points

For most light rail systems, to ensure the smooth turning of the vehicle, the curvature variation should be continuous: from straight line (infinite radius), to a spiral curve (a curve the radius of which continuously changing from infinity to a specific radius value), and to a circle with the specific radius value at the end of the spiral curve (Figure 1). Such curve shape has continuous curvature changes. In this research, we call the boundary point between the straight line and the spiral curve a "TS" point, and the boundary point between the spiral and the circular sections a "SC" point. This research focused on recognizing the parameter of the straight line, the spiral curve length between "TS" and "SC", and the radius of the circular section, because these parameters are controlled parameters having explicit as-designed values to be compared with the ones in the design drawings.

For such a cross-section of a guide beam, the critical features to be recognized are the web and two flanges, which could be simplified as three lines on the cross-section. With these three lines, it is possible to derive two geometric properties of the cross section: the width of the guide beam, and the angle between the flange and the web. This research focused on obtaining the width of the guide beam, but did not look into angles between web and flanges, since the former is usually a controlled property of the guide beam according to several interviews with domain experts. Table 1 lists the parameters focused on in this paper.

Table 1 Targeted features of a guide beam

Category	Feature Details (Symbol for Representing It)
Axis Feature	• Line parameters of the straight section • Spiral curve length (L): curve length between TS and SC • Circular section radius (R)
Cross-section Feature	• Flanges (F1 and F2) and Web (W) • Intersection points of W and F1/F2 (P1, P2) • Width (w): distance between P1 and P2

Overview of the Guide Beam Feature Extraction Approach

In most cases, guide beam axes are straight, or curves with small curvature (with radius larger than 100 m), so that the axis of a small guide beam segment (e.g., 1 m in length) can be approximated by a straight line linking the two ends of the segment. That line is called the "approximate axis" of a segment in this paper. For point clouds of a straight or approximately straight beam segment, projecting all points along its approximate axis results in 2D points profiling the cross section of the beam (Figure 2). The diagonal lines shown in this figure are formed by "mixed pixels" (Tang et al. 2007), which are data artifacts caused by laser spots spanning over spatial discontinuities (object edges). Figure 2 shows the location of the scanner to indicate that these diagonal lines are along the viewing directions of the scanner for guide beam edges.

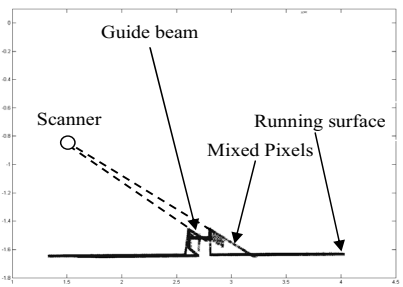


Figure 2 A segment of guide beam point cloud projected along the beam axis to form a cross section profile

In this research, we found that if a user can manually select a number of points roughly on the axis of a guide beam, these manually selected points were accurate enough to generate approximate axes of guide beam segments for generating their cross-section profiles. This observation motivates the development of an approach, which requires users to pick the rough locations of a number of guide beam axis points from point clouds, and then the algorithm uses these inputs to extract and refine cross-section and axis features of the guide beam (Figure 3).

Given the manually selected axis points, the semi-automated approach for guide beam feature extraction consists of six major steps: 1) Interpolating the manually selected axis points with a user-defined interpolation step size; 2) Identifying the locations of TS and SC points by fitting and growing straight lines and circular curves based on the interpolated axis points; 3) Generating a segment of point clouds for each line segment that link each pair of neighboring interpolated axis points; 4) Projecting points along its approximate axis and extracting cross-section features (lines representing the flanges and the web, and the intersection points between them) for each point cloud segment; 5) Using the extracted intersection points as refined axis points; 6) Using the updated axis points as input and starting the whole process to generate another set of cross section feature points along the axis. Once the updated points have no substantial deviations from the results of the

last iteration, then the algorithm concludes that the curve updating process converged, and reports the latest results of curve fitting and cross section feature extraction.

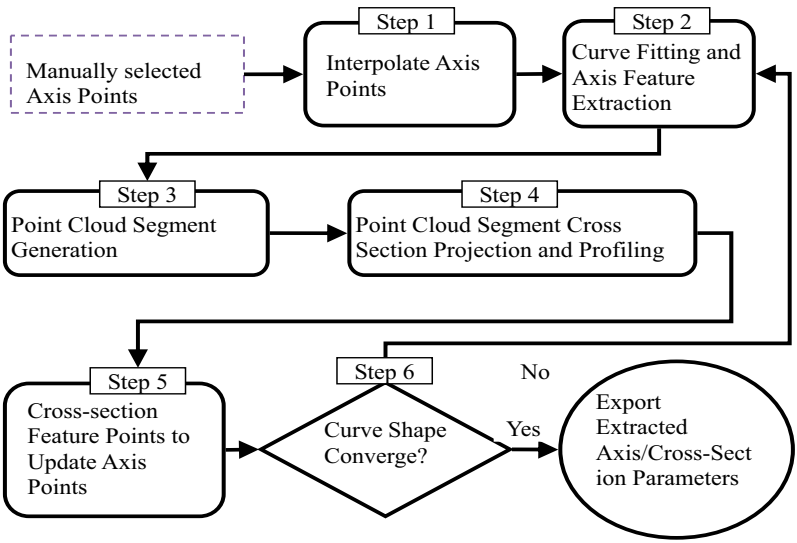


Figure 3 Overview of the developed approach for guide beam feature extraction

Detailed Feature Extraction Process

In Step 1, the algorithm utilizes the spline interpolation method to generate interpolated points along the x-axis (which we define as the direction of the straight section of the guide beam, toward the spiral section) with a fixed step size of 1cm. In other words, using the manually picked axis points, the algorithm generates a sequence of x values with 1 cm intervals, and interpolates corresponding y values.

In Step 2, the algorithm fits and grows straight lines and circles on the interpolated points for identifying TS and SC points through the following semi-automated steps. This step requires an inspector to visually inspect all interpolated points, and manually identify a point on the straight section and a point on the circular section. Then, starting from the manually picked straight section point and circular section point, the algorithm iteratively fits and grows a straight line (starting from the straight line point) or a circle (starting from the circular section point) toward the spiral section. These fitting processes use least-squares fitting. While growing straight/circular sections, the algorithm uses an "average deviation" metric to measure the fitting quality. Average deviation is defined as the sum of the deviation values of all axis points from the fitting line/circle divided by the total number of points. The algorithm will check through all possible TS and SC point locations, identify the locations achieving the minimum average deviation, and labels them as TS and SC. The concept is that since the two sections bounding a

spiral section are known to be a straight line and a circular section, it would be possible to find the TS and SC points by growing two parametric models and finding the best fit (Figure 1). This step generates the parameters of the linear (line parameters) and the circular sections (radius), and the TS and SC points for getting the length of the spiral section.

In Step 3, the algorithm splits the point clouds of a guide beam into segments of point clouds. With a sequence of interpolated axis points, the algorithm generates lines linking pairs of neighboring axis points. These line segments are linear pieces approximating the shape of the axis curve. Then, for each line segment, the algorithm identifies the x coordinates of the points in the point cloud that are falling into the x value range formed by the x coordinates of the end points of the line segment. Points for one line segment forms a slice of a point cloud capturing the shape of a beam segment.

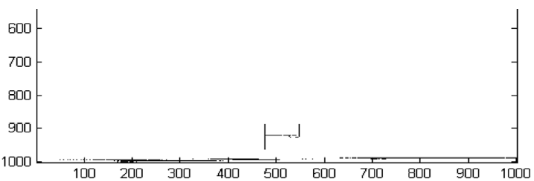


Figure 4 A binary cross-section occupancy image

In Step 4, for each point cloud segment, the algorithm processes the data in the following three sub-steps: 1) Projecting all the points along the direction of the corresponding line segment; 2) Generating a binary cross-section occupancy image depicting the cross-section profile of the guide beam (Figure 4); 3) Applying a series of Hough transforms to the binary cross-section profile to detect lines in it. In sub-step 2, noticing that the cross section profile parts generated from data artifacts (e.g., mixed pixels that form a sloping line in Figure 2) have lower data densities, the algorithm generates 2D rectangular cells with fixed 2D dimensions on the cross section plane, computes the number of points falling into each cell, and only label cells with more than a fixed number of points as "occupied" in order to ignore the lines formed by data artifacts. Based on large number of experiments on the data sets used in this research, the implementation in this research uses 3 mm by 3 mm as the cell size, and 20 points as the occupancy threshold, because these values were found to be able to distinguish lines formed by data points falling on actual object surfaces and diagonal lines formed by mixed pixels. The binary occupancy image generated in this sub-step serves as the input of sub-step 3.

In sub-step 3 of Step 4, the algorithm utilizes the Hough transform for detecting lines on cross sections (Vosselman et al. 2004). Hough transform is a feature extraction technique to find imperfect instances of objects within a certain class of shapes by a voting procedure. This voting procedure is carried out in a parameter space, from which object candidates (e.g., straight lines) are obtained as the local maxima in a so-called accumulator space explicitly constructed by the algorithm for computing the Hough transform (Vosselman et al. 2004). In this research, in order to improve the sensitivity of the line detection, the algorithm runs the Hough

transform multiple times. Each time, the algorithm extracts the longest line detected (the largest peak in the parameter space), and removes all occupied pixels on that line in the occupancy image. The next run of the Hough transform will be based on the updated occupancy image with the most obvious line removed. We found that this multiple-run Hough transform approach can detect more lines (especially short lines) in an occupancy image compared with the conventional approach of running the Hough transform once and report all the lines. Figure 5 shows five groups of points labeled by different colors, which are corresponding to five lines identified by five runs of the Hough transform on the occupancy image of a segment of point cloud. This figure shows that points on the flanges, the web, and the running surface are separated. The reason that the algorithm detected two planes in data points on the running surface is that the projection direction is not exactly parallel to the running surface, such that the projected points are not forming a line but a wide stripe. The algorithm detected that wide stripe as two lines.

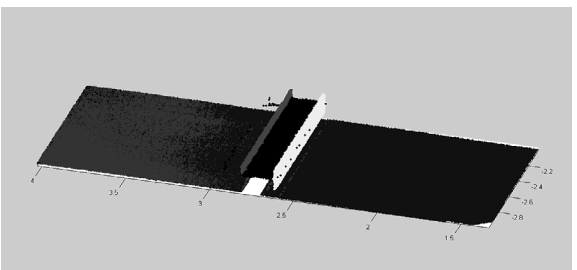


Figure 5 Five groups of data points corresponding to five lines detected on the cross section of a guide beam segment

In Step 5, with the detected lines on a cross-section, the algorithm computes the intersection points between the detected horizontal lines (the web and the running surface) and the vertical lines (the flanges). These feature points can be used to generate the width of the guide beam: the distance between two flange-web intersection points is roughly the width of the web. The only issue is that the flange is about 1 cm thick, and the detected flange line is actually the centerline of the flange cross-section. Using that flange center-line for calculating the guide beam width will generate values slightly smaller than the actual width of the guide beam, as will be shown in the following section.

In Step 6, the developed approach calculates the distances between the detected flange-web intersection points and the interpolated axis points used in Step 2 on each guide beam cross-section. If these distances are larger than a specific threshold, then the whole iterative guide beam feature extraction process will be repeated until the extracted parameters converge.

Evaluation Results and Discussion

The evaluation of the developed approach uses point clouds collected on a site for experimental run of metro vehicles. The laser scanner used in this study was a phase-based scanner, which is capable of collecting 3D point clouds with angular

resolution of 0.018 degree (20,000 pixels for a row in a collected panoramic range image), and with an accuracy of about 5 mm for every point within 50 m from the scanning location. After importing such dense and accurate point clouds into a commercially available reverse engineering environment, we manually selected a number of axis points, exported them as the input of our approach, and tested three critical components of the approach: 1) Axis feature extraction; 2) Cross-section feature extraction; 3) Axis updating using the extracted cross-section feature points.

Table 2 lists the results of axis feature extraction. This table indicates that for the straight section, the error of the generated axis is about 0.1 mm, which is very small. However, the extraction results of the length of the spiral curve and the radius of the circular curve are less accurate. These observations indicate that the developed approach needs to be improved for extracting axis features of curved guide beams, especially for spiral sections. More specifically, we found that the boundary point between the straight line and the spiral curve is difficult to be located accurately, and even large variations of the possible TS point (end point of the growing straight line) would not have substantial impact on the average deviation value of the straight line section. As a result, the generated TS locations have large uncertainties. This fact implies the necessity of developing a better fitting quality measure other than the average deviation used in this research for accurately locating the TS point.

Table 2 Guide beam feature extraction results analysis

Axis section	Recognized feature values	Errors
Straight line	A point on line: (-0.2099 m, 1.001 m) Line direction vector: (0.5042 m, 0.8036 m)	0.001 m (the average deviation of points on the generated line from the as-designed line)
Spiral curve	Length of spiral: 3.45 m (as-designed: 5.76 m)	2.31 m (difference from the as-designed spiral curve length)
Circular curve	Circle radius: 35.15 m (as-designed: 38.10 m)	2.95 m (difference from the as-designed circular section length)

For cross-section feature extraction, the algorithm extracted flange/web and flange/running-surface intersection points on all cross-sections for a straight guide beam (for curved guide beam, the exploration is on-going). Figure 6 shows (a) the extracted feature points of twelve cross-sections of that beam segment; and (b) the calculated guide beam width based on these feature points on those twelve cross-sections. An interesting observation is that, for cross sections closer to the scanning location, more feature points can be extracted (Figure 6a). The non-uniformity of the data density causes this phenomenon: point clouds closer to the scanning location are denser, so that in the sub-step 2 of step 4 of our approach (occupancy image generation), more cells will be recognized as “occupied” with the constant occupancy threshold 20 (any 3 mm by 3 mm cells with more than 20 points in them are labeled as “occupied”). As a result, more lines will be detected for cross-sections with higher data density (sections 5 to 12 in Figure 6); while for cross-sections further away from the scanning location (sections 1 to 4 in Figure 6), the algorithm could not extract enough lines for detecting all four feature points (two flange-web intersection points, two flange-running surface intersection

points). That's why in Figure 6 (b), for cross-sections 1 to 4, the generated width is 0 m (there were not enough feature points to compute the width).

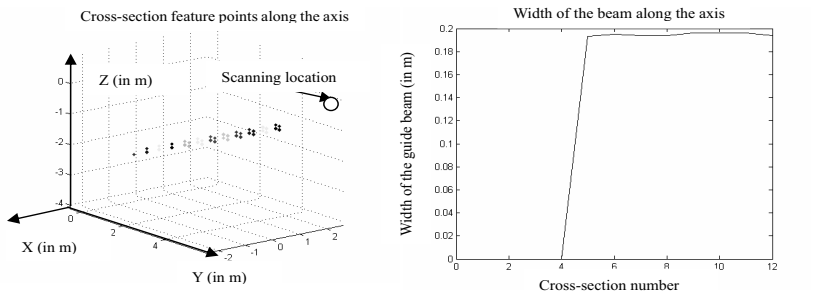


Figure 6 (a) Extracted feature points on 12 cross-sections along a straight guide beam; (b) Automatically extracted guide beam widths of the 12 guide beam cross-sections

For cross-sections 5 to 12, the obtained guide beam widths vary from 0.193 to 0.196 m; while the as-designed guide-beam width is 0.2 m. In-depth analyses indicate that the algorithm only extracts one line locating at the center of flanges, which are slabs of about 1 cm thick. The distance between two center lines of flanges should be slightly smaller than the actual width of the guide beam, which is defined as the outer-outer distance between two flanges. Therefore, the automatically generated guide beam widths are expected to be smaller than the as-designed value, and the testing results are consistent with this expectation: adding 5 mm (half of the flange thickness) back to the generated widths results in accurate results, the errors of which are equal or less than 2 mm.

For updating of the guide beam axis, several preliminary analyses and visual inspections indicate that utilizing the feature points can roughly adjust the selected axis points to particular cross-section feature points (e.g., cross-section center) for more accurate axis feature extraction. Due to the space limit of this paper, these results are not presented.

Conclusions and Future Research

This paper presents an integrated approach for combining the two aspects of guide beam feature extraction from 3D laser-scanned point clouds: axis feature extraction and cross-section feature extraction. The evaluation results of this approach on point clouds collected by a phase-based scanner indicate the potential value of this approach. The major findings of this research are two-fold. First, it has been showed that a fitting-and-growing approach can extract parameters of the straight section, spiral section, and circular section of a curved guide beam, and the primary difficulties of accurately extracting these parameters occur in the fitting of the curved sections and localizing the connection point between the straight section and the spiral section. Second, a multiple-run Hough-transform-based line detection

approach can accurately extract cross-section lines of a straight guide beam, and can automatically generate widths of the beam with 2 mm accuracy. The major difficulties occur in the non-uniform data densities of the point clouds, which require different parameter settings to achieve the best line detection results for different parts of the point clouds. Instead of setting constant parameter values of the algorithms, in the future, we plan to explore an approach which can automatically adjust the algorithm parameter settings according to the data density variations of point clouds.

Future studies should target at improving the axis feature extraction and cross-section feature extraction algorithms to overcome the difficulties mentioned above. In addition, in order to achieve an integration of axis extraction and cross-section feature extraction algorithms to get an iterative guide beam feature extraction approach for obtaining accurate axis and cross-section feature through several circles of the "axis fitting – cross section feature recognition" process, we plan to further test the mechanism of using recognized cross-section features to update axis points for converging to an accurate axis.

Acknowledgements

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Blind Spot Measurements for Real-time Pro-Active Safety in Construction

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Abstract
Equipment related fatalities account for about 25% of all construction fatalities in the United States. One leading indicator for equipment related incidents are blind spots that are prevalent around most construction equipment, inhibiting the operator's visibility of personnel and vital materials on jobsites. Incidents such as injuries and fatalities do occur because operators or ground personnel fail to identify that other objects can be in too close proximity to the work envelope they are operating in. This paper presents a new and unparalleled research approach to help identify the blind spots of equipment in order to quantify and protect the required safety zone(s) for such equipment. An automated blind spot detection tool is presented that determines the equipment blind spots rapidly and in 3D through analyzing the point cloud data from a laser scan inside the equipment cab. Terminology of planar and spatial blind spot measurements are defined and explained. Results to numerous vehicle types that were studied in the construction environment are presented and compared to existing manual and semi-automated methods for similarities. Future work and the applicability of automating the blind spot detection with alert technology in the construction industry are presented.

Keywords: Blind Spots, Construction Equipment, Laser Scan, Ray Tracing, Safety.

1. Introduction
Blind spots on construction equipment resulting in poor operator visibility are one of the leading causes of contact collisions in the construction industry (Fullerton et al. 2009). Blind spots create problems for operators by restricting their line-of-sight and eliminating their view of personnel, materials on the ground, and other equipment being close to their own work envelope (area of operation).
Safety statistics published in the 2009 Census of Fatal Occupational Injuries (CFOI) safety demonstrate that the construction industry accounts for about 21% of all

occupational fatalities or 1,204 of 5,657 total workplace related fatalities in 2007. Within the construction industry, most worker fatalities relate to being struck-by objects in heavy construction (10% of all construction related fatalities) and to specialty contractors (13% respectively). Other statistics indicate that 6% of all occupational injuries were from workers being struck-by vehicles (BLS 2009). Between the years 1992 and 1998, the CFOI reported that out of 465 vehicle related construction fatalities 318 involved workers-on-foot (BLS 2009). The most common vehicle types that were involved in struck-by incidents were trucks (60%), followed by other construction machinery (30%). 110 of the 465 fatalities occurred to equipment operators; and of these fatalities more than half occurred to an equipment operator who was operating a type of construction vehicle (53%) that was not a truck. The remainder of the 465-recorded fatalities occurred to supervisors and other personnel. The Bureau of Labor Statistics (BLS 2009) further reported that the majority of these fatalities (51%) occurred when a vehicle was in reverse mode; which was attributed to the large amount of blind spots that are prevalent in the backside of a vehicle (Pratt 2001).

The presented safety records indicate that a need exists for improving the situational awareness of workers-on-foot and vehicle operators, in particular in the construction environment where workers are often nearby or too close in proximity to heavy construction equipment. The Occupational Safety and Health Administration (OSHA) sets forth minimum guidelines to protect the health and safety of those working in the construction industry and other occupational fields. Construction safety can be found in 29 CFR 1926 OSHA Construction Industry Regulations.

This paper focuses on demonstrating the importance of several key aspects: (1) Understanding the impact blind spots have on construction safety through reviewing relevant safety statistics that have been reported, (2) Explaining existing standards, rules, and practical approaches that are currently applied in preventing injuries and fatalities related to construction equipment blind spots, and (3) Providing new approaches that have the potential to solve limitations in (1) and (2), and demonstrating and discussing results of the developed new approach. The following sections of the paper include a background review of existing blind spot detection and measurement approaches, introduction of the research objective and methodology, and experimental results and discussion. The conclusion includes a discussion of potential next steps and future research.

2. Background

Every construction work site is unique and the work tasks for construction equipment vary from job to job, therefore modifications to equipment are often necessary to get the job done. Even if modifications are not performed, equipment operators are typically little aware of the blind spots surrounding them. To overcome this limitation, heavy equipment manufacturers and researchers have conducted time consuming manual blind spot measurements on equipment in the design stage, on original manufactured and used equipment. Blind spot measurements and demonstrations also can become a useful tool in automated object detection and warning systems, and in construction equipment safety training and education for equipment operators and other workers. This section reviews existing blind spot

measurement and warning techniques and finalizes with a needs statement.

2.1 Current Methods for Measuring Blind Spots

The National Institute of Occupational Safety and Health (NIOSH) released a report in 2007 on potential systems that could aid in the issue of low visibility in heavy equipment operation. This report by Ruff (2008) focused on fatal accidents where victims were in the blind spot area of heavy (construction and mining) equipment. Ruff (2001) proposed also on methods of eliminating blind spots. A first step was to determine the blind spots of the equipment that caused equipment to struck personnel and materials or equipment that came into contact with other equipment and materials. Overall, four different methods to determine blind spots were found in the literature, two manual and two computer-aided blind sport detection techniques.

To study the performance to each of these techniques, Ruff (2008) examined five large pieces of surface mining equipment during this experiment using four measurement techniques: (a) the light bar method, (b) operator guidance, (c) computer-aided virtual reality, and (d) high quality photographs. A library of blind spot diagrams was published by Hefner (2004).

2.2 Warning Systems Addressing Blind Spots

Several commercially available warning systems are available to operators when objects appear in blind spots or for vehicles that are in reverse mode operation (Fullerton et al. 2009). These systems rely on accurate measurement of blind spots beforehand their use. Vision or radar based detection and warning systems for backing-up vehicles are the most commonly used pro-active approaches in the construction industry (next to the acoustic back-up signal alerts). Several automobile makers utilize camera or sonar sensors that are reliable in use, but require manual input or offer alerts only to shorter distances.

2.3 Need for Advanced Blind Spot Measurement for Construction Equipment

A combination of several blind spot measurement, distance ranging and alert techniques would benefit operators in the use of construction equipment. The advantages, limitations, and applications in the construction industry are identified in some more detail in Fullerton et al. (2009). Since OSHA allows for adjustments to be made to construction vehicles such that they can be used for the needs of the equipment owner, it is eventually important to check the blind spots of vehicles as they are on the work site frequently. To optimize any warning systems, however, precise and up-front measurements of the space that blind spots occupy and obstruct the operator's field-of-view are necessary. The true blind spots of the equipment as seen by the operators on a daily basis need to be measured as an accurate representation of the potential adverse conditions present in the workplace, such as low visibility due to dust or cracked glass. Therefore, blind spot measurements presented in this paper have been measured on heavy construction equipment and in the construction environment. Preference should also be given to a measurement technique that allows rapid, automated, and spatial blind spot measurement rather than providing 2-D blind spot measurements only. This becomes particularly important in heavy industrial construction operations where many lifts and equipment

movements are performed.

3. Research Objectives and Methodology

This research aims to collect more realistic and more accurate data on blind spots than any previous study before. This research uses a laser scanner to measure the geometrical properties of construction vehicles-in-use in an obstruction free environment in less than 2 hours per piece of equipment. Computational algorithms were developed to automatically identify spatial (and 2-D) blind spots from heavy construction equipment in field environments. Knowing the detailed location of blind spots, this research strives to identify and quantify the necessary (or minimum) safety zone required for all equipment analyzed. A sample 3D library of equipment blind spots is developed through experimental studies. the following research tasks are explained in more detail: Design of experiments for blind spot measurements utilizing a laser scanner; design of the developed automated blind spot measurement tool using a ray tracing algorithm; experimental data collection; validation of blind spot measurement tool, results and analysis; and identification of potential applications, research recommendations and future work.

4. Execution of Research Tasks

4.1 Laser Scan Data as Input for Automated Blind Spot Measurement Tool

Instead of using one of the previously discussed research approaches performed by other researchers, laser scans of heavy construction vehicles like excavators, dump trucks, motor graders, rollers, wheel loaders, and smaller heavy equipment were taken from outside the vehicle and by mounting the laser scanner on the driver's seat inside the equipment cab. A commercially available high-definition three-dimensional (3-D) laser scanner performed the automated distance measurement to all objects that were in the field-of-view of its laser beam. All recorded points (around 1.5 million per scan; varies per scan) were registered and stored in a point cloud file. The point cloud file was converted to a comma separated variable (CSV) file that has x, y, and z-coordinate representation of each distance point. This CSV file became the input to the developed blind spot calculation and analysis tool.

4.2 Ray-Tracing Algorithm

The developed automated blind spot calculation tool uses a ray tracing approach to calculate blind spots of any of the selected construction machines. Ray tracing is similar to the idea of using a perfect light source from the driver's perspective. Traced is the imaginary path of light emanating from the light source. Should rays from this imaginary light source hit a distance point the laser scanner measured, the further part of the ray would be considered a blind spot line. Blind spots can be identified once this process is repeated for all distance measurements. Blind spots are typically spaces that are not visible to the operator. Blind spots are typically visualized as areas and illustrated in plan view. Their nature, however, is volume. Thus, the (automated) measurement and analysis of blind spot spaces of construction vehicles is an important addition to existing blind spot research.

4.3 Grid Representation of Equipment

Since the laser scanner provides a dense cloud of distance points, a flexible 3-D cube system was designed to handle error measurements of the laser scanner as well as to reduce the computational power required for analyzing for blind spot volumes. The number of cubes and their size are variable and set by the user; for example X,Y,Z=300,300,300 with a single dimension of 0.1m per cube. A similar technique for personnel tracking has been applied before by Teizer (2007). Cubes that are in line-of-sight (LOS) to the operator are visible; the combination of all other cubes that are hidden behind the filled cubes creates the blind spot volume (space).

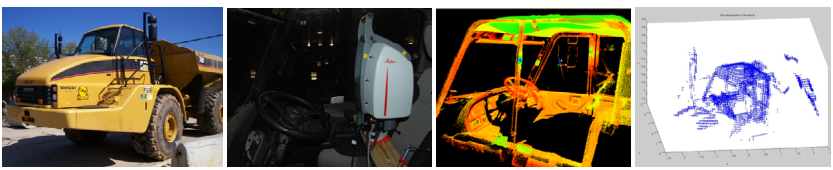


Figure 1: Laser scan within the cabin of an articulated dump truck and the resulting grid model representation.

4.4 Automated Blind Spot Measurement Tool

To limit the computational burden of the blind spot calculation algorithm further, the developed tool allows the user to select radius *R* and origin *O* of the field-of-view at any point in the range point cloud. The tool user is given a choice setting the origin and size of the radius of the sphere inside or outside the equipment, with preference placing *O* inside the cab (at the operator's eye position). Placing the sphere at the origin (X,Y,Z) = (0,0,0) (which equals the position of the laser beam of the laser scanner inside the equipment cabin) with a radius of R = 10 m, results in a cube size of 6.66 cm.

A ray tracing algorithm is then applied and a grid model of the equipment results. The grid model for an articulated dump truck is shown in Figure 1. Since the dense range point cloud is collected for each equipment type, the blind spot measurement tool itself can be applied in remote offices, reducing the down time of the actual equipment. The developed approach also allows adjusting for operators with different body heights or selecting different viewpoints (location and orientation of head).

4.5 Blind Spot Location Detection, Recording and Analysis

The goal of the automated blind spot location detection, recording, and analysis tool is to gain detailed blind spot information, for example, the ratio of blind spots vs. visible space, or when workers-on-foot are visible and when not.

To calculate the percentage of blind spots in the 3-D grid, the number of cubes that are labeled as part of "blind" spots, and number of cubes that are labeled "visible" are counted. According to ISO 5006's "Operator Field of Vision", generally a radius of 12m is evaluated for the ratio of blind spots. The ratio of the space that belongs to blind spots can then be defined as:

$$\text{Spatial Blind Spot Ratio [\%]} = \frac{\text{Sum of the Number of 'Blind' Cubes} * 100}{\text{Sum of the Number of ('Blind' + 'Visible' cubes)}} \quad (1)$$

The developed tool can also compute percentage of blind spots in a particular cross section of the space. For a constant 'k' ($-r \leq k \leq r$; r = sphere radius), the tool can be used to compute blind spots in XY plane for any Z=k, YZ plane for any X=k, and XZ plane for any Y=k. Therefore, the plane parallel to the ground level and at the level of equipment operator's eyes, would be XY plane at Z=0m. Figure 1 shows the laser scanner mounted inside the cab of the equipment; the level of the "laser" was defined to be always at the Z=0m reference location.
To calculate blind spots in a XY, YZ or ZX plane, the number of cubes labeled as "blind spots" and cubes labeled as "visible" in each of these planes are counted. Therefore, the ratio of blind spots in a user defined plane (or area) can be defined as:

$$\text{Ratio of Blind Spots in Plane [\%]} = \frac{\text{Sum of the Number of 'Blind' Cubes in Plane} * 100}{\text{Sum of the Number of ('Blind' + 'Visible' cubes) in Plane}} \quad (2)$$

Distinguishing from other research approaches (Fosbroke 2004, Ruff 2008), the developed automated blind spot calculation and analysis tool allows accurate blind spot measurements from a: (1) Cross-sectional view (planar view), and 2) Spatial representation. In addition, any experiment in this study was conducted in the construction environment.

4.6 Visibility of Personnel on Ground from Operator's Perspective

Because of the blind spots of any equipment, a person or construction worker standing on the ground may or may not be visible to the operator. In some situations, the person might be partially visible to the equipment operator. The developed blind spot measurement tool can compute the percentage of visibility of a person standing anywhere around the equipment. The tool user can define the location and dimension of the person. Decision can be made whether a person is standing too close to heavy equipment during operation.

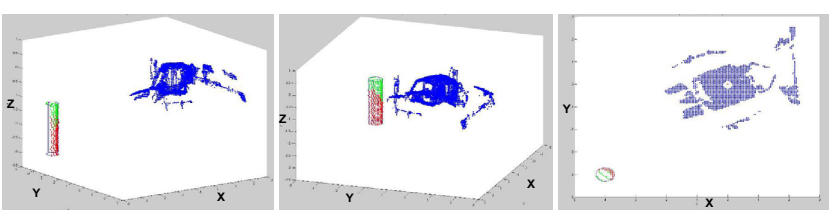


Figure 2: Visibility of a person standing on ground at X=-4m, Y=-4m, Z=-3.29m.

The developed tool applies a user-defined cylinder model to represent a construction worker. Height and radius of cylinder can be adjusted in the tool. For general understanding, a person 1.8 m tall with a diameter of 0.6 m is considered for the experiments explained in the following sections. The portion of a person (cylinder)

that is visible to an operator (laser beam origin) can be defined as:

$$Visibility\ of\ a\ Person\ [\%] = \frac{Sum\ of\ the\ Number\ of\ 'Blind'\ Cubes\ on\ Cylinder\ Surface\ *\ 100}{Sum\ of\ the\ Number\ of\ ('Blind'\ +\ 'Visible'\ cubes)\ on\ Cylinder\ Surface} \quad (3)$$

Different isometric and planar views of the cylinder's surface that were analyzed for blind spots can be seen in Figure 2. The area in green marks the parts of the person that would be visible to the equipment operator, and the area in red is marked as part of the blind spots.

5. Experimental Validation of Blind Spot Measurement Tool

The developed blind spot tool was designed to automatically compute the: (1) Percentage of blind spots in the work envelope (plane) of construction equipment, and (2) Visibility of a person when standing in proximity to equipment (calculation based on planar blind spot measurement). Experiments and results to each of these experiments are explained in the following subsections.

5.1 First Experiment (Blind Spot Measurement)

In the first experiment the ratio of blind spots in plane view is calculated by varying the radius of a circle encompassing the vehicle. This ratio of blind spots is the percentage of the area that is invisible to the driver of the machine. The illustration in Figure 3 shows manual and automated blind spot measurement for a bulldozer at a visible radius of 10 meters. The areas in blue are the invisible areas and the white areas are visible to the operator. The red points belong to the equipment cabin and are an overlay of the laser scan data points used in the computer tool on top of the blind spots. Differences in the blind spot measurements can be seen.

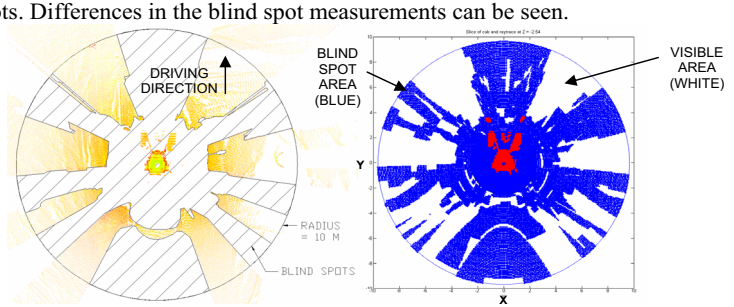


Figure 3: Manually vs. automatically drawn blind spots of a bulldozer (10 m radius)

Although the diagrams are similar to Hefner's (2003) and Ruff's (2008) experimental results, the automated method provides an efficient way for multi-view analysis at multiple planar comparisons without performing manual measurements (even after laser scanning). Similar to the argumentation in Ruff (2008), the ground plane, the 1.5m and1.8m-high planes (with respect to ground plane) were analyzed and compared to depict the differences in the blind areas for objects and people.

The default origin of the point file is the location of the scanner, but the location of the ray trace may be modified in the developed blind spot measurement tool. All

results included were calculated with the default origin established in the blind spot measurement tool. Reasons for creating such functionality in the program may be to account for the operator's ability to translate his/her head in the x-, y-, or z- within the cab of the equipment.

Table 1: Automated (a) vs. manual (b) blind spot measurement; worker visibility (c)

(a)

	z-value	Description	% Blind Spot
Bulldozer	0	Eye-level	36.97
	-0.74	1.8 m Tall	44.24
	-1.04	1.5 m Tall	46.60
	-2.54	Ground	61.06
Pick-up Truck	0	Eye-level	37.91
	0.34	1.8 m Tall	33.08
	0.04	1.5 m Tall	37.93
	-1.46	Ground	53.63
Art. Dump Truck	0	Eye-level	28.45
	-1.49	1.8 m Tall	48.82
	-1.79	1.5 m Tall	52.06
	-3.29	Ground	71.08
Roller	0	Eye-level	20.43
	-0.79	1.8 m Tall	25.17
	-1.09	1.5 m Tall	28.47
	-2.59	Ground	48.73
Excavator	0	Eye-level	40.71
	-0.77	1.8 m Tall	46.74
	-1.07	1.5 m Tall	48.74
	-2.57	Ground	63.77
Motor Grader	0	Eye-level	27.22
	-0.88	1.8 m Tall	46.32
	-1.18	1.5 m Tall	48.55
	-2.68	Ground	68.45

(b)

At ground level	% Blind Spot
Bulldozer	58.42
Pick-up Truck	63.69
Dump Truck	62.98

(c)

Position	Path	Distance [m]	Visibility [%]
A	1	2.5	43.1
B	1	5.0	98.2
C	1	10.0	87.1
E	2	2.5	5.2
F	2	5.0	3.9
G	2	10.0	0.0
I	3	2.5	23.6
J	3	5.0	23.5
K	3	10.0	0.0

Table 1a shows the ratio of blind spots to selected equipment types in the construction field environment. One radius was chosen (10 m) to provide comparative results. Since the experiments were conducted in the construction environment, site layout and existing obstructions had measureable impact on blind spots. The measurement of blind spots preferably uses smaller radii. It is interesting to note (and surprising to the common believe that dump trucks have the largest blinds spots) that the selected (standard) excavator had a larger blind spot (about 41%) than the selected (standard) articulated dump truck (29%) (at the operator eye-level). A reason for this observation is the boom of the excavator that is blocking the FOV of the operator.
Table 1b shows the results to the manual calculations that were completed for three types of equipment. Since the actual scan data is analyzed in a CAD program and by hand, only the ground level plane was assessed. From these few measurements it can be noted that the manual procedure includes generally blind spots that are larger than the automated measurements.

5.2 Second Experiment (Worker Visibility)

In the second experiment the visibility of a person standing on the ground was calculated while varying the distance from the person to the construction equipment. This component of the developed blind spot measurement tool allows the opportunity to effectively visualize which locations around equipment are more dangerous than others. This infers a new method for detecting any hazardous work areas around equipment. The next steps explain how the visibility of a worker-on-foot from the operator's perspective was measured.
The plan view of the laser scan for a bulldozer is shown in Figure 4. The same figure also displays a cross sectional view (point A-C). Concentric distance circles are centered in the origin (eye of operator). The white areas illustrate blind spots and the visible areas are in color. The three radii for the circles are 2.5 m, 5 m, and 10 m, respectively. The three straight lines drawn represent the selected paths to measure the visibility of a person that is 1.8 m tall and 0.6 m wide (defined by a person's shoulder width). Noticeable become the positions A through C, E-G, and I-K. These letters represent the positions chosen for the worker in "standing" mode.

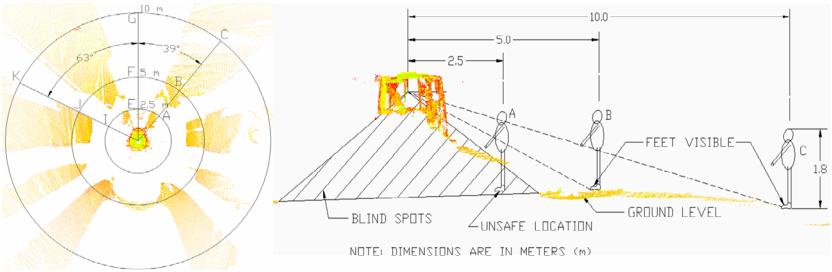


Figure 4: Worker visibility at different locations (A, B, and C) close to equipment.

Table 1c shows the percentage a person is visible at locations A through K. Notice that position B has many visible data points (visibility close to 100%) therefore a person at location "B" is most likely very well visible from the cabin of the dozer. Going from location B to C the percentage decreases from 98% to 87% visibility. This decrease is due to uneven ground conditions in the field. However, these results demonstrate that the developed blind spot measurement and analysis tool works in realistic construction environments.

On path 1, the decrease from B to C may also be due to objects on the construction site, or mounted objects inside or outside the dozer cab (e.g., mirrors), and a variety of other possibilities. Path 2 corresponds to locations E, F, and G (see Figure 4). The visibility of a person on path 2 is slim (less than 6% of a person's body is visible until reaching a distance of 10 m from the machine). This poor visibility is mainly the result of the operator's limited visibility due to obstructions on the front portion of the bulldozer (including the motor compartment, exhaust pipe, and front blade). Path 3 corresponds to locations I, J, and K, and runs parallel to a border between visible and invisible regions. Based on the initial hypothesis, parts of the worker-on-foot should be visible, while the other part may not be invisible. The results agree with the initial hypothesis, because approximately 23.5% of the person is visible at locations I and J, and 0% is visible at location K.

6. Limitations of Developed Approach and Future Work

Blind spot measurements, analysis, and results depend on equipment type and environment the measurements are conducted in. Several assumptions and limitations of the developed approach have been discussed in the sections of the paper where it the developed approach is most useful in. Future research is necessary to address its current limitations. Future research could focus on: (1) Expanding the current tool with more functionalities; (2) Build a spatial 3-D blind spot library (as it already exists for 2-D blind spot measurements); (3) Experimenting with safety zones and alert devices for operators and workers to protect their individual work envelopes; (4) Calibrating the developed blind spot tool to account for certain equipment characteristics; and (5) Developing a dynamic blind spot measurement and alert system that accounts for real-time tracking of the operator's FOV.

7. Conclusions

Equipment related incidents account for a large number of injuries and fatalities in

construction. Construction equipment blind spots are identified to be the cause for poor operator visibility. Existing practices have been developed for measuring blind spots but have limitations in the measurement approach as well as functionality. A novel blind spot measurement tool was developed. The terminology and a methodology that was used to determine blind spots were explained in detail. The use of a ray tracing algorithm to automatically measure the blind spots was demonstrated and results to experiments were presented. The functionality of the developed blind spot measurement tool was demonstrated under real construction conditions. It is envisioned that fully automated blind spot detection, worker-on-foot detection, real-time pro-active alert devices can be integrated in the operation of heavy equipment on construction sites and elsewhere. Safer and injury- and fatality-free work sites are a realistic goal.

8. Acknowledgment

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Identification and Assessment of Cost Estimating Competencies

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Abstract

Perhaps the greatest challenge facing the cost estimating community over the next decade is the loss of knowledge and experience of highly experienced estimators as a high percentage of them are retiring and a shortage of qualified cost estimators is evident in the construction industry. This study identified 23 core estimating competencies classified into skills, knowledge, and personal attributes and also identified the gaps between the current and desired level of the estimating competencies. In total, 228 completed questionnaires were collected through the Construction Industry Institute (CII) member companies, and the Association for the Advancement of Cost Engineering –International (AACE-I) and American Society of Professional Estimators (ASPE) workshops. A criticality matrix was developed to prioritize competencies based on the combined effects of the level of importance of each competency and its associated gap. The factor analysis technique has been applied to investigate the correlation effects of the 23 estimating competencies. An implementation tool which assesses the current level of competencies of an estimator or an estimating team and recommends appropriate training tools has also been developed. The findings of this study will help engineering and construction companies design and develop appropriate educational and training programs to enhance estimating functions.

1. Introduction

The cost estimate for a capital project is critically important to both owners and engineering/construction companies. Owners rely on cost estimates to perform

economic analyses for return on the investment from their capital expenditures. Engineering/construction companies rely on the cost estimate for bidding and negotiating work, which is the basis for securing future work and ensuring profitability of their companies. Most efforts to promote good estimating have focused on developing cost information, adjustments for time/size/location, and estimating tools, in particular automation of the estimating process by computer methods. However, those tools that aid the estimating process cannot replace the judgment and experience of a competent cost estimator. A recent article by the President of the AACE-I described a court case to illustrate that the sound judgment of estimators, based on their experience, is equal to and perhaps more important than the cost data information (Zack 2007). As a high percentage of experienced cost estimators are retiring, the construction industry is facing greater challenge of losing the knowledge and experience those estimators acquired through their career in the estimating profession. This study was conducted to identify and prioritize estimating skills, knowledge, and personal attributes required to develop qualified cost estimators and quantified the gaps between the current and desired level of the estimating competencies based on 228 completed questionnaires collected from estimating experts. This study grouped 23 competencies into seven major factors using the factor analysis technique and developed an implementation tool based on the findings of this study.

2. Data Collection

During spring and summer 2008, a questionnaire survey was conducted to obtain expert opinions on various issues in the estimating profession such as estimating functions, required estimating competencies, the gaps between the ideal and the current level of competencies, and current practices in recruiting, attracting, retaining, and training estimators. For this survey, a questionnaire of four sections with 37 questions was developed through a two day workshop with 22 expert estimators. The questionnaire was sent to all CII member companies, and also was distributed at the AACE-I and ASPE national workshops in 2008. A total of 228 completed questionnaires were collected. 79% of the respondents were from CII member companies, and 21% were from AACE-I and ASPE members. 31% of the survey participants were from owner companies and 69% were from non-owner companies. The data collected represented a total of approximately 3,500 years of experience in the estimating profession and 52% of the respondents had at least 15 years of experience in the estimating profession.

3. Core Estimating Competencies

Estimating competencies can be defined as a cluster of interrelated skills, knowledge and personal attributes required to properly perform an estimating job. In this study, 23 core estimating competencies were identified as important competencies required for developing good cost estimators. The identified 23 estimating competencies are

classified into skills, knowledge, and personal attributes. Skill is the ability to perform a certain estimating task, while knowledge is information an estimator has attained related to estimating, and personal attributes represent personal attitudes, traits or behaviors required to do good cost estimating. Furthermore, skills and knowledge are divided into soft and hard subcategories. Soft skills or soft knowledge is difficult to be taught or developed and requires more experience and training, while hard skills or hard knowledge is relatively easy to be taught, developed, and learned. Figure 1 shows the hierarchy of estimating competencies identified in this study.

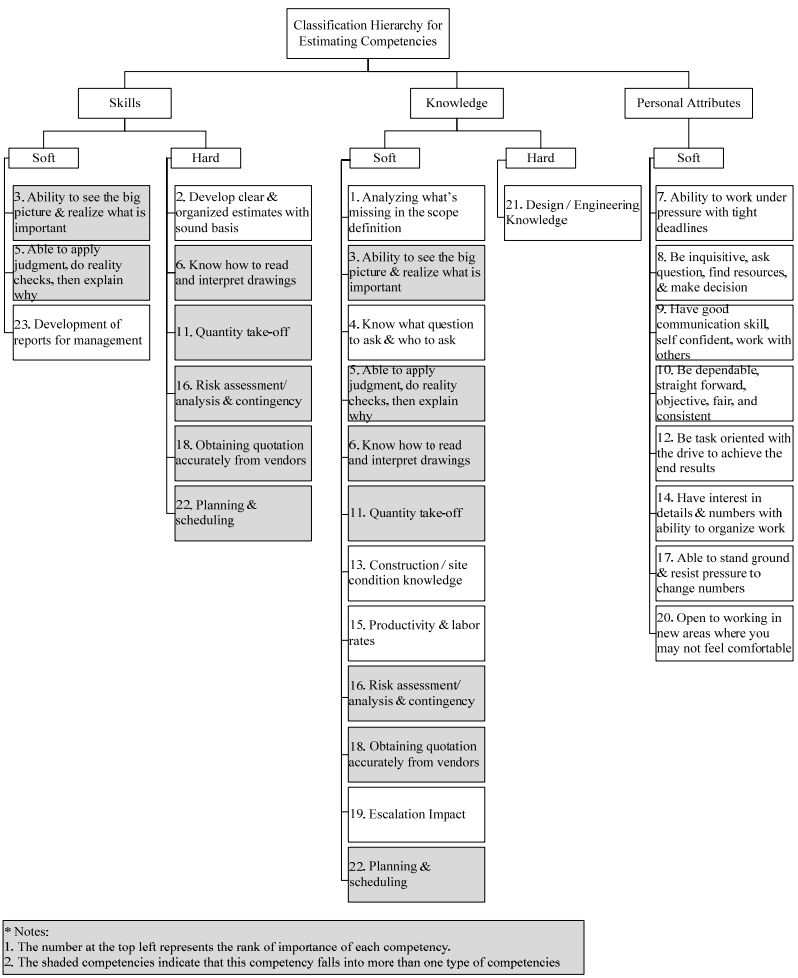
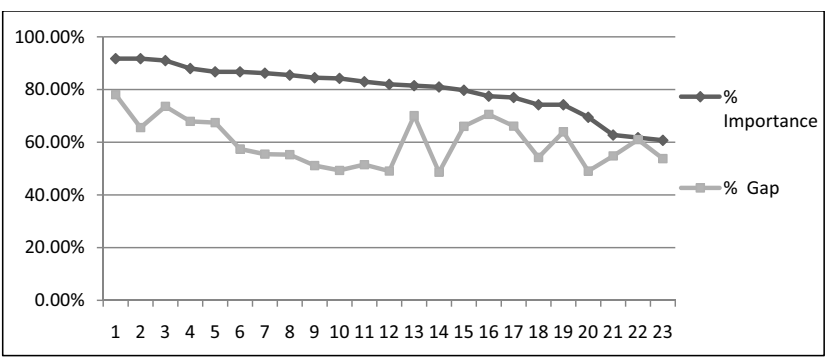


Figure 1. Classification Hierarchy of Estimating Competencies

4. Assessment of Estimating Competencies

In the survey, the importance of each of the 23 estimating competencies and the degree to which junior estimators typically lack in each competency were assessed using a 5-point likert scale. Figure 2 shows the assessment results of the survey data. The results are the average values after the 5-point likert scale was converted into a "0-100" percentage scale. The competencies are sorted in descending order on X-axis in terms of their importance values. The number of each competency matches with the number of competencies in Figure 1.

The top five most important estimating competencies are "1) analyzing what's missing in the scope definition", "2) develop clear and organized estimates with sound basis", "3) ability to see the big picture, realize what is important", "4) know what question to ask and who to ask", and "5) know how to read and interpret drawings". The top five biggest gaps exist in the competencies including "1) analyzing what's missing in the scope definition", "3) ability to see the big picture, realize what is important", "16) risk assessment/analysis and contingency", "13) construction/site condition knowledge", and "4) know what question to ask and who to ask". It is noteworthy that the largest gaps exist in competencies that are mainly classified as soft skills or soft knowledge. The nature of these competencies makes them very hard to be captured or learned.



X-Axis Legend	
1.Analyzing what's missing in the scope definition	12.Be task oriented with the drive to achieve the end results
2.Develop clear and organized estimates with sound basis	13.Construction/ Site condition knowledge
3.Ability to see the big picture, realize what is important	14. Have interest in details and numbers with ability to organize work
4.Know what questions to ask and who to ask	15.Productivity and labor rates
5.Able to apply judgment, do reality checks, then explain why	16.Risk assessment/ Analysis & contingency
6.Know how to read & interpret drawings	17.Able to stand ground and resist pressure to change numbers
7.Ability to work under pressure with tight deadlines	18.Obtaining quotations accurately from vendors
8.Be inquisitive, ask questions, find resources, and make decisions	19.Escalation impact
9.Have good communication skills, self confident, work with others	20.Open to working in new areas where you may not feel comfortable
10.Be dependable, straight forward, objective, fair, and consistent	21.Design/Engineering Skill
11.Quantity take-off	22.Planning and scheduling
	23.Development of reports for management

Figure 2. Assessment of Estimating Competencies

5. Criticality Matrix of Estimating Competencies

A criticality matrix was developed to prioritize the competencies based on the scores which are calculated using the importance value of each competency and the value of the associated gap with the competency. In calculating the criticality score of each competency, both the importance and the gap values of each competency are equally weighed. The criticality score of each competency measures the Euclidian distance from the point where an imaginary competency has the highest importance (100%) and the widest gap (100%) to a point where the competency is located in Figure 3 (see Equation 2). The criticality matrix classifies the competencies based on their criticality scores into five zones; most critical, more critical, critical, less critical and least critical zones. The criticality matrix provides an idea about which competencies should be given more efforts and time in training and educating estimators in order to improve the overall performance in estimating.

$$\text{Criticality Score} = \sqrt{(100\% - \%\ \text{Gap})^2 + (100\% - \%\ \text{Importance})^2} \quad \text{(Equation 2)}$$

Criticality Score	
0.00 – 28.28	Most Critical
28.28 – 56.57	More Critical
56.57 – 84.85	Critical
84.85 – 113.14	Less Critical
113.14 – 141.42	Least Critical

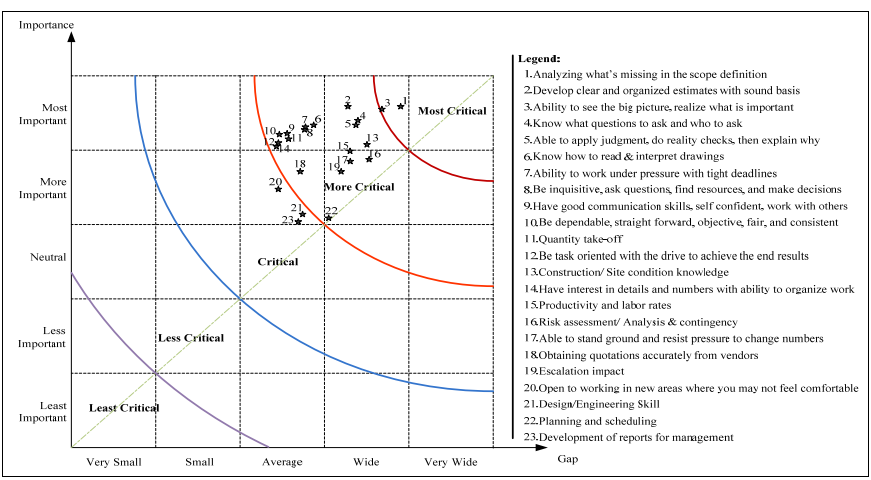


Figure 3. Criticality Matrix of Estimating Competencies

The criticality matrix (Figure 3) shows that all estimating competencies fall on three zones; most critical, more critical and critical zones. The two most critical

competencies are “1) analyzing what’s missing in the scope definition” and “3) ability to see the big picture, realize what is important”. These competencies are determined to be most critical because i) they are most important competencies for high quality estimating and also ii) they are the competencies that most estimators are significantly lacking (their gaps are very wide between the current level and the ideal level).

6. Factor Analysis

The factor analysis technique was applied to the identified 23 competencies in order to determine whether these competencies can be grouped under different factors and to categorize them into a manageable number of factors. The factor analysis investigates the correlation relationships between the estimating competencies. In order to use the factor analysis technique, the reliability of the scale used in the collected data and the appropriateness of using the factor analysis method on the data must be assessed first. The Cronbach alpha coefficient was used to test the reliability of the scale used in the collected data. The tests used for assessing the appropriateness of factor analysis include; Kaiser-Meyer-Olkin (KMO) for measuring the accuracy of the sample, Anti-image correlation for measuring the sample adequacy (MSA) for each variable, and the Bartlett test of sphericity (Akintoye and Fitzgerald 2000 and Field 2005).

The Cronbach alpha coefficient determines the internal consistency between the variables that measures particular characteristics, and the scale is determined to be reliable with cronbach alpha higher than 0.8 (Cramer 1994). The cronbach alpha coefficient on the 5-point likert scale used in studying the importance of the estimating competencies is 0.86, which indicates the scale is reliable. After testing the reliability of the scale used, the appropriateness of factor analysis was tested. The Kaiser-Meyer-Olkin statistic is 0.82 which means that the correlation pattern between variables is compact and thus makes the factor analysis appropriate. The Anti-image correlation matrix test shows that the MSA for all variables ranges between 0.68 to 0.91 and greater than 0.5 (Field 2005) which indicates that none of the variables needs to be eliminated and the factor analysis is appropriate. Finally, the bartlett test of sphericity was conducted to test whether the correlation matrix is an identity matrix or not. The result of the sphericity test is 1238.49 and its associated p-value is 0.000, which indicate that the correlation matrix of the variables is not an identity matrix and the factor analysis is an appropriate method.

After validating the appropriateness of using the factor analysis, the 23 estimating competencies were subjected to the factor analysis, with principal component analysis and varimax rotation. The principal component analysis uses the correlation between the variables to produce a smaller set of uncorrelated components, where the first component accounts for the greater variability in the data and the second component accounts for less variability and so on. The principal component analysis resulted in seven competency groups (factors) with eigenvalue greater than 1 and explaining 60.34% of the total variance in the data. Since the initial set of factors was difficult to interpret due to the unclear pattern of the factor matrix, the varimax rotation was used

to transform the principal component matrix into a new matrix for easy interpretation. The varimax rotation is an orthogonal rotation used to maximize the high correlations and minimize the low correlations. Table 1 shows the final seven factors resulted from the factor analysis along with the percentage of the variance that each factor explains. Each factor is a linear representation of the variables (competencies) and their loading on the factor.

Table 1. Seven Factors of Estimating Competencies

Factor 1 **(25.5%)** (Estimator's communication and work behavior)	Factor 2 **(8.70%)** (Basic knowledge required by an estimator)	Factor 3 **(6.79%)** (Preliminary tasks for developing quantity of work)	Factor 4 **(5.22%)** (Estimator's ability to analyze project scope and deal with the profession pressure)	Factor 5 **(5.02%)** (Ability to put together the project pieces and make decision)	Factor 6 **(4.68%)** (Construction process knowledge and judgment skill)	Factor 7 **(4.40%)** (Ability to produce a reliable estimate)
Be task oriented with the drive to achieve the end results	Escalation impact	Know how to read and interpret drawings	Analyzing what's missing in the scope definition	Ability to see the big picture, realize what is important	Construction/ site condition knowledge	develop clear and organized estimates with sound basis
Open to working in new areas where you may feel not comfortable	Risk assessment/ analysis and contingency	Quantity take-off	Know what question to ask and who to ask	Be inquisitive, ask questions, find resources, and make decisions	Able to apply judgment, do reality checks, then explain why	
Be dependable, straight forward, objective, fair, and consistent	Productivity and labor rates	Obtaining quotations accurately from vendors	Able to stand ground and resist pressure to change numbers			
Have good communication skills, self confident, work with others	Planning and scheduling		Ability to work under pressure with tight deadlines			
Have interest in details and numbers with ability to organize work	Design/ engineering knowledge					
Ability to work under pressure with tight deadlines	Obtaining quotations accurately from vendors					

For example, the third factor "preliminary tasks for developing quantity of work" includes competencies "know how to read and interpret drawing", "quantity take-off", and "obtaining quotations accurately from vendors" These competencies were grouped together because they represent the basic skills and knowledge required for developing quantity of estimating items. Another example is the sixth factor "construction knowledge and judgment skill" which consists of "construction/site condition knowledge" and "able to apply judgment, do reality checks, then explains why" competencies. These competencies are grouped together because for an estimator to make good judgments and justify his/her decisions, the estimator needs an extensive amount of experience in the construction field in order to familiarize himself/herself with different construction techniques, project execution methods, and different site conditions.

7. Implementation Tool

As a result of this study, an implementation tool was developed to help companies quantitatively evaluate estimating competencies, identify gaps and prioritize critical competencies, and design appropriate training programs for estimators. The implementation tool - Estimating Competency Assessment and Training Recommendations (EsCATR) is an independent excel based computer software program developed using Microsoft visual basic programming language. This tool is a user-friendly tool in which a user rates an estimator or an estimating team's performance for each of the 23 competencies and then, the EsCATR automatically generates five different reports including a competency assessment result, a competency assessment summary chart, a criticality matrix, a competency assessment result per factor, and training recommendations. The EsCATR tool provides companies with a means to evaluate their estimating workforce's capabilities and identify which competencies are most critical and require immediate attention in order to improve the estimating performance. The EsCATR can help companies in designing customized training programs for each individual or the estimating team based on the performance assessment results.

8. Conclusions

This study has addressed a growing concern about the loss of knowledge, skills and experience of cost estimators while the cost estimating profession is not fully prepared to solve this problem. This study has identified 23 core estimating competencies for developing qualified cost estimators. The competencies were classified into skills, knowledge, and personal attributes and were further classified into soft and hard subcategories. The criticality of each competency was assessed based on the importance of the competency and the associated gap of the competency between the current level and the ideal level. The study has found that most critical competencies are soft skills or knowledge which are difficult to be transferred. The study has grouped the 23 competencies into seven different factors using the factor analysis technique. A tool was developed to help and guide companies in evaluating the capabilities of their estimating department workforce, and gaps in each

individual's skills, knowledge, and personal attributes. The tool also identifies the most critical areas that require immediate attention to improve the estimating performance and the most appropriate training programs. This tool (EsCATR) is available at the CII website for download and use.

Future research in this domain should be geared toward identifying currently available education and training programs for cost estimators and assessing the coverage of the programs related to the core estimating competencies and the efficiencies of the programs. It will also be equally important to develop new methods and techniques to successfully capture soft and intangible estimating competencies and transfer them to the young generation of estimators.

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IMPROVING PROJECT PERFORMANCE USING THE PROJECT HEALTH INDICATOR TOOL

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ABSTRACT

The Project Health Indicator (PHI).was developed because traditional measures and tools used during project design and construction to track project progress often do not identify potential problems in a timely manner. The PHI tool is based on the identification and assessment of "leading indicators." Leading indicators are fundamental project characteristics and/or events that reflect or predict project health. Revealed in a timely manner, these indicators allow for proactive management to influence project outcomes. The PHI tool contains 43 weighted leading indicators based on survey methodologies and ranking analysis. The PHI tool quantifies non quantifiable measures, that is, "Gut Feelings," and provides an early warning of potential problems. The tool was validated using completed projects by checking statistical correlations between tool output scores and cost and schedule performance indices. Industry users of the PHI tool have successfully applied it in practice. The objective of this paper is to describe the research methodology for tool development and how it is being successfully applied by industry.

INTRODUCTION AND MOTIVATION

A typical construction project life cycle begins with planning where the project concept is developed and minimal scope definition is achieved. Projects proceed through different phases of development including design, construction and startup. Once a project budget is developed, traditional project control methods are used to monitor cost growth and keep actual costs as close to the initial budget as possible. Project cost increases are often an unfavorable project outcome that owners and contractors strive to avoid.

Project teams monitor the status of projects using traditional methods such as cost variance, schedule variance, performance ratios, milestone variances and earned value. These methods provide a measure of a project's current status relative to planned progress but may lack the ability to identify warning signs and project issues

that may indicate the degree to which the project is on the right track (Choi et al., 2006). Identification of issues as they emerge can draw the attention of the project team to potential problem areas that may require more attention. Using non-traditional methods such as the leading indicators (LI) identified in this research, project teams can identify issues that impact project outcomes significantly.

Past research indicates that managers have often not been satisfied with the use of traditional performance measures like return on investment and earnings per share in measuring organizational performance and have expressed concerns that the use of such methods could misrepresent a project's or an organization's performance (Kaplan and Norton, 1992). Kaplan and Norton (1992) developed a strategic performance assessment tool for use with traditional methods to measure project performance in terms of objectives.

To address concerns about the inadequacies of traditional methods to measure project performance, the Construction Industry Institute (CII) funded a research study involving industry professionals from CII member organizations. The research team developed leading indicators which could have significant impacts on project outcomes; these leading indicators are the basis for the development of the project health indicator (PHI) tool. The PHI tool was developed for use by project teams as an assessment tool that can forecast potential risk of not meeting specific project outcomes.

RESEARCH OBJECTIVES AND METHODOLOGY

The research team involved in the development of the PHI tool consisted of nine owners and ten contractors from CII member companies representing construction, petroleum, chemical, pharmaceutical, and manufacturing industries.

The team was formed with the main aim of achieving four research objectives (Choi et al, 2006):

- Identify leading indicators that impact project outcomes during project execution
- Determine the leading indicators which have the greatest impact on project outcomes
- Develop a tool for performing project reviews periodically based on the assessment of the leading indicators
- Validate the tool

The research team members established criteria that define a leading indicator. Some of the key characteristics of a leading indicator are that a LI must predict potential risks to future project outcomes and must correlate to project outcomes (Choi et al., 2006). The following definition of a leading indicator was established by the team members: *Leading indicators are fundamental project characteristics and/or events that reflect or predict project health. Revealed in a timely manner, these indicators allow for proactive management to influence project outcomes.*

The definition of a LI implies a relationship between LIs and project outcomes. This research therefore defined six project outcomes/factors critical to project success and

commonly used in industry as a measure of project success: 1) cost; 2) schedule; 3) quality/operability; 4) safety; 5) stakeholder satisfaction; 6) benefit attainment by research members. These outcomes were viewed against the planned objectives relating to that outcome. For instance, according to Choi et al. (2006) cost performance was viewed in terms of overall actual final cost versus the authorized project budget.

Initially, 181 potential leading indicators were identified by industry experts. The 181 identified LIs were then screened to determine those with the greatest impact on project outcomes. The industry experts reviewed the LIs using the following criteria:

- Did each leading indicator statement agree with the formal definition of an LI?
- What potential problem does each leading indicator address?
- What categories of project health does each leading indicator affect?
- Is there a tangible measure for each of the leading indicators?
- Is the leading indicator unique to the owner, the contractor or to both?

Of the 181 LIs reviewed by the project team, 66 similar LIs were screened out and eleven new ones were added bringing the total number of LIs remaining to 126. Three surveys were conducted to provide rationale for reducing the number of leading indicators and ensure consistency in the assessments. The first survey required that team members score the LIs based on their negative impact on project outcomes and further evaluate the 126 LIs by comparing owner, contractor and aggregate responses for each LI with the aim of eventually reducing the number of LIs further. Fifteen members responded to this survey (9 owners and 6 contractors) A four-point scale was used (Table 1) with a score of 3 indicating a high negative impact on the six project outcomes and 0 indicating minimal or no impact on these project outcomes.

Table 1. Four-point scale based on negative outcomes

Score	Impact on project outcomes
3	High negative impact on project outcomes
2	Medium negative impact on project outcomes
1	Low negative impact on project outcomes
0	Minimal or no impact on project outcomes

For the team member assessments, the LIs with the highest aggregate scores have the highest negative impact on project outcomes while the LIs with the lowest scores have the lowest negative impact on project outcomes. The maximum negative score for each LI was 45 (3 x 15 members) and assessments were performed for each of the six project outcomes making a maximum possible aggregate score of 270 (45 x 6 project outcomes) for each LI. Table 2 shows a sample of the overall assessments and ranking of the leading indicators for each outcome. For instance LI 148 was ranked number 1 by project outcome with a total score of 200 out of a possible 270.

Table 2. Overall Ranking of LIs by Total Scores for each Outcome (IR220-2)

LI No.	Cost	Schedule	Quality/ Operability	Safety	Stakeholder Satisfaction	Benefit Attainment	Total (max score: 270)	Ranking
148	36	38	34	27	34	31	200	1
79	36	40	35	22	32	30	195	2
43	40	39	25	19	36	33	192	3
123	37	37	36	17	30	31	188	4

There were significant variations in the results of the comparison of the overall rankings with the owner and contractor rankings. For instance LI number 148 which was ranked first in the group of owners was ranked 13 in the contractors group (Table 3). According to Choi et al. (2006) the variation may be attributed to differences in understanding, perception or interpretation of the LIs. This clearly shows that the understanding of an LI may be influenced by the nature of the project work, by the individual performing the assessment and the company perspective from which the assessment was performed.

Table 3. Ranking of LIs by Owners, Contractors, and Overall (RS220-11)

LI No.	Owners	Contractors	Overall
148	1	13	1
79	3	4	2
43	2	7	3
123	7	2	4

To reduce the number of LIs, the top 50 were chosen based on a comparison between the overall rankings, owners rankings and contractor rankings (Table 3) providing a list of 66 LIs because some LIs in the top 50 were selected by one group and not by the other. The top 10 LIs based on the project outcomes (ranked as shown in Table 2) were also included because the team determined that some key LIs may be left out otherwise if they were not included in the top 50 based on the comparisons. A total of 79 LIs were selected. Some new LIs were proposed by members and eight more were added to the list. The LI statements were then rephrased negatively to have more meaning since they represent potential future problems on a project.

A second survey was conducted to further reduce LIs that had the least impact on project outcomes. Thirty-three professionals from the industry participated in this survey. The team included 17 owners and 16 contractors. LIs were ranked as in the first survey using the four point scale (Table 1) based on their negative impact on project outcomes. The number of LIs was reduced to 53. At the end of the survey the 6^{th} project outcome (benefit attainment by research members) was dropped from the list of outcomes/factors because for owners it can only be assessed after a period of operation of a completed facility.

A third and largest of the three surveys was performed with a total of 84 respondents from CII member organizations, including 26 owners and 58 contractors/engineers/designers. They assessed the LIs and reduced the list to 43 LIs using a six point scale with the following options: no, very low, low, moderate, high and very high negative impact on five project outcomes. This scale was modified from the four point scale used in the first survey to improve the accuracy of assessments in reducing the LIs to 43. The 43 final leading indicators chosen were arranged in order of decreasing negative impact on project outcomes implying that the LI with the highest impact on project outcomes was first on the list. The same analysis and ranking was used for the third survey as used on the first and second surveys. The third survey formed the basis for the weighting of LIs based on the extent of their negative impact on project outcomes.

LIs were sorted into new categories called project practices to make it easier to analyze the final survey results, review the final list of LIs and build the project health indicator (PHI) tool. For this study, a project practice was defined as a process or method that, when executed effectively, leads to enhanced project performance. Eight project practices were identified from CII knowledge areas and used in this study. They are: 1) alignment; 2) change management; 3) constructability; 4) contracting; 5) quality management; 6) safety practices; 7) project control; 8) team building. Each of the 43 LIs was included in a project practice where it was most relevant. The eight categories can help users identify potential sources of risks to project outcomes and guide users towards developing potential mitigation strategies (Choi et al, 2006).

THE PROJECT HEALTH INDICATOR TOOL

The main idea behind the development of the PHI tool is that it should have the ability to measure project health and forecast the potential for meeting specific project outcomes. It should be a tool that can quantify a project evaluator's perception of current status based on weights assigned to each of 43 leading indicators identified by the research team (Choi et al, 2006).

The 43 LIs identified from the third survey form the basis of assessment the project health indicator (PHI) tool provides. Initial weights were determined based on survey responses for each of the LIs using:

$$Weighted\ score = \frac{Aggregated\ score\ of\ LI}{Standard\ deviation\ of\ the\ aggregated\ score\ for\ that\ LI}$$

Different weights were applied to each LI depending on how negative an impact it had on project outcomes and on the variation in the responses for each LI based on the 84 survey responses. Dividing by the LI standard deviation increased the weight for LIs with small standard deviations due to consistent survey responses for that LI. For tool development, different weights had to be applied to the LIs for use in assessing the project health.

To be able the fully understanding the meaning of the raw weighted scores and appreciate the extent of the negative impact on project outcomes, the weighted scores

were normalized to a total of 1000. The maximum of 1000 would only be attained if all the 43 LIs indicate that project is not experiencing any problems. On the other hand, a score less than 1000 indicates that the project is showing warning signs of potential problems. A lower the score reflects a higher risk of potential poor performance.

Measurement of Leading Indicators

Users of the PHI tool must assess leading indicators to be able to determine an aggregate score which would indicate how healthy a project is at that point in time. The PHI tool is designed for use at any point during project execution. Leading indicators are measured using a five point scale (Table 4) with a score of 1 indicating that the project may be experiencing serious problems or at the other extreme, a score of 5 indicating that the project is not experiencing any problems relative to the description of that LI.

Table 4: Five-point scale for measuring leading indicators

Scale	Focus
1	Serious problem
2	Major problem
3	Moderate problem
4	Minor problem
5	No problem

LIs are worded in a negative form to indicate potential problems achieving the desired project outcomes. The following is an example of a leading indicator stated negatively and showing the measurement considerations of each rating on the five point scale relative to that LI. An example of one LI with the scoring assessment scale is shown below (IR220-2):

Leading Indicator 37
Actual schedule activities are lagging behind planned scheduled activities over several reporting periods.
Measurement Considerations on a five-point scale

1. *The entire critical path has shifted beyond its planned dates, and previous non-critical activities are now becoming critical.*
2. *Critical path activities have slipped beyond their planned dates, but float remains on sub-critical activities.*
3. *A significant number of non-critical activities are being delayed, but the critical path is stable.*
4. *Some activities have lagged behind their planned dates, but they are non-critical and can be completed without becoming critical to the project.*
5. *Actual progress is tracking in accordance with planned schedule progress, and there are no delays.*

The ratings 1 to 5 on the scale focus on different measurement considerations for each of the leading indicators depending on the context in which it is used, that is a

rating of 1 on one LI may mean something totally different for another LI. For instance LI 27 is "The project manager (or team leader) is lacking in the required level of experience and skills" and rating 1 on the scale which implies a serious problem has the following measurement consideration: *Project manager is inexperienced and lacks many of the skills needed to lead the project to success.* The measurement considerations for LI 27 are different from that of LI 37. However, measurement considerations with the same rating express the same level of negativity on the five point scale for the LI measurement. All 43 LIs are described using a similar approach to LI 37.

LI Impacts on Project Outcomes and Project Practices

The impacts of the LIs are measurable and different for each of the five identified project outcomes: 1) cost; 2) schedule; 3) quality/operability; 4) safety; 5) stakeholder satisfaction. The LI with the most negative impact on a particular project outcome is the LI with the highest score for that particular outcome. The use of individual project outcomes can help focus a team's attention on general project areas that may need special attention, for example cost related versus schedule related outcomes. The different impacts of the 43 LIs on eight identified project practices can also be determined and can draw a project team's attention to potential or actual problem areas.

Using the PHI Tool

The PHI tool is a Microsoft excel based tool consisting of six tabs the first of which is the introduction tab that clearly details instructions for using the tool. The other five tabs are: Tab 2 - a user guide; Tab 3 - input tab; Tab 4 - an output-outcomes; Tab 5 - output-project practices; and Tab 6 - customization tab. The input tab (Figure 1) is where the user assesses each of the 43 LIs using the five-point scale as previously described. For each LI, the measurement considerations can be viewed by moving the pointer over the measurement scale (red comment indicator).

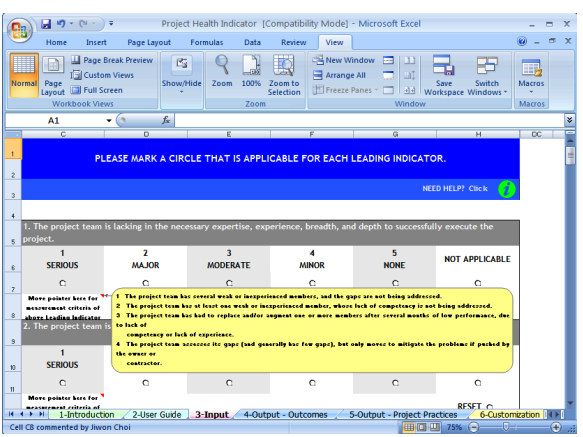


Figure 1: Screen Capture of the Input tab

Outputs of the assessments are shown on tabs 4 and 5 using calibrated speedometer-like gauges. Each gauge has three colors: red which is considered as high risk, yellow considered as moderate or medium risk and green considered as low risk of poor performance. The default ranges for the three colors are 70 percent, 15 percent and 15 percent respectively. The default ranges were set based on the results of the tool validation which indicated that a score below 700 (70%-red) was considered high risk (Choi et al. 2006). A score of 700 to 850 (yellow) was considered moderate risk and a score of 850 to 1000 (green) was considered low risk. Examples of the output outcome dials are shown in Figure 2. Similar gauges are used for the eight output-practices and can be customized according to user preferences.

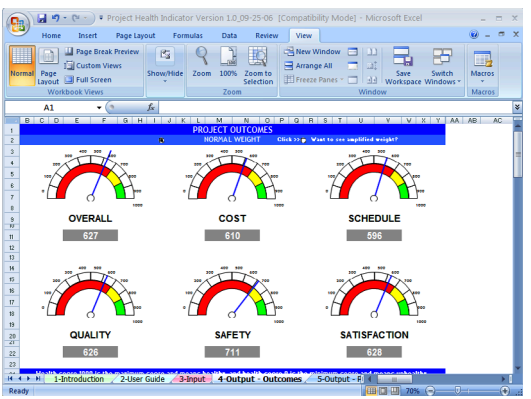


Figure 2: Screen Capture of the Output-Outcomes tab

Since riskiness is viewed in various ways by different organizations and levels of risk tolerance may vary, the dials can be adjusted based on user preferences.

PHI Validation

The PHI tool was developed using the 43 LIs as a basis for measuring the health of a project. The tool was tested and validated by industry professionals. Participants were asked to complete a questionnaire and provide performance data (such as planned versus actual cost and schedule) for past projects whether successful and unsuccessful. The actual performance data was required for comparison with the tool outputs for the same projects to determine if any correlations exist between the two. Past projects were evaluated in hindsight by one evaluator and current projects by a few different evaluators. An analysis of the data by regression indicated a high negative correlation between cost and schedule health scores and cost and schedule performance data (see Figure 3). This implies that projects that had higher health scores in the assessment were mostly projects that were completed on schedule or ahead of schedule, on budget or below budget. The tool was then finalized after the validation.

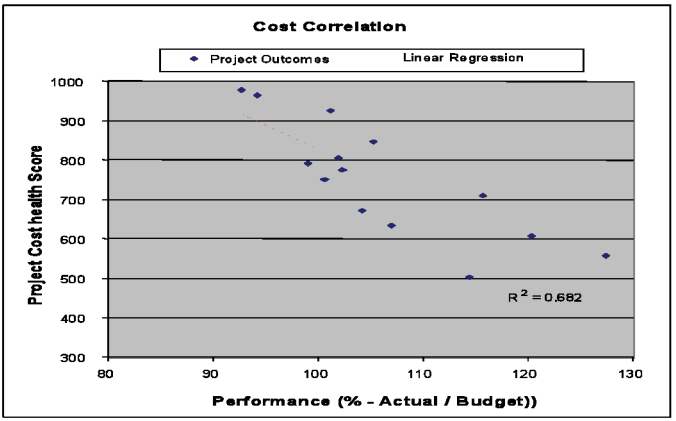


Figure 3. Cost Correlation Results

Use of PHI Tool

The tool is designed for use during the project execution phases. Prior to project execution, tools like the CII project definition rating index (PDRI) and the alignment thermometer can be used to assess the level of scope definition and team alignment with project objectives. The tool is most effective when used right after the completion front end planning and first use is recommended early in the detailed design phase. Tool effectiveness decreases as the project moves through the project development phases up until the end of construction as shown in Figure 4. The PHI Tool is not a replacement for traditional measures and its use is recommended to supplement traditional measures. Generally, LIs should as much as possible be evaluated through face-to-face meetings with project participants. Participation should include project participants from the various disciplines such as engineering, construction, safety, and procurement. All scores should be recorded even in cases when disagreements exist. Any disagreements will help draw attention of the project participants to areas where potential difficulties exist. Results can be communicated to and reviewed by the project team members to generate discussions and improve team focus.

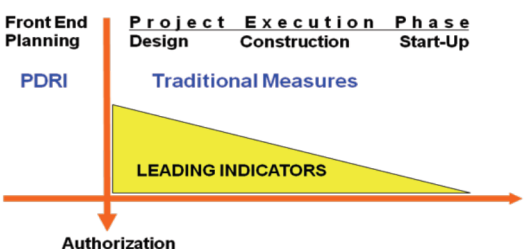


Figure 4: Change in Effectiveness of Leading Indicators

INDUSTRY APPLICATIONS OF THE PHI TOOL

When the tool was developed, its successful use was confirmed through case studies (IR220-2). One of the case studies was a schedule driven $3.2 million industrial revamp project. The scope of this project was to replace several aging refrigeration machines used to chill feeds to batch reactors. Initially, the main objective of the project was replacement of process machines without increasing the process capacity. The engineering contractor suggested a change in the process flow which would ultimately increase production rates without incurring any substantial additional costs. The suggestion was taken by the owner and the scope was revised to include the increase in process capacity. Some configuration changes and tie-ins posed difficulties as a result of the short notice of the process scope change. In addition the construction area was congested, a few key construction crafts fell ill and were replaced by new ones who were less experienced. Project forecasts indicated potential cost overruns and schedule slippage. One accident was recorded when a worker was injured by a loose piece of insulation sheathing.

The PHI tool was used by the owner and contractor project managers to evaluate project performance at 98 percent engineering completion and 35 percent construction completion. The assessments were discussed and combined. The results showed consistency with the project situation. It indicated a warning for potential cost overruns (red zone), and even greater potential problems with meeting the schedule (red zone) (Figure 5). Individual assessments of the LIs and reconciliation of the project managers' responses is useful for gap identification to focus the project team's attention on issues that may be critical.

A large engineering-contractor organization has used the PHI tool to evaluate project health. Practices were assigned to appropriate functional expert reviewers and the results were reconciled and analyzed by members of the review team. PHI Tool outcomes ranged from as low as 300 to 400 and as high as 800 to 900. Analysis of practices indicated few problems with alignment, safety, and contracting. On the other hand, constructability, quality management and change management were areas where poor performance was occurring. Gaps were identified for company-wide action based on low scores for specific LIs in the latter three practice areas.

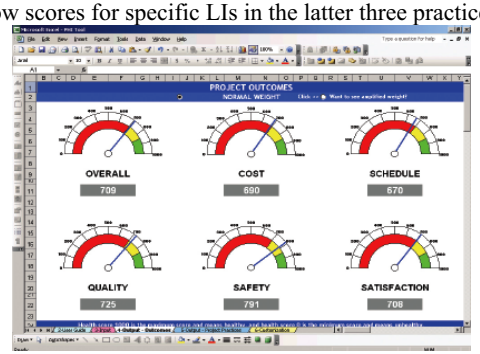


Figure 5: Case Study Project Outcome Gauges

A government agency and their consultant have utilized the PHI tool on the $12 billion waste treatment and immobilization plant project scheduled for completion over a 20-year horizon. The scope of this project involves the treatment of radioactive waste. The project has experienced technical uncertainties and cost growth which continued even after the project baseline was reviewed in 2006. Since 2007, the use of the PHI tool has provided early warning signs of problem areas that initiated corrective actions. Each year, PHI scores are compared with the previous year. Improvements shown in all measures are reflected in increasing PHI scores.

CONCLUSIONS

The research team identified 43 leading indicators that have a substantial impact on project outcomes and can effectively measure project health. The tool is most effective when used from the beginning of detailed engineering through construction. It can be used by project managers, directors of multiple projects and auditors for team evaluations, global project reporting and for review of project performance data respectively. The tool is designed to supplement traditional methods. The PHI tool was validated using actual projects and it was observed that there were high statistical correlations between the tool output scores and the actual project outcomes. Appropriate use of this tool will enable project teams identify early warning signs of project problems and take appropriate preventive action as suggested by industry applications.

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Quality Management Systems in the Capital Facilities Delivery Industry: Analysis of Best Practices in Leadership and Third-Party Certification

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Abstract

Quality Management Systems in the capital facilities delivery industry were examined to identify best practices. The research surveyed 118 owner, contractor and supplier firms, performed statistical analysis of the responses, and conducted targeted structured interviews with 17 firms. The survey revealed several statistically significant areas where organizations with self-reported highly successful quality management systems differed from those organizations with self-reported less successful systems. Structured interviews were conducted to examine the practices of successful companies in greater depth. Through a synthesis of the results of the survey, the structured interviews, and a literature review, the research found that organizations with highly effective quality management systems had demonstrable management commitment with adequate resources for effective quality management; capable and consistent quality procedures across the organization; integrated and aligned quality management and project execution processes; effective training; strong partnerships with suppliers and contractors across the project life cycle; metrics that met organizational and project needs; and quality metrics used during all stages of engineering, procurement, construction, and start-up and commissioning. The survey results for leadership and third-party certification are presented here.

Introduction

The quality management boom took place over 25 years ago, resulting in the development of a discipline known as Total Quality Management (TQM). There were many players and developments in this era, but the mark made by the so-called "gurus" including Shewhart (1931) for plan, do, study, act; Deming (1986) for his 14 Points for Management; Juran along with Gryna (1980) for their Economics of Quality Conformance; Crosby (1979) for his zero defects, do it right the first time, and the Quality Management Maturity grid; Ishikawa (1990) for his fish bone diagram; and Taguchi (1993) for his quality loss function were profound and still remain significant today. However, advancements in technologies, tools, and processes have changed the quality management systems (QMS) used for capital facilities project management. QMS and the associated knowledge base have evolved and expanded. Practices once thought to be valuable have lost some of their effectiveness. Consequently, there is a need to identify and analyze the QMS, programs, and continuous improvement activities being used in the construction industry today.

The Construction Industry Institute (CII), established in 1983, is a consortium of leading owners, engineering and construction contractors, and suppliers who have a singular mission: to improve the cost effectiveness of the capital facility project life cycle, from pre-project planning through completion and commissioning. Over the past 25 years, CII has sponsored research in the quality management domain within the following broad areas: quality management, risk reward, total quality management, quality performance measurement, and do it right the first time. Reports / documents culminating from these research efforts are categorized as Body of Knowledge (BOK) 8.01 on the CII website (see https://www.construction-institute.org/scriptcontent/index.cfm.) In total, there were 21 research documents developed (17 which are currently active) in five CII-sponsored Task Forces (TF) and Research Teams (RT). Table 1 shows the historical development and relationships of these 17 active documents in or related to the 8.01 BOK.

One of the first CII task forces was the Quality Management Task Force (QMTF), commissioned in the summer of 1985. The mission of this initial effort was to identify, develop and disseminate information to improve the effectiveness of quality management in the construction industry. During its four-year life, the task force undertook three research studies and published seven CII Publications (only three of which are still active CII documents and thus depicted in Table 1). It became readily apparent to this task force and CII that the topic of quality in the construction industry would need additional attention and focus long after they completed their work. One of the major recommendations of this first task force was for CII to continue research in this important area.

In the spring of 1990, CII formed two additional task forces focused on quality, the Total Quality Management Task Force (TQMTF) and the Quality Performance Measurement Task Force (QPMTF). The purpose of the TQMTF was to further investigate the implementation of TQM in the construction industry. One of the main products of this task force was a roadmap for implementing TQM from a broad,

company-wide perspective. The QPMTF focused its attention on measurement at the project level.

Table 1 – CII Quality Management Documents

Quality Management Task Force (QMTF) – 1985			
Document #	**Document Name**	**Authors**	**Pub Year**
SD-29	Cost of Quality Deviations in Design and Construction	Burati, J. L., & Farrington, J. J.	1987
Pub. 10-1	Cost of Quality Deviations in Design and Construction	CII	1989
Pub. 10-2	Measuring the Cost of Quality Deviations in Design and Construction	CII	1989
Total Quality Management Task Force (TQMTF) – 1990			
Document #	**Document Name**	**Authors**	**Pub Year**
SD-69	Identifying Customer Requirements Through Quality Function Deployment	Oswald, T. H., & Burati, J. L.	1992
SD-97	Adaptation of Quality Function Deployment to Engineering and Construction Project Development	Oswald, T. H., & Burati, J. L.	1993
Pub 31-1	Implementing TQM in the Engineering and Construction Industry	CII	1994
SD-74	Guidelines for implementing TQM in the Engineering and Construction Industry	Oswald, T. H., & Burati, J. L.	1994
Quality Performance Measurement Task Force (QPMTF) – 1990			
Document #	**Document Name**	**Authors**	**Pub Year**
SD-79	Quality Performance Measurements of the EPC Process: Current Practices	Glagola, C., Ledbetter, W. B., & Stevens, J. D.	1992
Pub 36-1	Measuring Quality Performance on EPC Projects	CII	1992
Pub 36-2	THE BLUEPRINT: A Process for Measuring Project Quality	CII	1994
SD-103	Quality Performance Measurements of the EPC Process: The Blueprint	Stevens, J. D., Kloppenborg, T. J., & Glagola, C. R.	1994
Risk Reward Task Force (QPMTF) – 1992			
Document #	**Document Name**	**Authors**	**Pub Year**
SD-80	Project Performance Modeling – A Methodology for Evaluating Project Execution Strategies	Alarcon-Cardanas, L. F., & Ashley, D. B.	1992
Cause and Effects of Field Rework Research Team (not in 8.01 BOK, but related to quality management) – 2001			
Document #	**Document Name**	**Authors**	**Pub Year**
RS153-1	The Field Rework Index: Early Warning for Field Rework and Cost Growth	CII	2001
RR153-11	An Investigation of Field Rework in Industrial Construction	Rogge, D. F., Cogliser, C., Alaman, H., & McCormack, S.	2001
Do It Right the First Time Research Team – 2005			
Document #	**Document Name**	**Authors**	**Pub Year**
RS203-1	Making Zero Rework a Reality	CII	2005
IR203-2	Zero Field Rework Self-Assessment Opportunity Checklist	CII	2005
RR203-11	Making Zero Rework a Reality – A Comparison of Zero Accident Methodology to Zero Rework and Quality	Smith, G. R., & Jirik, T.	2006

Additional research was conducted by CII over the next 15 years and documents were published in 1992 by the Risk Reward Task Force, in 2001 by the Cause and Effects of Field Rework Research Team, and finally in 2005 by the Do It Right the First Time Research Team.

Methodology

A survey of the CII membership was used as a data gathering instrument. The survey consisted of 31 questions and was divided into four areas relevant to quality management in the capital facilities industry. The Demographics/Respondent Data category included five questions about the organization such as the respondent's role in the organization, the title of highest-ranking management representative responsible for implementing quality procedures, the number of employees in the organization, and the number of employees in the organization with quality as a key responsibility. The QMS for capital projects category included ten questions regarding the standards and guidelines used by the organization, certification policies, training, documentation procedures, and audit procedures. Metrics used by the organization and its suppliers were determined in seven questions in the Metrics used in QMS for capital projects category. The Incentives, Methods and Programs used in QMS for capital projects category covered data regarding the organization's QMS processes in nine questions.

The CII membership served as the sample frame and in all, 148 surveys were sent to 118 organizations. It was left to the discretion of the organization to select the company personnel that would complete the survey. It was requested that the respondent should have the best perspective on the organization's QMS. After the survey was distributed, two reminders were sent to the organizations. Thirty three responses were received by the initial deadline and after reminders were sent, a total of 53 responses from 47 distinct organizations were received. The response rate based on distinct organization and total number of responses was 36% and 40% respectively. In order to maintain the confidentiality of the respondents, the surveys were coded by removing the respondent organization's personal information, i.e., company name, personnel name, title, location, contact information.

As a first step, the responses for the 31 survey questions were analyzed to obtain the descriptive statistics. For this analysis, the surveys that were submitted by the same organization were treated as a unique response, since the perspectives of respondents from the same organization may be quite different from one another.

The survey questions consisted of three types of questions: Yes/No questions, five-point Likert scale questions, and open-ended questions. The descriptive statistics for the Yes/No questions and Likert scale questions were straight forward. The open-ended question responses were categorized and classified based on their similarity in order to obtain the descriptive statistics. The purpose was to organize a large amount of data into a smaller number of categories such that statistical analysis of the question could be done. Categories were defined and iteratively refined into a final list of categories.

The survey responses were also analyzed by the following groups.

Organization type: The majority of the participant organizations are owners and contractors (49% and 32%, respectively). The descriptive statistics of the survey responses for "owners" and "contractors" were created to compare these two groups.

Organization size: By grouping the organizations into "large" and "small" categories, differences between these two groups were examined for certain questions.

Effectiveness of QMS: The descriptive statistics were split into organizations whose QMS was self-reported as "extremely effective" and organizations who did not self-report that their QMS was extremely effective.

QMS certification: Separate groups of descriptive statistics were created for organizations who certified their QMS by a third party or parties and those organizations who do not certify their QMS.

Several other combinations of organizational attributes were created and compared such as owner organizations that self reported that their QMS was extremely effective compared to contractor organizations that self reported that their QMS was extremely effective.

In the analysis of the data categorized and classified as described above, the research team focused on the differences among the descriptive statistics of the comparable categories such as "owners" vs. "contractors" and "extremely effective" vs. "others." Hypothesis testing and statistical analysis was used in order to determine whether there was a significant difference between any two categories. In the hypothesis tests, four statistical tools were used: the Chi-square, Two Proportions, and Fisher's Exact tests, and one-way Analysis of Variance (ANOVA).

Results

Leadership

The survey question "In your organization, what is the title of the highest-ranking management representative responsible for implementing quality procedures for capital facilities delivery?" was asked in order to determine where responsibility for quality management rested in the organization's management structure. This was a multiple choice question with an open ended option. Choices given were "Director," "Vice President," "Manager," or "Other."

Fisher's Exact Test was used to analyze whether the titles of the highest level individual responsible for quality procedures was significantly different for owners vs. contractors and for respondents that self-reported that their QMS was extremely effective compared to those respondents that did not. The following two groups had a statistically significant difference:

1. Respondents that self-reported that their QMS was extremely effective vs. those that did not when testing the number of responses of "President" and "Vice President" combined as the title of the highest-ranking management representative responsible for implementing quality procedures for capital facilities delivery; and

2. Owners that self-reported that their QMS was extremely effective vs. owners that did not when testing the number of responses of "President" and "Vice President" combined as the title of the highest-ranking management representative responsible for implementing quality procedures for capital facilities delivery.

There was a statistically significant difference at the 90% confidence interval (CI) ($p = 0.106$) between organizations that self-rated their QMS as extremely effective compared to organizations that did not self-rate their QMS as extremely effective when testing the number of responses of "President" and "Vice President" combined as the title of the highest-ranking management representative responsible for implementing quality procedures for capital delivery. Responsibility for implementing quality procedures were at a higher management level for organizations who self-rated their QMS as extremely effective compared to organizations that did not self-rate their QMS as extremely effective. Organizations that self-rated their QMS as extremely effective had more Vice Presidents and Presidents responsible for implementing quality procedures for capital projects compared to organizations that did not self-rate their QMS as extremely effective (see Figures 1a and 1b).

The research also found that in these organizations, management actively participates in quality management both at the project manager and the vice-president level. Participation is usually through ISO 9001 and monthly executive meetings. QMS implementation is seen as the primary responsibility of management. High rated organizations usually have a corporate vice-president for quality and have disciplined and standardized processes.

The research found that organizations with self-rated highly effective QMS had management that was highly committed, provided a great deal of support, and allocated budget for quality at the corporate level in addition to the business line level. In high rated organizations, quality managers are visible and in place. They make use of scorecards to measure effectiveness and their consistent leadership throughout the organization ensures that the QMS is applied.

There was also a statistically significant difference at the 95% CI ($p = 0.010$) between owners that self-rated their QMS as extremely effective compared to owners that did not self-rate their QMS as extremely effective when testing the number of responses of "President" and "Vice President" combined as the title of the highest-ranking management representative responsible for implementing quality procedures for capital delivery. Fifty-three percent of owners that self-rated their QMS as extremely effective had Vice Presidents and Presidents responsible for implementing quality procedures for capital delivery compared to 26% of owners that did not self-rate their QMSs as extremely effective.

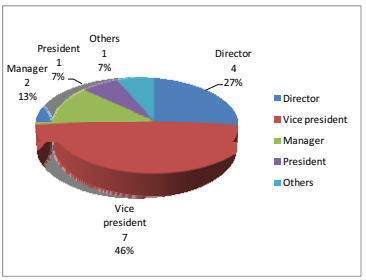


Figure 1a: Distribution for the title of the highest-ranking management representative responsible for implementing quality procedures for capital projects for organizations with self-reported extremely effective QMS (N=15)

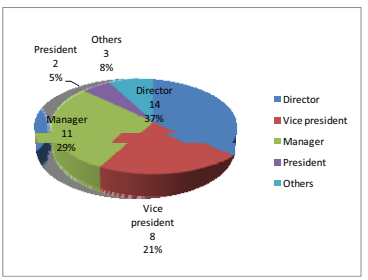


Figure 1b: Distribution for the title of the highest-ranking management representative responsible for implementing quality procedures for capital projects for organizations that self-reported their QMS other than extremely effective (N=38)

QMS Certification

The question "Is some, or all of your organization's QMS certified by a third party or parties?" was asked in order to determine the frequency and importance of third party certification. This was a yes/no type question. The "yes" response contained multiple choice options as well as an open ended option. Multiple choice categories were "ISO 9000," "Nuclear," "ASME," "API," "AWS," and "Others." Descriptive statistics for an organization's QMS certification by a third party or parties for all respondents reported 55% (29 respondents) indicating "no," 43% (23 respondents) indicating "yes," and 2% (1 respondent) who did not respond.

Fisher's Exact Test was used to compare third party QMS certification for owners vs. contractors and for organizations that self-reported extremely effective vs. not extremely effective QMSs.

There was a statistically significant difference at the 95% CI ($p = 0.000$) between owners compared to contractors when testing for "yes" as the response for third party certification of the QMS. Seventy-six percent of contractors had third party certification of their QMS versus 19% of owners.

There was also a statistically significant difference at the 95% CI ($p = 0.002$) between organizations that self reported their QMS as extremely effective compared to organizations that did not when testing for "yes" as the response for third party certification of QMS. Eighty percent of organizations that self reported their QMS as extremely effective had third party certification compared to 29% for organizations that did not self report an extremely effective QMS.

Finally, there was also a statistically significant difference at the 95% CI (p = 0.036) between owners that self reported their QMS as extremely effective compared to

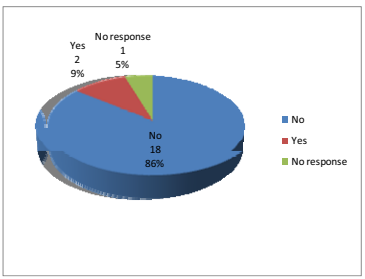


Figure 2a: Distribution for an organization's QMS certification by a third party or parties for owners that self-reported their QMS other than extremely effective (N=20)

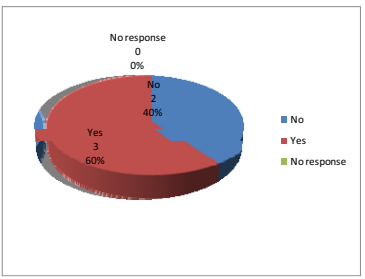


Figure 2b: Distribution for an organization's QMS certification by a third party or parties for owners that self-reported their QMS as extremely effective (N=5)

owners that did not self report their QMS as extremely effective when testing for "yes" as the response for third party certification of QMS. Owners that self reported their QMS as extremely effective had third party certification of their QMS more frequently compared to owners that did not self report their QMS as extremely effective (see Figures 2a and 2b).

For organizations with self-rated highly effective QMS, certification provides an external perspective and review of the QMS. These organizations reviewed their QMS anywhere from biannually to every 2 or 3 years, and these reviews were done by external reviewers. Management uses the results of the review to improve the QMS and the reviews are considered to be valuable for improving the QMS as well as the strategic alignment of the organization.

Conclusions

The research determined that there were differences in quality management practices regarding leadership and third-party certification between organizations. The following is a summary of the overall key quality management practices of effective organizations in terms of leadership and certification. These practices have generally been integrated into the organization's business management system and processes. This is not to say that other less effective organizations do not follow some of these practices, but what has been observed in organizations with highly effective quality management is a consistent commitment by top management with strong visible leadership and accountability.

Organizations that self-reported an extremely effective QMS had the following differences with respect to leadership and third-party certification as compared to organizations that did not self report an extremely effective QMS:

1. Leadership: Responsibility for quality rests higher in the organizational hierarchy.

Responsibility for implementing quality procedures were at a higher management level for organizations who self-rated their QMS as extremely effective compared to organizations that did not self-rate their QMS as extremely effective. Organizations with extremely effective QMS more frequently responded that the responsibility for their QMS was at the President and Vice President levels compared to other organizations. There is consistent, visible leadership that is more extensive throughout the organization, and at the highest level such as Vice President of Quality. Furthermore, highly effective owner organizations lead by example, not simply by delegating responsibility for quality to contractors including providing training to contractors that enhances their understanding of requirements and arranging meetings and work sessions with contractors to ensure alignment of project deliverables.

2. Certification: More frequently certify their QMS.

Organizations that self-rate their QMS as extremely effective are more likely to have third party certification compared to organizations that did not self-rate their QMS as extremely effective. Some or all of a highly effective organization's QMS is regularly reviewed (every 6 months to 3 years), adding value through the external audit by improving and validating the QMS and by improved project satisfaction and quality. The organization's top management reviews the results of the audit and uses them to improve the QMS and align certification with its strategic business interests. When owners and contractors are compared, contractors are more likely to have third party certification than owners, regardless of whether they self-rate their QMS as extremely effective or not. Contractors are also audited by owners in addition to 3rd party auditors, making it likely that contractors are more frequently externally audited than owners.

In conclusion, quality management is a broad term and there is a great deal of diversity in QMS interpretation and implementation across organizations. Further research is needed to define the appropriate elements and characteristics of a range of quality management criteria for capital facilities delivery by organization type, project type and for different business units.

Acknowledgements

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An IDP-BIM Framework for Reshaping Professional Design Practices

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Abstract
Integrated design process (IDP) and Building Information Modeling (BIM) have been recognized as two approaches to address the problem of fragmentation in the construction industry. Adopting these processes and tools nonetheless requires drastic changes in design practices. There is a need for generating and formalizing new knowledge practices, and discarding obsolete ones. However, traditional approaches to create and transfer this new knowledge cannot cope with this need. This research builds on social learning theories, such as activity theory, to propose a situated learning environment in which BIM-related technologies are structured in an IDP framework. This learning environment is designed as a laboratory where traditional practices in planning, managing and designing construction projects can be challenged. BIM and simulation models, together with collaboration tools are used as boundary objects to break barriers between professional practices. Design teams, by adapting to this new environment, generate new practice knowledge. This knowledge is captured using ethnographic methods to enhance and consolidate the IDP framework. The proposed approach contributes to accelerating the co-generation of new knowledge practices within the proposed environment.

Introduction

The problem of fragmentation has been widely recognized, both by the research community and in industry, as a core problem related to the industries loss of productivity (Allmon et al. 2000, Goodrum and Haas 2002), lack of or unreliability in meeting project constraints of cost, schedule and quality (Egan 1998), and/or the loss of value (Koskela 2000). Some large clients (the UK and the US governments) have taken stiff measures to induce changes in current practices, promoting the integration of design and construction processes or improving the management of information. The use of Integrated Design Processes (IDP), Integrated Project Delivery (IPD) or Building Information Modeling (BIM) is now part of the clients' requirements to the supply chain for the definition or realization of a building project. These new requirements have not, however, brought the expected improvements in existing practices. Authors argue (Moore and Dainty 2001, Forgues et al. 2009) that resistance

to changes, especially by design professionals, seems to hinder integrated team performance or the adoption of BIM. However, the construction management literature does not provide a convincing explanation about the source of the problem, nor its solution.

Research on practices suggests that the problem is related to the nature of the organization of work in construction. As opposed to disciplines in similar industries – in which collaborative work is built on task-discontinuous status structures with highly fragmented divisions of labor and diverse bodies of knowledge – design practices are built on a guild organization of work, in which relationships are defined around a structure of power and influence based on their members' skills, knowledge, experience, and mastery (Clegg and Hardy 1996, Forgues 2008). This actually hinders problem-solving and knowledge creation across functions, due to compartmentalization (Carlile 2002, Engeström et al. 1995, Janis 1982) and a lack of knowledge articulation among experts (Blackler et al. 1999, Boland and Tenkasi 1999).

We argue that the change from fragmented to integrated processes and management of information is a change of paradigm. The standard organization of work and bodies of knowledge or codes of practices are becoming more or less obsolete in this new context; and the generally-recognized theories and research paradigms in engineering may not be appropriate to address this problem. There is thus a need to build on a new set of theories and related empirical research related to the generation and transfer of new knowledge in construction; and to devise a research approach for generating new knowledge of practice. The research goal is to develop a new IDP-BIM body of knowledge integrating planning and design practices at the definition phase of a project. The amount of new knowledge of practice to be generated is significant. It is our view that this challenge requires breaking boundaries within research disciplines and between research and industry. One of the aims of this paper is to encourage and motivate the academic research community into preparing a first version of an IDP-BIM body of knowledge. We present here the first version of an IDP-BIM framework, and the preliminary results of a pilot project in which students were involved in a design simulation based on this framework. Some of the expected contributions from this work are to theory, regarding new methods for generating knowledge of practice, and to industry, by proposing ways to address socio-cognitive barriers that hinder the performance of integrated teams.

Background

In information technology research, it is acknowledged that to fully reap the benefits of technology, the organization of work, processes and methods often have to be redesigned. Pundits in IDP agree that integrated design is irrelevant without the validation of design solutions using simulation tools (Eastman 2009). These tools have now been related to BIM technologies. We put forward that the rethinking of design practices to meet new client requirements has to occur and will occur around IDP and BIM. The challenges, therefore, are to generate a new body of knowledge of practices to cope with these changes in the environment of construction projects, and to accelerate the knowledge transfer to practitioners.

Koskela (2000) posits that the problem with the existing professional practice codes is that there is a lack of adequate theory supporting the understanding of the construction process. He suggests that the design and construction process should not

be based on project management but on production theory. According to his theory, production in construction should balance three "views": transformation, flow and value (TFV). He asserts that the problem with existing practices is that they are built around only the transformation view: this Taylorist model of work organization is weak at managing the interdependencies between work packages and inefficient in generating value for the customer. Winch (2002) emphasizes the problem of information processing within this view. The sequential and fragmented design and delivery process creates information gaps between phases, resulting in a building product that is sub-optimal and not up to client needs and expectations. To address the flow and value problems, research and studies have suggested integrating project information within one product model through interoperability; or reorganizing the project definition and delivery around an integrated design or construction process (Larsson 2002, Löhnert et al. 2002). These concepts present two different perspectives: linking distributed work within an integrated virtual environment, or organizing work around multidisciplinary teams. In the former, project teams replicate traditional interactions in a virtual world; in the latter, client and supply chain representatives actively collaborate within a new, iterative framework in which the team members are co-located, a process that encourages learning and innovation.

Research on initiatives to "rethink construction" or to adopt integrated design and BIM technologies indicate that there are three socio-cognitive factors that hinder the implementation of the required changes to existing design practices (Forgues 2008). First, professional associations in construction are based on what could be qualified as a guild structure. The traditional role of a guild is not to endorse the evolution of existing bodies of knowledge but to preserve the status quo (Lawson 2006). Second, research in construction reflects the fragmentation of the industry – researchers work in isolation and there is little integration of knowledge, even within engineering. Third, the market value of a design professional is based on their specialized knowledge. Changing roles and methods put this unique knowledge at risk (Carlile 2002). Dominating actors may use their power and influence to create barriers to developing shared meanings by refusing to modify the knowledge and interests from their own domain (Brown and Duguid 2001, Carlile 2004).

Emerging theories and empirical research in design science and social learning shed new light on how to address the socio-cognitive problems obstructing the evolution of design practices. For example, researchers in social learning have done empirical studies in the military and chemical industries in an effort to pinpoint the origin of conflicts between management and engineering in the process of changing the configuration of work to fit a new logic of value centered on innovative products (Blackler et al. 1999, Vinck 2003, Vinck and Laureillard 1996). It was observed that engineering groups resisted the changes in roles and relationships required by management – specifically, moving the leadership of product definition from engineering to marketing or business units and involving users in the design process – with the aim of offering innovative products that were based more on user needs. These researchers posited that such a change demands an evolution of the engineers' practice frameworks and of the way they conduct design activity. The proposed changes to the framework included: greater involvement during shorter amounts of time; moving from a prescriptive to an adaptive approach to requirements, from

sequential contributions to a collective process, and from specialized expertise to devoted individuals.

These changes demand not only reconfiguring existing bodies of knowledge, but also breaking the fragmented mental models and work structures that define roles and relationships in the traditional project design and delivery process.

A theoretical foundation for evolving design practices

In the field of construction, there is almost no literature related to how to address the problems, the socio-cognitive barriers hindering the generation and adoption of a new body of knowledge for integrating design practices. The problem is not limited to the construction industry. According to Vinck (2003), there is little ethnographic research that addresses the problems related to barriers created by specialized knowledge. One of the obstacles is the fragmentation in research work. Engineering is concentrated on developing working rules (*règles de l'art*) and tools; management on increasing performance by changing delivery models from sequential to concurrent or integrated; psychology on defining cognitive processes; and sociology on shaping these cognitive processes. Not much is said about how people interact during the design process. It is still difficult to identify all the actors, activities and roles: the sharing of activities remains ambiguous within the new organization of work for integrated design (Vinck and Laureillard 1996).

Nonetheless, there have been some breakthroughs from studies in social learning (activity theory and situated action theories). These theories suggest that learning and knowledge generation occurs mainly within a social process defined as an activity. "The activity itself is the context. What takes place in an activity system composed of object, actions, and operation, is the context. Context is constituted through the enactment of an activity involving people and artifacts" (Kaptelinin and Nardi 2006). Hatchuel (2002) argues that the design activity is regulated by the final object, which is absent until it is achieved. The conceptualization of this "*objet absent*" is realized through the representation of intermediary objects, also called "objects-in-use." Design professionals are surrounded by these objects-in-use: tools for designing, validating and exchanging. For example, even if new technologies are used in design, the collaborative process within building design workshops is still paper-based and dominated by architects.

As asserted by Lawson (2006), the perception that design is the result of one individual creative act is rooted in architecture training and is deeply embedded in architects' practice knowledge and tools. To be effective, multidisciplinary teams in design workshops need to break the power and knowledge barriers and build a shared mental model. This means that all participants need to be able to develop a shared ownership of a project, and engage in a mutual learning process. This also demands retooling, i.e. redefining the collective objects and artifacts around which the integrated design process can be articulated. Changes will be required not only in practices, but also in the way that design science is researched and taught.

Research and teaching in engineering is built on the paradigm of natural science. In contrast to the natural or social sciences, social learning theories (activity and situated action) regarding design are not just about explaining but also about intervening in phenomena with the aim of transforming its reality Niiniluoto (1993). Simon (1996) argues that the "raison d'être" for research regarding design is to advance both

science and practices. But this role remains elusive, hence the justification of design science as a new science paradigm aimed at creating "practice knowledge". From design science we adopt the concept of developing a set of rules, namely a body of knowledge; and from the social learning theories the concepts of situated learning (Lave and Wenger 1991), boundary objects (Carlile 2002, 2004) and expansive learning (Engeström 2002). According to these theories knowledge is created through interactions between the individual and the collective (situated learning) and between individuals, tools and the collective (activity theory, distributed cognition). The integrated design activity is viewed as a mutual learning process in which people interact through mediating objects to achieve a common goal.

In summary, Koskela's TFV theory provides a theoretical foundation for the technical aspects in devising a new body of knowledge. Social learning theories, taken from a design science perspective, offer a fertile ground in which to devise a research approach for addressing the socio-technical issues.

The research design and method

Other disciplines have developed evolving bodies of knowledge. For example, there are two international organizations (the Association of Project Management and the Project Management Institute) that are producing and updating a project management body of knowledge on a regular basis. Our first design strategy for an adaptive process to evolve an IDP-BIM body of knowledge is to borrow from the experience of IEEE in the development of the Software Engineering Body of Knowledge (SWeBoK). This body of knowledge started as a research project. It was developed in three successive iterations (straw man, stone man and iron man). The straw man version was produced by the researchers and included the development of the ontology of knowledge and a first draft of the content, which was based on relevant literature. The stone man version was then evolved by practitioners that were recognized as experts in one or more of the themes. Finally, the iron man version was the result of an overall review of the proposed practices by the broad base of the community. This review is now conducted every four years to update the content of the body of knowledge.

These bodies of knowledge are nevertheless built on existing knowledge, focusing on developing consensus on recognized practices. IDP and BIM are new approaches to design for which it is required to learn "what is not yet there". It is creation of new knowledge and new practices for a new emerging activity. The second strategy is derived from the work development methodology proposed in activity theory for expansive learning, i.e. a method aimed at generating, mediating and routinizing new knowledge for design practices. It combines three approaches. First, there is the *learning laboratory*, in which new technology is introduced to destabilize existing practices. According to Engeström's (2002) activity theory, collective learning can be accelerated by acting on the objects used in an activity within a laboratory (in this case BIM technology), inducing the creation of new knowledge within the IDP. New knowledge is mainly generated during unique activities involving multiple disciplines (Leonard-Barton 1995). Second, *communities of practice* are to be created for mediating and routinizing this new knowledge. According to Blackler's (1999) theory on knowledge and innovation, organizations are networks of knowledge and sense-making activities systems, grouped around communities of practices. A proper

context has to be set at the beginning, to stimulate the production of this new knowledge (perspective shaping), and then each community, through consensus, has to review, mediate and incorporate this new knowledge within their own body of knowledge (perspective shaping). Third, BIM and collaborative technologies are used as *boundary objects,* a specific type of mediating object for representing, learning about, and transforming knowledge to resolve the contradictions that exist at a given boundary between two or more of these communities (Carlile, 2002). Several authors (Engestrom 1995, Carlile 2002, 2004) suggest that boundary objects could play a key role in generating and mediating learning in the context of an activity involving representatives from different practices.

A *learning laboratory* was first set up, into which the design team is placed in an unfamiliar context that challenges their traditional work patterns and power structure. Engeström's Development Work Methodology is used to facilitate the co-production of new knowledge. The laboratory consists of a large room equipped with a new set of *boundary objects*: collaborative tools: intelligent boards and wireless technology that allows files or URLs to move between screens (thereby saving digital drawings from a whiteboard) and thus allow collective web browsing and file sharing with the whole group, BIM technology (parametric software for 3D, 4D, 5D and energy simulation) and a 3D projector. The researcher then approached a 3D software user group and helped them develop a *community of practices* for IDP-BIM. Next, a *pilot project* was devised. A pilot project is a good approach to validate a research strategy and to calibrate the instruments to be used in the core of the research. The pilot consisted of an experiment with an early version of the IDP-BIM framework. It involved a group of 38 students, comprising 12 graduate students in architecture, 14 students in construction engineering (structure and cost estimating) and 12 students in mechanical engineering. One of the teams worked in the learning laboratory; four other rooms were equipped with similar technology, for a total of 5 teams.

Identifying relevant research methods was a challenge, since the research community in construction and engineering is not familiar with most of the methods used in research on social learning. Nardi (1996) advocates the use of a varied set of traditional data collection techniques including interviews, observations, video, and historical materials, without undue reliance on any one method (such as video) and recommends paying attention to broad patterns of activity rather than narrow episodic fragments that fail to reveal the overall direction and import of an activity. Interactions using technology as boundary objects for collaboration, planning, design and management are captured through audio and video and coded using Nvivo 8. Data from the observations are triangulated with interviews, questionnaires, and the review of the electronic documents and data exchange through the virtual network. The result is then framed using cross-comparisons within the ontology of patterns devised by researchers for task analysis and that of the team members' level of maturity in collaborative work (Fruchter 1999). All of the design sessions were videotaped. Students also filled out two types of questionnaires, one to identify conflicts and contradictions in the team interactions, one to measure the evolution of team members' perceptions of their ability to share knowledge with other disciplines.

Devising the IDP-BIM framework

This first draft of an IDP-BIM framework is derived from two sources: best practices in system and software engineering for conducting collaborative design work; and findings from previous research in the experimentation of a requirement-based approach to integrated design (Forgues and Eugenie 2009). The framework focuses on the project definition, i.e. the development phases preceding the preparation of the working drawings. It is well-recognized that opportunities to maximize value occur at the early phases of a project. This is the reason why proponents of IDP suggest moving the core of design efforts from the detailed design stage to the project definition, which encompasses planning, program, concept and preliminary design.

The core of the framework is the combination of a gating process derived from configuration management and an agile process derived from software engineering. Integrated Design Processes (IDP) was first used in product and system development after World War II (Ziemke and Spann 1993). With the development of complex software-intensive products in aerospace, software engineering evolved these processes-combining agile development methods with the configuration management process from system engineering. Agile methods are based on short and intense collaborative design phases that deliver successive versions of a complete solution. Configuration management is a rigorous requirement-based validation and verification process conducted at the end of an iteration (identified in industry as a gate) to measure the level of compliance of the solution (at this point) to the functional and technical requirements. The combination of these methods has permitted the defects, development time and cost of complex products to be drastically reduced.

The framework is divided into three successive iterations, the first to validate the users' requirements, develop the sustainability strategy and devise the model of reference, the second to analyze the options and generate a concept, and the third to refine the concept that proved to be effective to design, and to do it within the constraints, each closed by a gate. At the outset of the process, the integrated team receives a set of targets and requirements to meet at each gate. They collect feedback from the gating reviews as inputs to improve their design within the next iteration.

The technologies are divided into three groups within the framework: automating the verification and validation of the design outputs in the gating process; facilitating visualization using 3D design software; and supporting options or constructability analysis and collaborative design with simulation tools.

Conducting the pilot study

The project is a future building that will be dedicated to the student community of a university in Montreal. The future users wanted to be involved the in the design process. It was proposed to develop a special course using a situated learning approach. Three universities and two departments in engineering participated in the project. The program was rich and complex from a sustainability perspective. It encompassed diverse functions such as a hockey rink, a swimming pool, commercial space and offices for students' clubs and associations. A coffee shop was included in the project. Soil conditions were a challenge as the site had been a landfill over an ancient river bed. At each stage, the teams had to demonstrate the financial and technical feasibility of the project.

The *learning laboratory* was duplicated in four other spaces to accommodate the five teams. Each team had access to an intelligent board or Sympodium**,** collaborative software**,** 3D parametric software for architectural design, cost-estimation and energy simulation. The process followed the IDP-BIM framework with the exception that no technology was used for validation or verification of the design outputs. An electronic version of the 3D model of the site and its surroundings was provided to the students. The teams worked over three two-day intervals, separated by two-week intervals. Iterations were closed by a three-step verification and validation process. For the verification process, the teams had to comply, for each step, with a set of requirements to demonstrate the value of their strategy in regard to sustainability, financial and technical feasibility, and compliance to budget and program constraints. This verification was conducted by professors in the related disciplines. The validation process was realized through a public presentation in two stages. In the first stage, experts from industry and representatives from the administration and student associations were invited to provide comments regarding the design, sustainable construction or the management of the future facility, and their perceptions about the suitability of the solution. In the second stage, the public was invited to give their evaluation on three criteria using an electronic voting device.

The results were quite impressive considering the fact that most of the students were unfamiliar with the technologies and had never worked with other disciplines in a collaborative environment. The simulation also allowed interrogation of the hypotheses found in the literature regarding the concept of interoperability. Integration is not only a matter of exchange protocols, but also of rules to be developed on the conduct of the design process. For example, the way that 'rooms' are defined in 3D software will determine if the energy simulation software will be able to extract or analyze the design data that were transferred. Therefore, within an IDP-BIM environment, it is not only necessary that the disciplines develop a common language for sharing knowledge, but also that they share a common understanding on how each BIM technology works and how they communicate with each other.

Discussion and conclusion

The aim of a pilot study is first, to validate the value of the theories to be verified through an empirical investigation, and second, to select and calibrate the research instruments to be used for the core of the research. One of the key contributions of the here defined first version of the framework is to propose a process in which technologies are used as accelerators for innovation and knowledge generation in the project definition process. In current IDP frameworks, little has been written on how technology is integrated in the process, whereas it is recognized that IDP is almost worthless without the use of simulation tools. Literature on BIM focuses on how to increase productivity by facilitating coordination during detailed design and construction. Thus far, there is almost nothing in the literature about how technology can contribute to improve the project definition process. Another contribution is the integration of multiple feedback loops within and between design iterations to accelerate collective learning and knowledge generation. The proposed theoretical foundation and its application for this empirical research proved to be convincing and to justify the acceleration of collective learning between disciplines and the capture, mediation and routinization of knowledge.

The pilot project also helped to identify knowledge gaps in both architectural and engineering teaching that could be addressed in future work. Architectural teaching is focused on developing a student's ability to resolve wicked problems through design; engineering teaching concentrates on the procedural problem-resolution of 'tamed' problems. Unsurprisingly, at the conceptual phase of the project, engineering students did not demonstrate the same level of reflexive skills in devising solutions to complex design problems as the students in architecture. Both replicated the traditional pattern of power and influence conveyed by industry, in which the architect designs before the engineer specifies his/her solutions for making the building work. This fragmentation was also reflected in the way teachers in architecture and engineering assisted the students in solving design or technical problems.

The core concept of activity theory – as opposed to situated action theory – is the ability of the researcher to help the members of the activity to pinpoint the conflicts and contradictions that affect their collaborative work and to resolve them. This means that the researcher has to be able to first capture and analyze patterns, and then provide feedback to the team within a very short time. However, this proved to be a difficult task to manage. Too many quantitative and qualitative tools were used. They permitted the capture of a large set of data for research, but hindered the researchers' ability to provide feedback to the team in a timely or effective manner. For example, a quantitative method using a questionnaire to assess the members and team's ability to resolve conflicts was used. The students had to fill in the questionnaire at the end of an iteration. They received the results of the analysis before the next iteration. The aim of the tool was to help the team to become aware of the conflicts and resolve them. However, the students were too preoccupied to realize the deliverable within the short timeframe and did not use this feedback to improve their efficacy.

This research is exploratory. The contributions to knowledge or practice may be limited at this stage. However, as asserted by Van de Ven (2007), understanding how research can advance scientific and practical knowledge is an ongoing challenge for scholars researching professional practices, and developing such an approach could be considered as a contribution in itself, at both the theoretical and empirical levels. The pilot project helped to test and asses various methods and instruments and to develop a more robust research protocol.

The next step will be the building of the knowledge base to complete the first version of the framework. Ontology was developed as a canvas for the framework with relevant information regarding the organization of work, process, methods and tools, based on the literature and on experimentation conducted in the laboratory (Forgues et al. 2009). Preliminary results from this experiment will be added to this knowledge base and shared with the BIM community of practices. A group of early adopters from industry (client, architects, engineers and contractors) will participate in workshops for sharing their own experience in IDP and BIM. A pilot project is in negotiation with a major public client to test an updated version of the framework derived from these workshops. In parallel, a more focused effort will concentrate on a unique boundary object, 3D energy simulation software, for mediating the interactions between architects and mechanical engineers for the development of holistic solutions to the design of high-performance buildings.

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CONSTRUCTION ENGINEERING EDUCATION: NEED, CONTENT, LEARNING APPROACHES

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ABSTRACT

Market demands for improved infrastructure and a more sustainable built environment are increasing the importance and scope of construction engineering throughout the project development process. Despite this, many construction programs face pressures to increase coverage of construction management topics, lessening time for construction engineering. These two opposing trends form the background for this paper.

The goal of the paper is to provide compelling reasons and useful guidance to restore the balance between engineering and management in construction education. The method of analysis is to identify the priority fundamental elements of construction engineering knowledge and to describe the learning approaches applicable to each. The main contributions are a structure and methods for learning about construction engineering that are applicable to all types of construction.

The paper also includes recommendations for educators to increase coverage of construction engineering using new learning approaches, for industry to assist in offering relevant courses, and for researchers to further develop construction process models and other tools with potential benefits for construction engineering education.

INTRODUCTION

Many characteristics of current construction markets and firms create a need for increased attention to construction engineering education. Increasing priority for certain project objectives and criteria, such as life cycle performance of the facility, is increasing the technical scope of buildings and infrastructure. New technologies with significant potential to help increase project performance, such as increased integration and modeling, are requiring new technical capability in

firms and on projects. However, other drivers are increasing emphasis of construction management topics in many graduate and undergraduate construction programs. Both engineering and management topics are important for young engineers seeking successful careers related to the built environment; a balanced approach is needed.

The purpose of this paper is to help restore the balance between the engineering and management in construction education. The major sections highlight the importance of construction engineering education, describe what it includes, and suggest use of proven and encouraging new ways to help young engineers learn about it. The conclusions highlight actions by all stakeholders in construction to advance construction engineering education.

NEED FOR CONSTRUCTION ENGINEERING EDUCATION

Several key new features of constructed projects and rapid technological advancement create a strong need for young engineers to bring a solid technical background to their initial positions in design and construction firms. This section reviews trends in requirements and new technology. It argues that a technical foundation can also provide major advantages for diverse types of careers related to the built environment.

Trends in market and project requirements

Leading owners, now even more than in the past, want constructed products with increased performance, sustainability, and life cycle value. As a result, many parts of the built environment are increasing in scope and technical complexity. In addition to wanting an improved product, leading owners are seeking significantly improved performance of all project activities required to meet each type of objective: cost, schedule, quality, safety, and sustainability. These increasing demands on projects prompt the involvement of many types of specialists during design, construction, and commissioning. This requires broader technical understanding by the project managers, project engineers, and construction engineers who engage, coordinate, and manage these specialists in performing activities such as environmental compliance.

New technology

Rapidly advancing information technology creates major opportunities and challenges for increased project performance and needs for construction engineering. Research to develop new tools for construction process modeling encourages greater creative breadth and technical depth in evaluating alternatives for construction methods and other parts of field planning (Kunz 2009). This will increase the effectiveness of design-construction integration, construction planning, and construction engineering activities to support field operations (Tatum 2005). However, taking full advantage of the potential offered by these tools will require background in construction engineering.

Increased offsite work and mechanization or automation of specific fabrication and limited erection operations require understanding manufacturing operations and detailed planning for assembly operations at the site. Realizing each of these opportunities for project performance improvement requires a basic technical understanding of design processes and products along with construction resources and field operations.

Students' background and career opportunities

Many young engineers are very comfortable with information technology and attracted to modeling tools and activities to support planning and analysis. Real estate development, facility management, and other possible careers related to the built environment are potentially interesting to a growing number of students and graduates. These and other career paths related to constructed facilities benefit from construction engineering knowledge. Using this knowledge to get very good at performing an important task can provide significant benefits for the start of careers in design or construction. Construction engineering knowledge can also provide a major career advantage by increasing communication and rapport with all professionals, disciplines, and trades involved over the full lifecycle of the project.

CONSTRUCTION ENGINEERING ACTIVITIES, EDUCATIONAL GOALS

For this paper we will define construction engineering as the application of technical fundamentals and knowledge from experience to integrate design and construction, foster innovation in both, provide technical information and physical resources for field operations, avoid and solve field problems, and transfer experience between projects. Technical input to planning and estimating is a key construction engineering activity early in the project.

The activities mentioned in the definition lead to two broad goals for construction engineering education. First, students completing a set of construction engineering courses will be able to apply technical fundamentals and knowledge related to resources and operations to provide construction engineering support to meet all project objectives, to learn quickly from doing this, and to gain increased capability and responsibility. Second, they will continue learning from experience and gaining career advantages based on superior performance of construction engineering.

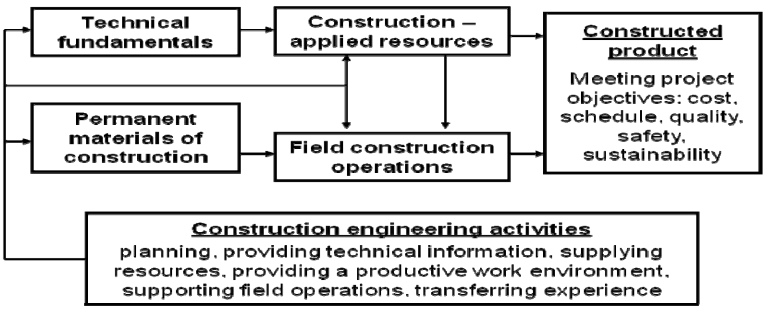


Figure 1. Knowledge elements and activities for construction engineering

PRIORITY CONTENT

Construction engineering knowledge consists of four elements: technical fundamentals, materials, construction resources, and field operations (Figure 1).

Technical fundamentals

Technical fundamentals provide a foundation or context to understand design and construction products and processes. They are the engineering basis for the performance of both the constructed facility and the resources and construction operations needed to build it. Including fundamentals from multiple disciplines as a main topic in construction engineering education recognizes the interdisciplinary nature and provides a generalizable foundation for experiential and lifelong learning.

The major engineering disciplines involved in most types of constructed facilities include: materials science and engineering; mechanics and dynamics; geotechnical engineering; structural engineering; fluid mechanics; thermodynamics, psychometrics, and heat transfer; electric power, and process control and instrumentation. Design engineers apply engineering fundamentals to define the function and performance of systems and for analysis and design. Construction engineers need to understand the fundamentals for each discipline and how they are applied in the design of the permanent facility and temporary works.

Materials of construction

The basic bulk materials of construction are soil, concrete, steel, other metals, and architectural materials. Engineered materials included permanent equipment and fabricated portions of distribution trees in systems. Design properties of materials include chemical, physical, performance requirements, and special restrictions such as toxicity. Construction properties include: cost, availability, potential for substitution, interdependency with construction operations, and toxicity.

Knowledge of the basic materials properties and of the standards that define them, such as ASTM, is necessary to understand design intent and avoid and solve field problems. Design and construction properties of materials are often a key consideration in establishing many types of design requirements and in evaluating alternate construction methods. Materials properties are a major part of the shared knowledge required for effective design-construction integration. Materials of construction and field operations are highly reciprocally related; they influence and constrain each other. This means that selecting materials of construction requires knowledge of field operations and planning construction operations requires knowledge of materials properties.

Construction-applied resources

To build the work, construction forces use many types of materials and equipment that do not remain with the completed facility. These include consumable materials, salvageable materials, tools, and construction equipment. The capabilities and limitations of these resources are often the major consideration in selecting construction methods. Criteria to select types of construction-applied resources described in construction engineering courses include: widely used, influence on project objectives, young engineers involved, and includes an IT component.

Important construction engineering knowledge related to resources includes: technical requirements and performance for typical uses, how it works, capabilities and limitations, best applications, degree of mechanization and potential for automation, major risks of use, implications for all types of project objectives, and examples of evaluation and selection. For more complex and critical construction resources, such as large cranes and construction equipment, full understanding of capabilities and applications will require analysis at a systems level, such as traction or power train systems for earthmoving equipment (Tatum et.al 2006).

Field construction operations

Completing any part of a constructed facility requires a series of field operations. These activities required to complete a specific type of work follow a sequence:

Earthwork: erosion control, clearing and grubbing, stripping topsoil; excavating, hauling, placing, compacting, and testing soil; finishing surfaces, grade checking.

Concrete: fabricating and erecting formwork; placing reinforcing steel and other embedded items; batching, transporting, placing, finishing, curing, testing, and repairing concrete. Concrete work may also include special methods and operations such as precasting, shotcrete, underwater concrete, slurry wall construction, and roller compacted concrete.

Structural steel: ordering and detailing steel shapes; fabricating, coating, transporting, and shaking out fabricated steel members; raising, plumbing, connecting, and testing portions of steel structures.

Permanent equipment for building or plant systems: specifying performance requirements, reviewing technical information from suppliers; fabricating and testing equipment; transporting, receiving and storing equipment items; installing, connecting, and testing equipment.

Piping and ductwork: detailing, coordinating, and fabricating pipe spools or duct pieces; transporting, erecting, supporting, connecting, and testing pipe or duct branches.

Electrical systems: detailing, coordinating, fabricating, transporting, and installing raceway; transporting, positioning, pulling, terminating, and testing electrical cable.

Priority learning for each type of operation is determined by the knowledge required to complete construction engineering activities.

LEARNING APPROACHES FOR CONSTRUCTION ENGINEERING

Felder and Brent (2009) developed a model of learning styles that contrasts four activities: perception, input modality, processing, and understanding. *Perception* contrasts sensing learners who focus on external input and practical and concrete thinking with intuitive learners who focus on internal input and imaginative and abstract thinking. *Input* contrasts visual learners who focus on images with verbal learners who focus on spoken or written words. *Processing* contrasts active learners who learn best doing something and thinking out loud with reflective learners who think about presented material and work introspectively. *Understanding* contrasts sequential learners who learn by logical sequential steps with global learners who want to view the big picture, absorb information randomly, and synthesize it.

Felder and Brent report that most students are sensors and most faculty are intuitors and encourage using a varied approaches to appeal to all types of learners. They advocate active learning approaches, often linked with inductive methods, involve the students in inductive processes to increase their understanding. They define and solve problems and receive instruction and assistance during the process.

Building on these learning styles, possible methods for teaching and learning the elements of construction engineering knowledge identified above include the three approaches described in this section: traditional, active, and integrated.

Traditional learning approaches

The classroom portion of traditional learning is often mostly passive and deductive in nature. Teachers communicate the fundamentals using one of the methods described below and students then deduct increased understanding through derivations, examples, and applications in assignments Felder and Brent (2009).

Lecture with examples. Class description of selected topics from each element of construction engineering knowledge can provide a useful starting point. The broad scope of the discipline and the potential depth of each topic create a major challenge for the instructor. Even devoting the majority of class sessions to this approach, and missing the opportunity offered by the active and integrated approaches described below, does not allow adequate coverage in most programs. Focusing on lecturing also does not give the students the experience of application. Traditional problem sets can provide part of this if focused at the correct level of analysis.

Reading, analysis, and application. Guided by questions that require critical analysis and application, students can gain valuable understanding of construction engineering topics from course notes, textbooks, or handbooks. Some form of input from the students prior to the applicable class session, such as a response to a query or a set of questions on the reading, increases their learning. If reviewed in advance of the session, this input also helps the instructor structure the class to further develop the topics that were especially interesting or difficult to understand.

Find, analyze, and apply. The vast amount of information available on the Internet supports learning through discovery and application. Many of the types of information used in construction engineering activities, such as the technical aspects of materials or construction equipment, is easier to find, more complete, and more current when obtained from the Internet rather than hard copy. Learning to use this resource in the most effective way also provides background for continued learning. Assignments involving this approach need to include requirements for comparison and analysis of results, along with specific findings related to the construction engineering topics.

Active and cooperative learning approaches

Brief pair discussions. Each of the four elements of construction engineering knowledge is a good candidate for brief discussion between pairs during class sessions, as strongly advocated by Felder and Brent (2009). Examples include: use fundamentals to analyze a site condition or a resource; forecast the implications of materials properties such as plastic concrete; speculate on the most likely failure mode of a crane making a specified lift; or develop a recommended sequence of installation for plant systems.

Extended group class exercises. Group exercises to select a construction method and forecast production rates are a very effective learning approach for all the elements of construction engineering. Completed during class sessions, these exercises typically require prior analysis of project conditions and alternates for resources and operations. The student groups then receive the detailed questions at the start of the class session, complete the analysis to respond to the questions, and submit a summary report by the end of the session. Student feedback indicates that this is an effective learning method for construction engineering

topics and also provides valuable experience concerning task organization for effective group processes.

Structured visits and field trips. Visiting firms and active construction projects provides a very valuable learning opportunity. Progressive design and construction firms welcome student visits and willingly share information that contributes to learning about construction engineering. Realizing the full potential value of this learning opportunity requires a structured approach. This can include prior research and questions by the students, assignments to collect and analyze specific types of information, and reports to summarize what they learned.

Group projects to analyze resources or construction operations. The overall objective of group assignments is to increase learning through analysis and application of construction engineering knowledge. Possible activities include modeling operations, forecasting production rates for alternate construction methods, and analyzing different types of risk. A course project for groups to focus on a construction operation and its analysis and application on a project or in a firm can also provide an excellent learning experience. This learning method requires student groups to investigate a field operation in a firm, ideally on a project.

Integrated learning approaches.

Context-sensitive learning approaches provide many benefits. Related to construction engineering topics, they require some background but can potentially add breadth and depth of understanding by providing a situation and requiring application of the four elements of construction engineering knowledge.

Design-construction integration and design build. A Stanford degree program focusing on design-construction integration provides a very valuable opportunity for learning construction engineering topics with emphasis on those that involve linkage with design. The purpose of the program is to prepare students for multidisciplinary collaborative teamwork in an integrated design and construction process. It extends background with courses that emphasize integration decision making related to the design and construction of concrete and steel structures.

Virtual design and construction. Researchers seeking to improve work processes in design and construction, manufacturing, and other fields have developed modeling and other tools with potential applications in construction engineering education. These tools allow individual, group, or class exercises to evaluate multiple alternatives for design approaches and construction methods.

A Stanford course focused on virtual design and construction illustrates this learning approach (Fischer, Kunz 2009). It includes product, process, and organization modeling. The course project applies construction engineering knowledge to visualize, integrate, and automate design and construction work processes. Examples of construction engineering activities in student course

projects include: analyzing construction access and workspace, avoiding conflicts between collateral work activities, obviating safety problems, and considering alternatives for temporary ground support.

Project-based learning. These group activities to develop a design that fully considers the methods to build the facility can provide excellent learning opportunities related to each phase of a project. The members of the group who provide construction input can apply construction engineering knowledge to develop plans and estimates for alternate design approaches. This increases learning for the team regarding the benefits of considering construction methods early in the project.

A long-term course at Stanford illustrates the benefits of this approach (Fruchter 2001). Structured by global project teams, it requires an integrated process with team members in the roles of owner, architect, structural engineer, and construction manager. The collaborative process requires analyzing construction requirements and constraints, along with developing a cost estimate and a schedule. Examples of construction engineering activities in the projects include: construction input to the architectural and structural design, construction site and logistics planning, erection planning for precast concrete or steel structures, and planning and estimating to evaluate design alternatives.

CONCLUSIONS, IMPLICATIONS, AND RECOMMENDATIONS

The analysis of construction engineering education in this paper leads to conclusions regarding the critical need, a helpful structure for the contents, and effective learning methods in the classroom and on the jobsite. These conclusions highlight implications for all the stakeholders in construction engineering education.

Need, elements, and learning methods for construction engineering education

Need. Challenging projects, new requirements for field operations, new materials, and new IT-enabled resources for construction increase the need for attention to construction engineering. The combination of opportunity in specific market segments, new uses of information technology, and the interests of young engineers prompt opportunities for rewarding career paths related to the built environment.

Construction engineering activities are critical for project success in meeting all types of objectives. Completing many of these activities early in the project increases the alternatives available for design, construction, and the value chain, along with the potential for integration and innovation. Absent this, construction crafts complete the activities most directly related to construction operations in the field, making the best they can of the constraints they inherit.

Construction engineering knowledge, diligently pursued and carefully applied, will provide a major career advantage. It will foster critical analytical thinking to increase performance of current activities and keep learning. A foundational

understanding of the four elements will help to select and excel in an early-career activity, bringing increased visibility and responsibility. It will also create a motivating preview of the satisfaction that comes from contributing to the built environment. Finally, related to restoring the balance between construction engineering and construction management, an increased scope of construction engineering education can strengthen the construction management portion of programs by providing technical understanding for more effective use of management techniques and tools.

Elements. The structure of construction engineering knowledge described in this paper includes two fundamental and two applied elements. Technical fundamentals are an essential basis for gaining other types of construction engineering knowledge and for the evaluation of alternatives for construction methods. Materials properties are basic to the performance of temporary and permanent facilities and components.

Construction-applied resources, used to complete construction operations, transform permanent materials into a constructed facility. Coverage of construction operations captures how to build the work, including field challenges. The full scope of construction engineering includes other specialized topics, but these four can provide an effective foundation for continued learning throughout careers in design, construction, or other parts of the project lifecycle.

Learning methods. A combination of traditional, active, and integrated methods provides an effective approach for learning the diverse elements of construction engineering knowledge. As with appealing to different learning styles, a mix is best. Many faculty and students rely on traditional learning methods because they are familiar. Active methods get both more engaged and increase learning by inductive thinking. Integrated methods offer significant potential to increase the effectiveness of learning each element of construction engineering knowledge through application.

Implications and recommendations for stakeholders

Young engineers. A beneficial approach for continued learning involves alternating between two types of construction engineering knowledge and learning methods. The first step is experience-based or empirical. The second step is self study to gain deeper understanding of the technical fundamentals that are most applicable to the empirical knowledge gained in the first step. The Internet provides an increasingly valuable resource for this second step. An iterative process between fundamental and empirical knowledge provides a deeper and broader basis for continued learning from experience.

Regular and adjunct construction faculty. Considering possible coverage of the knowledge elements identified in this paper will encourage increased attention to construction engineering in construction education. This should include analyzing linkages with construction management topics in the program to leverage both parts. Developing a shared approach that includes the fundamentals

along with examples described by industry professional can increase both learning and interaction with industry. Using alternate methods of learning will increase the students' understanding and potential for an increased rate of learning from experience.

A core of basic teaching materials for each of the elements would help additional faculty offer construction engineering courses. The author is developing parts of these materials, including notes and class presentations, to make available for the construction education community. They will complement the many excellent textbooks available to describe some of the elements of construction engineering knowledge and help direct students to these sources for increased depth. Taking full advantage of different learning methods for construction engineering education will also require assignments and case studies using active and integrated learning approaches. Professor Michael Vorster is developing these key ingredients.

Construction researchers. Many construction researchers are now focused on developing model-based tools to assist in analyzing design alternatives and selecting construction methods that best meet all project objectives. These new tools can provide major benefits for construction engineering education by helping to bring the jobsite into the classroom. The four types of construction engineering knowledge identified in this paper can also provide assistance in selecting the scope of representation and reasoning for the models. This can assist in tailoring the models to the owner's priorities for project objectives, the type of construction, and the special challenges of the site.

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Identifying Competencies for Baccalaureate Level Construction Education:
Enhancing employability of young professionals in the construction industry

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ABSTRACT

The competence of a construction program in the core area of construction project management is in imparting to its students the necessary expertise in order to practice professionally in the construction industry. The study identifies the competencies for baccalaureate level construction education in Alberta, Canada. To achieve the study objectives, a questionnaire survey was carried out to collect information on industry's perspective on construction professional competences. Responses from 32 construction industry professionals were analyzed. The results suggest that the construction acumen, project management and leadership, business acumen, professionalism, and communications were considered as the most important (top five) and desirable competencies for baccalaureate level construction education. Other important competencies include building techniques, international project management, research, cost management, conflict resolution, ability to learn, contracts management, risk management, teamwork, and technological competency, procurement management. It is recommended that the breadth and depth of the core's syllabi ensures sufficient coverage of fundamental and extended topics on construction project management. Construction programs should help to equip our students better to participate in the local and global construction industries that await them. The findings from this study would also be valuable for all academicians and researchers involved in the area of academic development in general.

INTRODUCTION

As the Canadian population grows, so does the demand for residential and commercial property. Construction is and always has been a major player in Canada's economy. The construction industry employs close to 1 million Canadian men and women and chalks up volumes of $123 billion annually (Arain, 2009). The construction industry also has been accounting for about 12 percent of Canada's GDP. The construction industry has a growing need for management professionals and effective project management, which are crucial for major building or renovation projects, especially given the growing complexity of large construction projects and construction-related law (Ling and Leow, 2008). For these reasons, positions in construction management

increasingly require a specialized degree. Construction management requires a broad skill set in a variety of areas, and construction project managers are ultimately responsible for every aspect of their projects, including planning and scheduling project activities; managing employees, contractors, equipment and materials; project design; and budgeting.

Construction project management is the study of how the principles of scientific management are applied to construction projects (Kramer, 2005). It also covers maintenance of existing buildings and management of construction companies. Various management tools and theories are used to solve problems relating to the planning and control of construction projects. The core establishes the professional basis for successful operations in development projects as well as a strong basis for advanced studies in related areas (Arain, 2007).

Construction projects are complex because they involve many human and non-human factors and variables (Arain *et al*., 2004). The construction process can be influenced by changing variables and unpredictable factors that could derive from different sources. These sources include the performance of the parties, resources availability, environmental conditions, involvement of other parties and contractual relations (Arain and Low, 2003). As a consequence, the projects may face problems possibly causing delay in the project completion time.

It is commonly accepted that the construction industry has for many years been criticized for not developing consistent projects that are on time, within budget and with high quality standard (Arain, 2007; Ling and Leow, 2008). Generally, failure to deliver successful projects has been considered in relation to schism between design and construction, lack of integration, lack of effective communication, uncertainty, changing environment, and increasing project complexity (Arain and Low, 2003; Arain *et al.*, 2004; Arain, 2005a). Turner and Muller (2003) pointed out that committed people with high team spirit are essential for effective project management. Successful implementation of projects has always been a critical factor to the success of organization (Conrad and Sireli, 2005).

The rapid trend of globalization and technological changes have made difficult for construction organizations to survive in the competitive world (Babcock and Morse, 2002; Arain, 2007). Consequently, the importance of construction project management has been increased many folds. It is difficult to face the challenges of present international business arena without being more agile, adaptive and efficient. To develop the required expertise and resource, construction project management education is the key. In order to effectively operate in such competitive environment, the construction professionals should have project management knowledge and essential skills and competencies (Arain, 2007). The objective of this study is to identify the graduate competencies for baccalaureate level construction education in Alberta, Canada.

COMPETENCIES FOR BACCALAUREATE LEVEL CONSTRUCTION EDUCATION

The construction industry is becoming increasingly global and the role of construction management professional now includes many front-end services, which increases the required skill set of new construction graduates (Choudhury, 2000; Kay 2001). Alternate contractual delivery systems, collaborative partnerships, new management initiatives, and global product markets require students to have a broader awareness of construction methods and project management issues (Kramer, 2005).

Due to the complex nature of present construction business environment, the organizations often undertake multiple projects which are varied in nature and call for more specialized expertise in project management (Arain and Low, 2005). The engineers are often assigned management responsibilities as a result of promotion to higher level or due to the nature of work. Therefore, the engineering managers must have project management skills and ability to have the holistic view of the project from initiation till closing. The engineering managers have to work in an organizational setting that demands high degree of cross-functional integration. In order to effectively operate in such environment, the engineering managers should have required skill set and project management knowledge (Babcock and Morse, 2002).

Leading companies want and need construction professionals with solid foundations in both construction and project management, specific training in complex and challenging management problems, and sufficient workplace experience to assume leadership roles quickly. Construction Project Management program is a management-based course of study that prepares students for leadership roles in the construction industry. The program aims to provide participants with structured management and leadership techniques that will provide the basis for broader management decisions as well as on-site leadership in construction operations.

Graduates competencies of the construction project management program should be determined based on advice from leading regional industries, professional bodies, and the experience of other local and international for improving graduate's educational preparation for the construction industry (Arain, 2009). Program curriculum should be designed using a learner-centered model that provides choice, project based learning, opportunities for student interaction and active learning. Current best-practices in education, which encourage problem solving and critical thinking as key components of the learning process, should be employed.

Due to the technological advances in the IT industry around the world, the need for better project management skills is becoming more evident. Hartenian *et al.* (2001) pointed out that there is need that construction schools strive to improve the course offerings that incorporate the issues of complex dynamic environment. They particularly pointed out that the graduate students do not possess required knowledge of project management related skills. Arain and Tipu (2009) wrote that the issue of lack of project management skills has been realized by many technical schools and

there is encouraging sign that schools are considering developing a complete project management curriculum addressing key competencies sought by the industry.

Management decides and implements the ways and means to effectively and efficiently utilize human and non human resources to reach predetermined objectives (Bryde, 2003). Project managers are expected to marshal resources to complete a fixed-life project on time, on budget, and within specifications. Project managers are the direct link to the customer and must manage the interface between customer expectations and what is feasible and reasonable (Arain, 2005a). They provide direction, coordination, and integration to the project team, which is often made up of part time participants loyal to their functional departments. Project managers must ensure that appropriate trade-offs are made between the time, cost and performance requirements of the project (Arain and Low, 2003; Arain, 2007). At the same time, project managers, unlike their counterparts, generally enjoy only rudimentary technical knowledge to make such decisions. Instead, they must orchestrate the completion of the project by inducing the right people and resources, at the right time, to address the right issues and make the right decisions (Arain, 2005b). Certainly, resource optimization for successful project management is a unique and challenging task. Choudhury (2000) pointed out that the underlying reasons of the issues, such as time delays and high cost, could be lack of knowledge of the project management skills.

Many researches indentified the competencies for construction education that assist in increasing employability of construction professionals. The competencies include project management, leadership, business skills, professionalism, construction acumen, contracts management, research, communication skills, conflict resolution skills, cost management, procurement management, risk management, building techniques, technological skills, teamwork, ability to learn and global project management (Choudhury, 2000; Kay, 2001; Hartenian *et al.,* 2001; Babcock and Morse, 2002; Turner and Muller, 2003; Arain *et al.,* 2004; Conrad and Sireli, 2005; Karmer, 2005; Arain, 2007; Arain, 2009; Arain and Tipu, 2009).

The studies above discussed many competencies for construction education for enhancing employability of young professionals in the construction industry. The literature study assists in compiling a list of competencies for undergraduate construction education, as shown in Table 1.

Table1: Competencies for baccalaureate level construction education for enhancing employability of young professionals in the construction industry

SNo.	Competencies for Baccalaureate Level Construction Education
1.	Project Management: *Apply principles of project management to plan, scope, schedule, cost, resource, complete and evaluate construction projects*.
2.	Leadership: *Assume leadership role within teams to achieve the intended outcome.*
3.	Business Acumen: *Apply knowledge of business processes, organizational structure, management principles and financial requirements to core business*

SNo.	Competencies for Baccalaureate Level Construction Education
	practices such as human resources, business operations, financial management, information systems, organizational behavior, business negotiations and law.
4.	Professionalism: *Integrate professional and ethical responsibilities that contribute to a safe and positive working environment*.
5.	Construction Acumen: *Interpret plans, drawings, shop drawings and materials information documents for different types of construction projects*.
6.	Contracts Management: *Prepare and negotiate contracts common to construction projects and the construction industry*.
7.	Research: *Apply research and analytical skills to solve problems within construction projects*.
8.	Communications: *Communicate effectively in both written and oral forms to a variety of audiences in a professional and ethical manner*.
9.	Conflict Resolution: *Apply conflict resolution strategies to resolve current and emerging conflict*.
10.	Cost Management: *Utilize current technologies and established practices to plan and manage construction budgets*.
11.	Procurement Management: *Incorporate procurement management skills to evaluate and select bids for materials and skills needed to complete construction projects.*
12.	Risk Management: *Incorporate risk management skills to evaluate and select construction projects*
13.	Building Techniques: *Demonstrate a robust knowledge of building techniques and construction methods*.
14.	International Project Management: *Differentiate and apply the management strategies and requirements for local versus international projects*.
15.	Technological competency: *Apply recent technological knowledge to manage projects.*
16.	Teamwork: *Assume various roles within teams to achieve an intended outcome in a professional and ethical manner.*
17.	Ability to Learn: *Demonstrate a capacity to learn through formal and informal methods, in order to confirm and extend their knowledge and skills when addressing new or emerging challenges.*

The literature study forms the basis for the questionnaire survey to collect information on industry's perspective on construction professional competences. The study is a unique research that identifies the competencies for baccalaureate level construction education for enhancing employability of young professionals in Canadian construction industry for the first time. The study sets the foundation for future larger research study on identifying competencies for baccalaureate and graduate level construction education on a larger scale.

RESEARCH METHODOLOGY

Through the above literature review, the 17 competencies for construction education for enhancing employability of young professionals in construction industry were identified. These provided the basis for the formulation of a questionnaire.

A survey of 32 professionals from the Albertan construction industry was carried out. They included vice-presidents, directors, senior managers, project managers, construction managers and project engineers. A total of 32 questionnaires were distributed personally to the respondents, together with an explanation on the purpose of the study and assuring them of anonymity.

In addition to collecting information via the questionnaires, face-to-face discussions using the questionnaires were also carried out to ensure that all questions were answered and the respondents have a chance to clarify any doubts with the research team. A 5-point Likert scale was used in the questionnaire to gauge the most important competencies for baccalaureate level construction education for enhancing employability of young professionals in the industry.

BACKGROUND OF RESPONDENTS

A total of 32 professionals were asked to gauge the importance of the competencies using a 5-point Likert scale. They included 14 professional from contractor side, 11 from consultant side, 3 from academia, 2 from governmental organization, and 2 from professional association. Table 2 shows the details of the responses.

Table 2 Survey response rates

Respondents	Responses received	Interviewed	Percentage
Contractors	14	14	43.76%
Consultants	11	11	34.37%
Academia	3	3	9.37%
Governmental organization	2	2	6.25%
Professional Association	2	2	6.25%
Total	32	32	100%

As shown in Table 3, of the 32 professionals interviewed, 5.25% were vice presidents, 21.87% were directors and 34.38% were senior managers. 18.75% of the interviewees were project managers, 12.50% were construction managers, and 6.25% of the interviewees were project engineers. Professionals were involved with the construction industry for more than 10 years; therefore, they were likely to be better able to assess the employability issues and graduate competencies sought by the construction industry. As a majority of the interviewees were professionally positioned at management level or higher, a certain level of accuracy in the data collected was assured.

Table 3 Professional interviewees' statistics

Respondents	Appointments	Responses received	Percentage
Professionals	Vice Presidents	2	6.25%
	Directors	7	21.87%
	Senior Managers	11	34.38%
	Project Managers	6	18.75%
	Construction Managers	4	12.50
	Project Engineers	2	6.25%
Total		32	100

ANALYSIS OF RESULTS

The data collected from the 32 questionnaires was analyzed statistically. As shown in the Table 1, the 17 competencies for baccalaureate level construction education for enhancing employability of construction professionals were identified from the literature review and feedbacks from the professionals in the construction industry. The questionnaires containing 17 graduate competencies and section for feedback (additional competencies) were provided to the professionals involved in the construction industry. The competencies for construction education for enhancing employability of construction professionals were analyzed and ranked according to their responses. As shown in Table 4, the 17 competencies for baccalaureate level construction education were tabulated according to their means and standard deviations.

Table4: Competencies for baccalaureate level construction education for enhancing employability of young professionals in Canadian construction industry

S No.	Competencies for Baccalaureate Level Construction Education	Mean	Std. Dev.
1.	Project Management	3.62	0.64
2.	Leadership	3.62	0.58
3.	Business Acumen	3.56	0.64
4.	Professionalism	3.48	0.75
5.	Construction Acumen	3.64	0.73
6.	Contracts Management	3.14	0.59
7.	Research	3.22	0.64
8.	Communications	3.39	0.83
9.	Conflict Resolution	3.18	0.67
10.	Cost Management	3.21	0.92
11.	Procurement Management	3.07	0.58
12.	Risk Management	3.11	0.70
13.	Building Techniques	3.32	0.77
14.	International Project Management	3.25	0.65
15.	Technological competency	3.07	0.73
16.	Teamwork	3.11	0.70
17.	Ability to Learn	3.18	0.64

Furthermore, the competencies for baccalaureate level construction education for enhancing employability of young professionals in the construction industry were categorized into the most important ones as shown in Table 5. The results suggest that the construction acumen, project management, leadership, business acumen, professionalism and communications were considered to be the top five most important competencies for baccalaureate construction education for the construction industry in Canada.

Table5: Top five competencies for baccalaureate level construction education for enhancing employability of young professionals in Canadian construction industry

S No.	Competencies for Baccalaureate Level Construction Education	Mean	Std. Dev.	RANK
5.	Construction Acumen	3.64	0.73	1.
1.	Project Management	3.62	0.64	2.
2.	Leadership	3.62	0.58	2.
3.	Business Acumen	3.56	0.64	3.
4.	Professionalism	3.48	0.75	4.
8.	Communications	3.39	0.83	5.

DISCUSSION AND CONCLUSIONS

The study results showed that all program competencies were considered important by the respondents. It is revealed through in-depth interviews that employers expect construction graduates (young professionals) to possess the key competencies to be beneficial part and prosper in the construction industry. The construction acumen was ranked as the most important competency for enhancing employability in the construction industry. Considering the technical nature of the construction project management discipline, this was not unexpected. Many research studies have suggested that the construction acumen is the foremost skill that is sought by the construction industry. It was revealed through in-depth discussions with the professionals that ability to interpret plans, drawings, shop drawings and materials information documents for different types of construction projects is an integral skill that construction graduates should possess to be a beneficial part of the construction industry.

Project management and leadership were jointly considered as the second most important competency for baccalaureate level construction education. The graduates of the construction project management baccalaureate program are expected to demonstrate sufficient knowledge of principles of project management application to plan, scope, schedule, cost, resource, complete and evaluate construction projects. Project management is all about providing efficient leadership at every level of the

construction projects. Young construction professionals should be able to assume leadership role within teams to achieve the intended outcome.

The results revealed that business acumen was perceived as the third most important competency for young construction professionals. Business acumen would help construction professionals to participate in the construction organization beyond the implementation and management of construction projects. It was acknowledged by the professionals interviewed that construction graduates should be able to apply knowledge of business processes, organizational structure, management principles and financial requirements to core business practices such as human resources, business operations, financial management, information systems, organizational behavior, business negotiations and law.

Professionalism and communication were considered fourth and fifth most important competencies for construction graduates respectively. It is evident that the construction industry requires professionalism as an integral component to encourage a conducive and professional environment. Construction graduates are expected to have ability to integrate professional and ethical responsibilities that contribute to a safe and positive working environment. Effective communication is an important attribute of project leadership, construction graduates should be able to communicate effectively in both written and oral forms to a variety of audiences in a professional and ethical manner. Construction education should address to these required competency to produce career ready professionals for the local and global construction industry.

In the face of this changing economic environment, existing and upcoming professionals in the construction industry must be adequately trained to adapt to different markets and cater to regional demands in a more internationalized market. The skills needed to be successful in the international market such as project management skills, construction acumen, professionalism, business acumen, construction laws and regulations, communication, and cultural knowledge will become increasingly vital for construction industry professionals who wish to compete in the global arena. Present student generation in construction-related disciplines is well aware of the changing market conditions ahead and realizes that they need to reach out to developing regions to expand and build their careers.

Academic institutions now realize the need for courses in global project management, language skills development as well as working environments, laws and regulations in emerging markets. Nevertheless, additional efforts are required for further adjustments to their curricula in response to this emerging need. Incessant pace in education development to train students in construction-related disciplines for working in local and global, emerging markets can help add a degree of flexibility to their arsenal, enabling them to have fewer restrictions, thus opening a wider venue of opportunities for them. This added flexibility can reduce the chances of construction professionals leaving the field for other professions, thus ensuring a more constant and stable supply of human resources. Overall, these combined advantages will ultimately lead to a healthier industry and promote a better image for the entire profession. It is recommended that the breadth and depth of the core's syllabi ensures sufficient

coverage of fundamental and extended topics on construction project management. Construction programs should help to equip our students better to participate in the local and global construction industries that await them. The findings from this study would also be valuable for all professionals, academicians and researchers involved in the area of construction education in general.

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Interdisciplinary Team Learning in the Context of Integrated Design Studio

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Abstract: Scientific literature and practical experience point out fragmentation of the building design process as one of the reasons for ineffective design and construction processes. This paper proposes interdisciplinary team learning in the context of an integrated design studio as a successful approach for both: achieving sustainable design solutions and transforming disciplinary cultures into integrated practices. In a rather unique collaborative experience based on strategies from situated learning and activity theory, students with different design and construction backgrounds were placed in multidisciplinary (co-located) teams to work on a real architectural project with specific requirements for sustainability. This integrated design studio was timed in three intensive 2-day *charrettes*. A coherent digital environment for integrated design was proposed in order to meet the needs of the multidisciplinary teams. The results from this experience were very positive in respect to both individual and team learning.

1. Introduction

Scientific literature and professional experience point out one of the reasons for ineffectiveness in construction is due to a bi-directional fragmentation of the building design process: horizontally (between disciplines contributing to the project) and vertically (along the time axis, between different phases of the project). Environmental design requires the participation of a number of experts early on, thus adding complexity to the process. According to a recent bibliography authored by Sanguinetti (2009), Building Information Modeling (BIM) aims to provide an integrated model (common & unique) of a projected object which is meant to optimize the design process and facilitate the interactions between specialists by concentrating them around one (digital) object. Thus, the purpose of integrated design process is to increase productivity (Eastman et al. 2008) and to stimulate innovative solutions (Egan 1998).

This transformational process is essentially lead from within design and construction practices. Pedagogical strategies remain limited by traditional methodologies which do not address the unique expertise and requirements of

integrated design demands. The respective expertise of students combined with effective and collaborative tools are essential to engage in an integrative approach to design. In this paper, the authors discuss the main findings of an experimental and environmental design studio that intertwined architecture and civil engineering. More specifically, this study asks the following research questions:

- How does a multidisciplinary design studio influence team learning in terms of team organization, collaboration, (individual) design strategies and project definition?
- How commercially available software maps to the needs of a multidisciplinary team in a context of co-situated design?
- How "integrated" was the design experience of the *Maison des étudiants* (MDE)-project studio? What was integrated and what was not?

The design proposals were presented publically and (according to the voting results), were well received by the student community and were well evaluated by the instructors. For the purposes of this research, though, the importance is put on the process rather than on the result. The best indicator of the success of this teaching experience is considered the learning that has occurred on individual and on team levels. First, scientific work related to the research is presented. Second, the context and the methods of the study are described. Third, data is discussed in the light of each research question. Finally, some conclusions and proposals for future research and pedagogy are put forward.

2. Related work

The studied phenomena are complex and therefore require a variety of complementary viewpoints. The following section focuses on some of them, namely: learning, collaborative design, transformational learning and technological environment.

On learning

Design studios are the traditional form of teaching architectural design at universities. Trying to recreate the environment of an architectural office, they exploit the method of "learning by doing" (Schön 1983). Studios are traditionally uni-disciplinary (with some rare exceptions). Conversely, engineering students do not go through the same type of education and thus, do not build a 'studio' culture. This leads them to different methods of work (compared to architects) from a cognitive point of view (Cross 2006, Lawson 1980). For the purposes of designing a sustainable building, multidisciplinary teams have the greatest potential for optimisation and innovation of a design solution (Blackler and Crump 2000). Even more, according to the socio-constructivist theory of the historico-cultural nature of learning (Vygotsky 1978), such a context creates a fertile context for learning. That is why this teaching approach was chosen for the MDE-project design discussed in this article.

On collaboration during design

Much research has been undertaken on collaborative design, especially on remote collaboration. Recently, interest in co-situated and technologically-assisted collaboration has gained prominence because multidisciplinarity is essential to achieve a successful integrated design process and because multinational teams require that spatially dispersed designers contribute to a specific project.

As sustainable building design is one which combines efficiency in building performance, economy and socio-cultural impact, it requires the implication of

various specialists. As the most important decisions for a project are made in the initial conceptualization phase (and errors at this moment are the most costly), multidisciplinary teams are summoned to work together from the very early stages of the design project. This process of integrated design is successfully applied in other domains of production for a long time now (Forgues and Eugenie 2009). Some avant-garde AEC companies integrate in their design teams various specialists at the conceptual phase of the project. Such a collaboration requires considerable transformation in the professional traditions of the AEC professions (Backler and Crump 2000, Carlile 2004).

In a large qualitative research (ethnological enquiry) on a co-situated multidisciplinary design team of professionals, Tory et al. (2008) study the role of physical and digital design artifacts during the design-collaboration process. The authors analyze the interactions between team members, find various bottlenecks in the communication via digital technology and propose some simplifications for better use.

In a co-situated collaborative learning environment, Fruchter (1999) proposes a new metric for cross-disciplinary learning as a "journey from the state of island of knowledge (discipline-centric) to a state of understanding of the goals, language, and representations of the other disciplines". This approach helped establish the basis for the evaluation of our multidisciplinary design studio learning.

On boundary objects and transformational learning

Multidisciplinary design sessions immerse students in a context of knowledge sharing and situated learning around their project while manipulating various kinds of representations of the building-to-be. The concept of *boundary object* identifies a specific mediating artefact that will help represent, learn about, and transform knowledge to resolve the existing contradictions at a given juncture between two or more disciplinary 'communities' (Star and Griesemer 1989). Authors of this paper have previously reported on the augmented role of digital boundary objects compared to physical ones in the framework of multidisciplinary design processes (Forgues and Eugenie 2009).

Activity theory, a social learning theory that uses mediating artefacts to systemically study the role and influence of boundary objects on practices and organisations. It has its roots in Vygotsky's theory of social learning. An *activity* is viewed as a mutual learning process in which people interact through mediating objects to achieve a common outcome.

Transformational learning occurs when teams successfully achieve a shared mental model. According to Engeström's (2002) theory of expansive learning, joint design activity is characterised by a community of multiple points of view, traditions and interests. When participants join a team, they bring their own diverse histories, and the activity system itself carries multiple layers and strands of history engraved in its artefacts, rules, and conventions. Conflicts and contradictions between various perspectives are sources of change and development that trigger transformational learning. They accumulate and hence, create structural tensions within the system. As the contradictions of an activity system are aggravated, some individual participants begin to question and deviate from the established norms. Expansive transformation occurs when the members of the activity system embrace a radically wider horizon of possibilities than in the previous mode of the activity. Boundary objects can serve as enablers or drivers of this transformation by facilitating generative learning at a given

boundary. Simulation tools are an example of an innovative technology that encourages the creation of new knowledge between novices and specialists by graphically expressing complex problems (Dodgson et al. 2005). Engeström (2002) suggests the introduction of new boundary objects – a new technology for example – in order to destabilise existing practices and push them to radically explore new ways of achieving the expected outcome. Building Information Modeling (Eastman et al. 2008) provides technological basis for the creation of project representations functioning as a boundary object to bridge information and knowledge between practices in construction. This approach is put into practice in the context of the current integrated design studio.

On technological environment

Technological environments represent a strong avenue for design learning and practice (Jabi 2004). As a concept, BIM has the potential to revolutionize construction and help environmental design become easily accessible (Krygiel 2008). Some governments require the use of BIM for public projects. Nevertheless, its implementation is rather heavy and demands greater technical resources (in terms of information and calculating power), which renders its access difficult for small practices. In addition, the interoperability of the different modules or software remains fragile and time consuming. Energy, cost and life-cycle simulations are mostly separated from the main modeling software (Eastman et al. 2008). Architects state that it is difficult to nurture creativity in such an environment (Yessios 2006). Yet, it offers new integrating and simulation functions, inaccessible through other forms of representations by now. That is why the use of BIM-enabled software for the purposes of integrated design was encouraged. Other modeling programs (SketchUp, Rhino 3D and 3D-Max) were used during the ideation process or for representation of the project.

3. Design studio context

The research project was conducted in the context of a multidisciplinary design studio combining students in architecture (from McGill University's School of Architecture) and students in civil engineering (from the ETS-Montreal) to work on a real design project. The proportion of work expected from students in the different disciplines, and the number of interested students in taking the course (13 students in their first year of a master's level in architecture and 24 undergraduate students, usually in their final year of engineering) lead to the following composition of each of the 5 teams: 2 or 3 architects, 2 or 3 engineers in building mechanical systems, 1 or 2 cost estimation engineers and 1 structural engineer, for a total number of 7 or 8 (which is the limit for a self-managed team). Their motivation was clearly expressed before the beginning of the studio and their engagement in the project was evident. Each team was allocated an individual space equipped with a PC, Internet and a local network access, a projector and a printer. Additionally, students brought their personal computers (mainly laptops). A communication board was provided in the form of either a vertically standing interactive (smart) board, an interactive tablet or a white board.

The cluster organization of the tables provided an optimal configuration for teamwork, especially successful in the collaboratory of the ETS. The work-area of the other spaces was more flexible and the organization depended on the available furniture. Some configurations (big round table) were more favorable to teamwork than others (two or more clusters) and had an impact on the frequency

of the discussions in which all the team participated (one cluster favors the higher frequency).

The work was organized into three intensive *charrettes* of two days with two-week pauses between them. Information sessions and software capsules were offered in-between the *charrettes*. As the workload was quite heavy, students were not required to work between the sessions. Nonetheless, instructors expected them to practice and familiarize themselves with the presented software but this did not happen. The three-stage organization helped provide substantial feedback to the students and encouraged them to propose new solutions at each stage, thus inciting innovation and creativity (as reported in another paper on the ID-framework of this studio (Forgues et al. 2010). In terms of input from the tutors, it was limited to a minimal frequency feedback in order to allow the students to self-organize and learn from the other disciplines. This organization was pertinent, but somewhat insufficient for some of the disciplines. Inputs from specialists in sustainable technologies and techniques were highly appreciated.

The students had access to technology that helped: (1) facilitate collaboration through the use of TeamSpot and interactive-board or tablet software, and (2) assist knowledge sharing and the evolution of the building design through AutoCAD 2010, Revit Architecture 2010, SketchUp, Ecotect Analysis, Design Builder and D-Profiler. While the architecture students had good knowledge of CAD and digital modeling (but were less familiar with Revit and Ecotect), most of the students in engineering were novices to software tools. This is an important difference, because previous research has shown that often, who 'possesses the tools' leads the team (Forgues 2009).

The project, a student centre for the ETS is an actual project with a complex program including: a soccer field, a hockey arena, a swimming pool and an underground parking, in addition to the administrative, health and leisure services for the students. A variety of structural, systems-organisation and spatial challenges compose this building. The requirements for sustainable building were fundamental.

4. Methods

According to the specialized literature, quantitative research methods are inappropriate for research on design processes and especially on collaborative design (Fruchter and Emery 1999, Backler and Crump 2003, Cross 2006). Due to the complexity of the studied processes, this research relies on qualitative methods inspired by grounded theory and case study (Creswell 2007, Glaser and Strauss 1967, Yin 2004). Rich and extensive data was gathered by: 1) camera recordings of the *charrettes* and the public presentations, 2) semi-directive interviews and 3) questionnaires. As this is a participative research, the observations of the instructors are taken into consideration.

Mainly based on the interviews and on the questionnaires, inspired by the methodology used to evaluate collaborative learning (Fruchter and Emery 1999), after the first and last *charrette*, the students were asked the question: *How do you estimate (at this moment) your level of knowledge of the work of your colleagues from the other disciplines?* Four levels were defined and proposed as answers: (1: islands of knowledge): *I master my discipline, but do not have experience in the other disciplines represented in our team.* (2: awareness): *I am aware of other disciplines' goals and constraints.* (3: appreciation): *I am interested to understand and support the other disciplines' goals and concepts and know what questions to*

ask. (4: understanding): *I can negotiate and I am proactive in the discussion with other disciplines, I provide input before the input is requested, and begin to use the language of another discipline.* The students were asked to justify their answers. A final question was asked: *After this experience, do you plan to take any courses in any of the other disciplines? Which topics?*

5. On situated learning

Judging from the general attitude and from the interviews, the students have shown a very high overall satisfaction from the multidisciplinary studio experience. All of them have stated having learned a lot from their colleagues: on their working habits, on the aspects treated by each discipline and on the way to collaborate. Answers on the level of knowledge of the work of the other disciplines showed a manifest but not drastic increase of the 'level' after the third *charrette*, compared to the first one (average values: 2.47 to 3.31). We speculate that this is due to (at least) two factors:

(1) the fact that the first questionnaire (Q1) was given after the first two days of intensive design sessions, and not at the very beginning, so there was already some learning even before it (here is an example form Q1: *I am **now** aware of the dynamics of the other disciplines **and was able to learn** new ways of thinking and attitudes from them.*) The researchers were aware of the shortcomings of the questionnaire' timing but wanted to present it together with another one meant for a different research in order to minimally disturb the students.

(2) the effect of 'learning' during the studio: at the end of the third *charrette* the students know more about the work of the others, but have a better understanding of the large quantity of knowledge manipulated by their colleagues (i.e., they know of what they are ignorant).

The diagrams on Figure-1 present the distribution of the four levels of knowledge as reported in Q1 (in blue) and in Q2 (in red). The diagrams in the center and to the right show different patterns for architects and for engineers. The fact that a large number of students in engineering have stated having an "understanding" since the very beginning, in our opinion, demonstrates that they were not prepared enough for conceptual design.

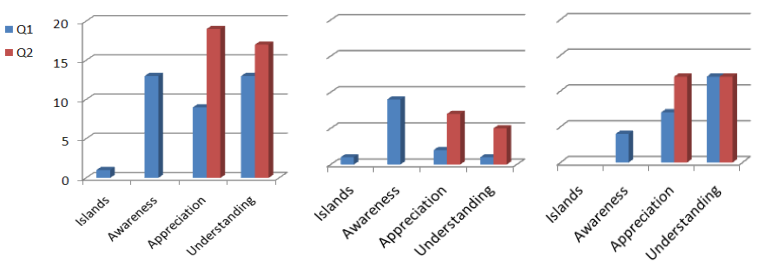


Figure 1: Levels of knowledge of the work of the other disciplines: (left): general for all disciplines; (center): students in architecture; (right): students in civil engineering.

The differences observed between the teams are negligent. The distribution per disciplines shows a more important increase of the level for engineers (2.57 to 3.46) than for architects (2.28 to 3.04).

Here are some examples of the justifications given by the students: architect, showing awareness (2) at the beginning and proactive participation and comprehension (4) at the end:

- Q1: *I have a good understanding of their work without necessarily understanding the material processed by these specialists*
- Q2: *I am interested to understand and to learn this language and the technical concepts behind mechanical and structural systems. I learned a lot with this project. The team was very well integrated.*

The interest in taking additional courses slightly decreased after the end of the multidisciplinary experience. In our opinion, this demonstrates that what has been learned throughout the project has filled in gaps of knowledge for several team members. Many students have answered this question as such: «*Not necessarily, but I wish to do integrated design projects»,* which means that the multidisciplinary studio experience gives them valuable knowledge and can replace a course in another discipline. In general, students expressed an interest in taking courses in the following areas: sustainability, BIM, and simulation software.

The justifications given by the students witness for some other aspects of their experience too. For many engineering students, this was a first contact with a design process and they showed special interest (even fascination) to architectural design and its creative aspects: (1) *I would like to learn about architectural trends. If I was younger, I would take up studies in architecture;* (2) *Architecture is a fascinating domain* ...Another testimony: *My knowledge of the work of my colleagues from their disciplines has improved over the course of this project, and as such I have become more interested in their work. It also helped me communicate with them in a more efficient manner.* On developing common language and project strategies: *The hard work of structuring and organizing ideas forces me (in a positive way) to use a common language, and gives me a (general but improved) understanding of the topics.*

The subject of the differences in the way of working for engineers and architects reoccurred consistently during the *charrettes.* Here is very significant statement coming from an architectural student: *I am aware of what they are doing but I wish they would suggest directions for development (related to their interests) more often.* The fact that engineers are used to (maybe even taught to) "make (a design decision) work" and to simply analyze and dimension elements, does not fit onto an integrated strategy of design. That is why, at the beginning of the design sessions, the engineers were "waiting" for the architects to give them a design to analyze and "make work". The different cognitive models of study and work of engineers and architects (verbal & analytic *versus* visual & holistic) are pointed out by Lawson (1996) and Roberts (Roberts 2006). The integrated design studio proves to be an appropriate experience for decreasing these differences or at least make them explicit.

6. On the use of digital means and its present limits

Throughout the duration of the integrated studio, instructors encouraged the use of digital technology and especially BIM software with the objectives to facilitate team work and the workflow of multidisciplinary information. It is necessary to mention that the technological setting of team #3 was more stable because it is permanently installed. Other teams occasionally encountered technical problems that were repaired in a short amount of time, nonetheless the interruption in the

collaborative design process prompted students to turn back to some "good old" ways of doing.

Technology for facilitating team work. Interacting through a SmartBoard was surprising and motivating for the students. Judging from the partial data analysis, this way of communication was mainly used during the first *charrette* after its use was demonstrated, but referring to the interactive functions increasingly became seldom. Projecting and writing on the white board was especially appreciated by the students.

TeamSpot, a collaboration program with various possibilities to communicate, show content, and exchange files, can enable a team member to "take possession" of the computer of another member (upon his agreement), to use his programs, and to project the files on one's screen, annotate them and keep traces of the discussions held, etc. Some limitations of this program were found, mainly due to the rather high number of participants trying to access the projected screen at the same time, or because of the intensive memory and processor requirements of the CAD and BIM software used simultaneously.

BIM and simulation software. Prior to the integrated studio, a special effort was made to put together a BIM environment in order to facilitate the project data workflow. As the commercial software are yet far from offering an unified and fluid environment for integrated design, it was proposed (1) to begin the project by creating schematic models in different specialized software (Rhino, SketchUp or Revit-massing for the architectural design; D-profiler for the cost estimation and Design builder or Ecotect for energy simulation); (2) to continue the project in Revit Architecture; and (3) to export this model to D-profiler, DesignBuilder and Ecotect for iterative analyses following the design modifications (and proposing such modifications based on obtained simulation data). We encouraged the students to repeat these cycles, to a greater or lesser extent, during each *charrette.* This scenario was conceived with the purpose to give consistent and continual project feedback after each iteration and to encourage a reconsidering of the building design, thus stimulating creativity and incorporating innovation.

It seems though, that, experiencing time pressure, the students (1) progressively abandoned the use of different technologies because they were not familiar enough with them, and (2) preferred to stick to the design idea (*parti*) from the very first *charrette* in order to have time to develop it and to represent it in greater detail.

Two other factors created difficulties: (1) the software were briefly introduced to the students shortly before their use was required. This did not give them the possibility to acquire an appropriate ease of use during design. (2) the interoperability between Revit and the other modeling and simulating tools is both incomplete and very fragile. Simulation calculations are quite time-consuming, especially for heavy models.

Another shortcoming is that simulating software tools rarely have an output to modeling software, and almost never have generative abilities (i.e. cannot propose a more optimal solution or a new form, but can only analyze a given design model). This means that interdisciplinary learning can occur based on the technological environment, but new knowledge creation would occur mostly outside these software programs.

7. Integrative aspects of the multidisciplinary design studio

A major objective of the multidisciplinary studio was to provide an appropriate context for situated learning of integrated design process. The organization of the design process was new to the students. Judging from partial results from the interviews, from the direct observations of the researchers, as well as from the results presented by the students, 'horizontal' integration was considerably successful. The disciplines of all team members influenced the design proposition, thus proposing sustainable design solutions.

The design tasks were relatively well planned at the beginning of each *charrette* during a 'brainstorming' discussion. Then, periods of working in discipline-specific groups were followed by general discussions. In most of the cases communication was fluid and direct. Team #3 tried a temporary organization into 3 mini-multidisciplinary teams which worked in parallel for several hours. The results from this experience were of great value to the team.

Most of the teams continued to communicate between the *charrettes*, mainly via Internet. Communications intensified as the final *charrette* approached. Team #3 physically met for a discussion during this period.

Different kinds of representations of the design object were used. BIM models were partially used, sometimes with difficulties due to inadequate interoperability or lack of knowledge and limited software practice. Free hand sketches were mainly used by the architects to explain their ideas to students in the other disciplines. In developed stages of the project, models were built (sometimes 3 different models were made: for photorealistic renderings, for simulations and for the layout of the building). The lack of time was given as an explanation for not working on a main and unifying Revit model. They had to choose to deliver a reasonably good result, or to learn to work with BIM.

8. Conclusion and proposals

Through this research we could answer the questions asked at the beginning of the paper. Findings reveal a very satisfactory level of collaborative learning during a multidisciplinary design studio. Cross-cultural influences and interdisciplinary understanding helped creating a fruitful experience for the students.

As for the technological framework, an additional effort is necessary by software industry and by instructors in order to combine creativity and building performance under the same digital environment. As simulation software tools do not generate design proposals, they are limited to analytical aspects of the project, whereas designs create spaces (Iordanova 2007). In consequence, a future integrated design studio could envisage the integration of a collaborative environment as developed by (Muramoto et al. 2009). These researchers aimed to define a collaborative digital environment which can meet the conditions of "possibility for a creative design process". The ability of this environment to cohabit together with BIM-enabled models could be evaluated then. The level of collaborative learning and creativity could be assessed.

Design proposals elaborated by the teams were well received by potential future end-users. Based on this, as well as on the sustainable strategies used, this experience can be considered a successful "integrated design process". Hence, future research can lead to defining the outline of other similar design studios, and to expending this experience to the professional practice and the industry.

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Repositioning the Faculty Internship Experience in Construction Management

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Abstract:
Previous studies have confirmed that industry internships help young faculty sharpen their teaching portfolios. Few studies, however, have explored the potential of research enhancement and the benefit that industry sponsors gain from the internship experience. This paper discusses how industry internships impact: (1) junior faculty's scholarship, and (2) industry sponsors' work. The paper presents an analysis of the authors' internship experiences through case studies with supporting data obtained from interviews involving industry personnel. The analysis suggests that an industry internship can, besides improve teaching methods, enhance the richness, quality, and scope of scholarly research and support industry sponsors. The paper also discusses a successful internship strategy and how the internship experience can be tailored to different faculty research areas. In the end, recommendations to guide future faculty internship programs are presented.

1. Introduction

In the practice of construction engineering and management (CEM), professionals cultivate clients, execute technical and managerial tasks, and juggle the demands of fast-paced project schedules and questions from and for colleagues, contractors, suppliers, designers, owners and users. Although some parallels can be made, the varied demands of full-time tenure--track faculty members in CEM are quite different than those in the industry. Faculty are expected to achieve proficiency in teaching and to learn pedagogical methods through self-study and in-classroom trial by fire. Faculty are also expected to develop and execute research agendas while guiding graduate students through the processes of independent thinking and research methods. Lastly, faculty are expected to give their time and energy to the department, the college, the university, and the community.

For faculty in the professional disciplines such as CEM, there is an additional expectation – they are expected to have had some work experience in the field and then continue to remain current while teaching, conducting research and doing service. Industry experience ranges from an informal expectation to a formal requirement in CEM programs. The accreditation boards insist on and support a balance between

academic research and industry practice. According to the Accreditation Board for Engineering and Technology (ABET), a construction program must have at least one faculty member who has had full-time experience and decision- making responsibilities in the construction industry (ABET, 2006). For the American Council for Construction Education (ACCE) accreditation, the council states that, "Evaluation of faculty competence must recognize appropriate professional experience as being equally as important as formal educational background." (ACCE, 2009)

Although in each department, there are faculty who have extensive industry experience, there are a growing number of faculty members who have little–to-no field experience. A study done by McCuen (2007) pointed out that only 21% of tenure-track faculty job announcements in the area of CEM in 2006 required any industry experience in addition to a Ph.D. degree. This is striking when compared to the period between 1992 and 1994 where 71% of faculty job announcements in CEM required industry experience but not a Ph.D.(McCuen, 2007).

While a handful of previous studies (see Section 2) have confirmed the educational impact of faculty internships in professional disciplines, it is not clear what strategies could be used to launch, embolden or even enhance research agendas through faculty internships for a discipline such as CEM that is very much an applied science. Models from the disciplines of medicine and law, where most faculty have practiced and continue to practice as a medical doctor or as an attorney (Gunderson & Gloeckner, 2006), might not be applicable to CEM as fewer construction programs are making industry experience a job requirement (McCuen, 2007). Schools of Architecture, Art and Design also often have faculty who are actively practicing their profession, and those activities constitute scholarly work that takes the place or complement research in the Teaching-Scholarship-Service triad. For junior faculty in CEM, for whom many faculty internship programs are focused, it is a dilemma whether they should pursue professional practices since the associated benefits in research enhancement are not self-evident and professional practices can distract the faculty from other activities more closely associated with tenure and promotion.

Incentives for the industry sponsors present another issue. With student interns, companies seek to cultivate future employees, and have a business motive for investing time and effort in on-the-job training and education. This same motivation is not there for faculty because the benefits are one step removed from the host firm who seeks to gain some value from a faculty's presence in their company. At the end of the faculty internship, the company cannot hire the faculty member as a full time employee (or at least that is not the goal of the program), so the benefits of training the faculty member are not as clear and immediate. One can argue that the internship experiences will be brought into the classroom and improve the education for all students, some of whom will then be hired by the company. However, for the company to support a faculty internship project, academia often needs to be able to present a more immediate value to the company above and beyond educational service.

The challenge then is to align the faculty member's research interests and industry experience goals, and the needs of the hosting company.

The authors participated in the faculty internship program at the Department of Construction Management (CM), University of Washington (UW) and were interested in addressing the following two questions associated with the faculty internship experience:
(1) How does the experience impact the faculty member's scholarship and research?
(2) How does the experience impact industry sponsors?

The authors have research expertise in three different areas including, (1) building information modeling, (2) supply chain management, and (3) document management and information searching, which provided a good spectrum of insights to explore the two questions. The authors used case study observation and analysis supported by interviews with industry internship hosts as the research methodology. In this paper, the authors present the case study analysis and discuss how the internship experience impacts industry sponsors and CEM junior faculty, not only in teaching, but also in their scholarship.

2. Faculty Internship Significance

There is a proven need for faculty internships in CEM. Benefits include improved classroom instruction, enriched relationships between academia and industry, and enhanced career counseling and networking (Tener, 1996). Hynds (2000) also called faculty internships a win-win opportunity for construction faculty.

Improved Classroom Instruction
Previous studies have confirmed that internship experience helps junior faculty sharpen teaching portfolio and improve their classroom instruction in many professional disciplines, including computer science (Hartman and White 1990), accounting (Hendricks, 1993), construction engineering (Tener 1996), and business (Griffin and Homkes, 1999). "Through internships faculty can gain a better understanding of the workplace [into] which students enter when they leave the college or university environment and the skills which are essential to survival." (Hartman and White 1990) The internship experiences help faculty connect academic concepts to current practice (Hartman and White 1990), improve the practice with students experiencing practical, up-to-date classroom instruction (Hendricks 1993), and enhance the credibility of the faculty in the eyes of the students, who are looking for 'real world' knowledge they can use when they graduate (Griffin and Homkes 1999).

Enriched Relationships between Academia and Industry
Many CM programs have industry advisory councils whose companies often participate in the faculty internship program. Faculty internship opportunities enable the academic faculty to work directly with these industry professionals and enrich the connection between academics and industry (Griffin and Homkes 1999). Mutual

appreciation and understanding can lead to a stronger industry connection to the academics to support not only education but research as well. Through working with the faculty member, practitioners will be exposed to research and, hopefully this exposure will increase their awareness of research and subsequently increase the perceived value of research. The connection to industry can also develop into an ongoing resource for the faculty to draw upon for guest speakers, advice from industry as questions about current practice arise, and potentially research sponsorship.

Career Counseling and Networking
A better understanding of local industry practice and companies enables faculty to counsel students about career opportunities (Hendricks 1993), particularly those in the local job market. Furthermore, recommendations for students to industry contacts improve both the reputation of the program and the faculty's ability to advise our students about career options.

Research Opportunities and Enhancement – Where is the Niche?
"Problems identified during the internship usually are related to practical problems as opposed to theoretical projects…" (Hendricks 1993). On the one hand, CEM is very much an applied science and research questions often necessitate observations of or data collection from the industry's day-to-day operations or practices. Therefore, at the very least, working embedded in an industry setting provides an opportunity for the CEM faculty to enrich their frames of reference for research. On the other hand, faculty are trained to challenges themselves with the research topics which exhibit "intellectual merits" and can make "broader impacts", two of the main funding criteria of National Science Foundation. Therefore, the research topics rooted in the practicum of the construction industry have to be meticulously selected to avoid projects that are job-specific or business applications.

Benefits to the Industry Sponsors – Are They Larger than the Drawbacks?
According to Griffin and Homkes (1999), industry sponsors of internship programs can benefit from leveraging existing university-based centers and research outputs while the cost is shared by the university and the corporation. Hendricks (1993) also identifies three specific key ways internship sponsors benefit: 1) "providing well-educated capable employees", 2) "adding unbiased perspective to the company", and 3) "suggesting new approaches and constructive comments". In some situations, the faculty intern can host a corporate training session or sessions during residence (Griffin and Homkes 1999). However for the hosting companies, there could also be drawbacks such as time reallocation of the involved professionals, resource diversion (e.g. office space, parking, computer equipment), confidentiality concerns, and an altered work environment (e.g. complicated working culture with the presence of an outsider) (Gibson, 2001).

3. Methodology

The research relies on the soundness of using qualitative research methods, interviews and case studies in order to know how the internship experience impacts faculty's

scholarship and research as well as the industry sponsors' work. Structured interviews with participating industry sponsors were designed to obtain feedback from the hosting companies (particularly from the internship coordinators) and to see how the sponsors perceived the resulting benefits (or drawbacks) of the internship program. The data presented here includes three case studies which are built upon faculty observations and interviews of industry hosts. This enables us to reflect on how and to what extent the internship experiences launch, embolden or even enhance faculty research agendas and further industry-academia relationships through research activities.

Interview questions were initially prepared based on post-internship reviews reported in the literature (Lantos, 1994) and then subsequently refined by the authors to remove unrelated or ambiguous questions. Two additional rating questions using a 5-point Liker scale were included to identify and measure specific impacts that the industry sponsors perceived throughout the internship experience. The questions are listed in Figure 1 below. Each of the authors interviewed the internship coordinator from his or her industry sponsors in a face-to-face meeting that took approximately 20 to 30 minutes in the summer of 2009, although Dr. Dossick and Dr. Kim had their internships in Year 2007 and Year 2008 respectively. Each interviewee was given a list of the questions prior to the interview and the transcripts were taken during the interviews. All three interviewees had more than 20 years of construction experiences and held decision-making, managerial to executive level of positions at times of the interviews. The authors then assessed the feedback from interview transcripts to identify the industry perspectives.

Open-ended Questions:

1. Why did you invite faculty to do an internship with your company?
2. Before the faculty internship, what were your expectations?
3. What did your organization learn from the experience?
4. How did the faculty influence the company activities and practices?
5. How has your opinion or understanding of research and the role of research in professional practice changed?
6. What are the drawbacks to hosting a faculty member?
7. What recommendations do you have for other companies hosting a faculty internship?

Rating Questions:

1. How did the faculty influence the company?
   Individual rating criteria include "meetings", "talking to employees (informal)", "working as member of team", "conducting seminars", and "individual work output".
2. What did the faculty influence?
   Individual rating criteria include "educational/training programs", "work processes", "culture – leadership", "culture – teamwork", "creativity", and "attitude toward UW".

Figure 1 - Questions for Personal Interviews with Coordinators from Industry Sponsors

4. Case Analysis

Case A

Background: The faculty's goal for an internship was to expand her knowledge in the areas where the author had least experience – "cost control", while the industry sponsor hosting the faculty hired her for her strengths and experience in BIM research. The faculty and the internship coordinator were able to design a summer internship that both allowed the faculty to explore cost control practices while adding immediate value to the firm through research activities related to BIM. The faculty used her expertise in research to discover and study current practices in cost control and then applied them to BIM methods that provided the internship host company insights as to how they could and should adopt BIM tools for cost control as well as other applications.

Impacts on the Industry Sponsor: The hosting company had been motivated to be the leader in 3D applications in construction and was able to bridge that motivation with the faculty's expertise for its own benefit. Over the course of the summer, based on their collaboration and experience the faculty and industry host developed theory, coined here as "it's-not-one-model", and presentation graphics to describe the theory. The internship coordinator confirmed that "the interactions and the discussion have been really helpful." "… going through all the graphics and everything of IT'S-NOT-ONE-MODEL is holding so true. We are finding more and more reasons that our estimating models are just not the same as your coordination model. We are not going to share the estimating model with the field guys…somebody to go through that thought process and say 'is this model good for that purpose?'" It is clear that the faculty's presence in the hosting company has impacted the way BIM was thought of within the organization. This has also resulted in changes of philosophy in adopting the technology within the hosting company because the coordinator mentioned that "It wasn't just a matter of putting the technology in place and reviewing what needs to be done with the person (i.e. the GC MEP [General contractor mechanical electrical plumbing] coordinator), but really having a step back and saying, 'is this the right person'" After the internship program, the hosting company also made a very conscious decision to have internal critics where employees review and discuss the applications of the technology. From this end, the internship experience instituted the hosting company's internal reflection.

Impacts on the Faculty's Research Agenda: The faculty and the company employees together developed a theoretical basis to explain how the use of BIM is evolving in industry. In the interview, it became clear that this theory provided a basis for the company's BIM program. Likewise, the theory has been fundamental to the faculty's research exploration. During the internship, the faculty had the opportunity to collect data through interviews with field personnel, project managers, superintendents, as well as the home office managers. After the internship, the faculty was able to build upon the internship experience with the theory as a foundation and continued her

research along the developed theory, explored more opportunities in the BIM domain, brainstormed research questions about the way people work and the way that the technology either challenges or reorganizes the ways that people work, and obtained research funding to support her data analysis on the theory.

Case B

Background: The faculty's goal for an internship was to expand his knowledge on lean construction to the domain of lean design or pre-project planning while the industry sponsor hired him for his expertise in lean construction. The sponsor was involved in its very first lean construction project, which necessitated the need to get assistance in its lean journey from experts. The faculty joined a new lean delivery project for approximately six weeks and participated in the pre-construction process including design coordination, management coordination, and target costing. He used his internship experience to discover current practices and identify areas to be improved.

Impacts onthe Industry Sponsor: The industry sponsor launched its lean implementation in its very first lean construction project. Over a six-week period, the faculty worked as an internal member in the pre-construction group of the industry. Together with the pre-construction group, the faculty developed a lean production plan, and attended coordination meetings and target cost meetings. He also informally assessed the company's opportunities and challenges in lean implementation. Additionally, the faculty contributed to two lean construction seminars hosted by the sponsoring company and its subcontractors. The broader impact is that the lean pre-construction model has affected other projects within the company in the way pre-construction planning is managed using the lean principles.

Impacts on the Faculty's Research Agenda: The benefits to the faculty member included exposure to industry and an opportunity to update his knowledge and to extend his research area to pre-construction. Even though the faculty had more than 10 years of experience in lean implementation , his area was limited to the lean implementation during the construction phase. Only a limited number of projects have adopted lean in their pre-construction phase. The internship project was the first lean construction project where lean is applied throughout the project including pre-construction phase in the Northwest area. Therefore, the internship experience expanded his research area to the pre-construction phase and enabled him to consider the mechanics and challenges of lean principles when applied to the pre-construction phase.

Case C

Background: The faculty had the goal to observe active examples and best practices in construction safety, estimating, and project management for her teaching and student advising duties at UW. Although the faculty has the expertise and technical skills in "document management" and "information searching", the original scope of the internship arrangement did not include activities where she could specifically apply her information technology background and knowledge. The industry sponsor has a

long standing relationship with the construction management program at UW and offered to host the faculty intern as a way to improve the quality of its future employees, many of whom were educated in the CM program at UW. Therefore the internship was very education-oriented as it commenced.

Impact on the Industry Sponsor: As the internship coordinator stated "We didn't have very high expectations since it was the first time the company took a faculty as its summer intern. The original idea was that it's going to be a one-way conversation with the faculty observing most of our practices. However, it turned out to be a two-way conversation and we were able to obtain different perspectives about the industry from the faculty". The faculty had several individual assignments during her internship and some, although they were in the contexts of "bidding" and "safety violation tracking" but not document management, provided opportunities for her to exercise her research expertise in IT. One of the work products was to compile a list of sub-contractors that were certified as small, female-owned, veteran-owned, or disabled-veteran-owned businesses. The faculty demonstrated to the hosting company how her knowledge in data cleaning and enhancing could add value to delivering the work product more efficiently and effectively and how the existing method, i.e. manual compilation, could be improved. The industry sponsor was involved in the internship with the main purpose of participating in construction's future. However, the coordinator also reflected that there is a place for research in that "Construction management is a very practical business. However, the internship experience allows us to be removed from our daily practices and have an unbiased look for possible improvement."

Impacts onthe Faculty's Research Agenda: The faculty has benefited from the internship not only in teaching but also in her research development. The faculty observed how the construction industry adopted technology in its day-to-day operations and the potential opportunities for IT-based research in construction. The faculty also noticed that an abundant amount of data, which could be analyzed for useful knowledge, was not being studied or utilized. For example, one of the faculty's research interests (and challenges) is to identify ways to generate and represent construction knowledge in order to support applications such as information searching in construction. To her surprise, during the internship, the faculty discovered an existing practice within the hosting company that naturally generated and organized a specific type of data that can be converted into useful construction knowledge. This could significantly reduce the level of laborious efforts that are traditionally-deemed as necessary during knowledge compilation. The discovery has a high potential to fundamentally support a range of knowledge-oriented IT research in construction and is added to the faculty's future research agenda for experiment and validation. Last but not least, the internship provided the faculty with rich construction contexts as a foundation for her research expertise.

Ratings for All Three Cases

Table 1 summarizes the data obtained from the rating questions for the criteria that were applicable to all three cases. Criteria which received one or more "N/A" in rating

responses are removed from the summary table because they were too specific and only applicable to some cases. From the data, it is clear that all three intern faculty influenced the industry sponsors by working as member of a team and all three sponsors held constructive attitudes toward UW after the internship. These reflections also suggest that a promising faculty internship strategy is for the participating faculty to seek opportunities in which he or she could team up with employees in the hosting company, as opposed to working individually.

Table 1 Result of the Rating Questions

	Case A	Case B	Case C	Average
1. How did the faculty influence the company?				
Meetings	4	4	3	3.67
Talking to employees (informal)	4	2	4	3.33
Working as member of team	4	4	5	4.33
2. What did the faculty influence?				
Attitude toward U. of Washington	5	4	4	4.33

5. Discussion

In cases A and B, the faculty interns have research interests set in particular "construction contexts", which provide explicit opportunities to match the faculty's expertise with industry sponsor needs. For example in Case B, the faculty was involved in a specific project where the faculty expertise on lean construction was greatly appreciated. The industry sponsor obtained assistance from the expert (i.e., the faculty intern) in its very first lean construction project throughout the internship. On the other hand, the faculty achieved his research objectives through implementing his knowledge and expanding the domains of the "lean construction" knowledge to the pre-construction stage. In both cases, the faculty intern worked with a specific department or team within the hosting company and explored new issues collaboratively with his or her colleagues at the company. The impacts of the internship experiences were bi-lateral and bi-directional in both cases. In case C, the faculty intern's research area, although broadly applicable, does not fall into a specific "construction context". The industry sponsor hosted the faculty intern because of its relationship with the university. Eventually, the faculty benefited from the practices she observed, and the hosting company learned about the faculty's expertise and although it was unanticipated the company benefited from her expertise. The impacts of the internship experiences were bi-lateral but unidirectional in case C. Therefore, there are different models in which successful faculty internships can be molded and one of the model determinants is the nature of a faculty's research expertise and the goals of the host company.

6. Conclusion

Faculty internships can be a great way to add real-world experience to the classroom setting. We have found that they also enrich faculty's research experiences and thereby impact industry sponsors. Our analysis suggests that a promising internship

strategy is for the participating faculty to seek opportunities in which he or she could team up with other employees in the hosting company, as opposed to working individually. Our analysis also indicates that there are different models in which successful faculty internships can be molded and one of the influential factors is the nature of a participating faculty's research areas and the industry host's goals.

Our study helps both the CM academic and professional communities comprehend the often under-looked perspectives of faculty internships:

1. The study enhances our understanding of the faculty internship dynamics and how that leads to impacts upon academic scholarship and the industry sponsors' work.
2. The study provides a spectrum of CM faculty internship experiences to identify common and promising strategies for successful internships.
3. The study shows how internships could be designed with the faculty's research focus in mind and that it's not one model.

Consider treating the faculty internship as a research project. Just as a research proposal, the internship should be planned with a specific timeline and goals and objectives. Then, as the internship is executed, the plan evolves as discoveries are made. In the end, all parties should document and discuss the impact of the experience - perhaps resulting in internal or external publications or presentations. The authors would like to encourage all involved - faculty and industry personnel- to have an open mind about the internship and allow the researcher to explore the goals and objectives and, through dialog and work product, the discoveries of the internship unfold. Particularly for faculty, we recommend they explore their learning objectives as well as their research interests. We all found very compelling and unanticipated things at this intersection.

7. Acknowledgements

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The Need and Challenges for Interdisciplinary Education in AEC

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Abstract:

Interdisciplinary collaboration is becoming standard practice in the Architecture/Engineering/and Construction (AEC) industry. However, educational models in AEC have been slow to adjust to this rapid shift in project organization and execution. In recent years, industry leaders have expressed an increasing need for interdisciplinary professionals in the AEC industry. AEC education has great challenges ahead in order to address these needs.

This paper explores the needs and challenges for interdisciplinary education in AEC and introduces initial efforts at the Georgia Institute of Technology to meet this need. The results of a survey of students, alumni and other groups are presented as well as the analysis of data from an on-line petition. Analysis of the data collected shows that there are conflicting views of the benefits of such an initiative. However, the results also highlight opportunities for enhanced collaboration through digital tools and greater inclusion of engineering departments in the process.

Introduction:

Collaboration between multidisciplinary teams is becoming standard practice in the Architecture/Engineering/and Construction (AEC) industry. However, educational models in AEC have been slow to adjust to this rapid shift in project organization and execution. Most students in these fields spend the majority of their college years working on individual projects that do not build interdisciplinary teamwork or communication skills. When these students confront the intensively collaborative reality of today's AEC practice, the inadequacies of their education suddenly become clear. For example, a survey of architecture alumni revealed that only 46% felt their school did a good job fostering their ability to work cooperatively in interdisciplinary teams (Boyer and Mitgang, 1996). Therefore, opportunities for improvement of AEC education must be pursued.

Engineering education, as well as AEC education, has great challenges ahead. The 14 Engineering Grand Challenges proposed by the National Academy of Engineering involve energy, sustainability, medicine and health care, reducing our vulnerability to natural and human threats, and advancing our human capabilities and understanding our world and ourselves (Vest, 2008). In particular, AEC education can address many if not all of these challenges by adapting to provide learning experiences that incorporate creativity, sustainability, and interdisciplinary interactions on a greater scale.

Industry has also expressed the need for changes in curriculum to address present and future challenges for the engineering profession, such as the need for skills in an increasing global and virtual workplace, as well as the aptitude and attitude required in sustainable development, discipline-mixing, and experience-based innovation (Fouger, 2008). It is no longer acceptable for engineers to just analyze problems or mathematically derive models of problems; they must experience design, creativity, and innovation (Almgren, 2008). In order to empower the next generation of engineers, it is necessary for education systems to focus on "green engineering" for sustainable growth (Gopalakrishnan, 2008).

The National Academy of Engineering has identified the need to expand current messages about engineering beyond the need for math and science skills. These messages ignore other vital characteristics of engineering, such as creativity, teamwork, and communication (National Academy of Engineering, 2008). These last three are part of the focus of the study of the need for interdisciplinary education in AEC. Therefore, the significance of the findings discussed in this paper is the contribution to the understanding of this need, and the challenges in embarking in such an endeavor. Finally, the paper will share The Georgia Institute of Technology's experience in the pursuit of a new undergraduate education model that integrates various disciplines within the College of Architecture.

Interdisciplinary education in architecture, engineering, and construction (AEC): The concept of integrated curriculum has been discussed as early as 1937 (Hopkins, 1937). The exploration of interdisciplinary education in AEC was recommended as one of the seven goals outlined in the Boyer Report (1996). The special report by the Carnegie Foundation for the Advancement of Teaching points to the need for a "full exploration of the interdisciplinary potential for architectural education and practice", and "interdisciplinary connections to better serve society's needs"(Boyer and Mitgang, 1996). The desire and importance for reforms in engineering education has resulted in significant efforts, such as the Synthesis Coalition and Project Succeed, which emphasize reforms in multidisciplinary content, teamwork and communications, hands-on and laboratory experiences, and open-ended problem formulation and solving. Through the years, various academic institutions have experimented in interdisciplinary collaboration. Researchers in construction education have studied the integration of disciplines in their academic programs by developing a range of learning experiences. A summary of relevant examples is shown in Table 1.

Table 1. Studies on Interdisciplinary Education in AEC

Authors	Institution(s)	Description
Fenves, 1995	Carnegie Mellon University	First year graduate level course intended to foster an interdisciplinary setting for domain-independent problem solving for engineering students.
Mills et al., 1996	Virginia Tech	Vertical and horizontal integration at the undergraduate level.
Mills and Beliveau, 1999	Virginia Tech	Capstone course across academic levels in the Building Construction Department
Robson et al., 1996	University of Oklahoma	Architecture, interior design, landscape architecture, and construction science students worked in teams.
Fruchter, 1999	Six universities from Europe, Japan, and the United States	Developed a distributed learning environment.
Hussein and Peña-Mora, 1999	MIT and CICESE in Mexico	Developed Framework for the development of a distributed engineering laboratory.
Graham and Geva, 2001	Texas A&M	Interdisciplinary studio between architecture and construction science students.
O'Brien et al., 2003	University of Florida and the University of Illinois at Urbana-Champaign	Master's level capstone design course which involved architecture, structural engineering, and construction management students.
Breit et al., 2006	Various universities in Europe	The concept of Project Oriented Learning Environment (POLE) was used to conduct a collaborative course
Leicht and Messner, 2009	Penn State	Interactive workspaces for improving learning in the engineering and construction context.

As past and current research shows, collaborative and interdisciplinary education models in AEC education have been explored with positive results. In spite of this, interdisciplinary education in AEC has not gone beyond test courses and limited application.

Case Study: Interdisciplinary Education at Georgia Tech's College of Architecture

In the Spring of 2007, the Construction Resource Center at Georgia Tech held a workshop to gain understanding from industry practitioners and academics about AEC Integration. The workshop resulted in ideas that would help the College of Architecture (CoA) at Georgia Tech to develop a curriculum centered on AEC integration (Construction Resource Center Report, 2007).

Experts from different sectors of the AEC industry, representing the private and public sector, as well as academia, were invited to participate in the event. Faculty from Georgia Tech's College of Architecture (CoA) also attended, and included representatives from the Architecture; Building Construction; City and Regional Planning; and PhD Program departments as well as from the Dean's Office.

The workshop was organized in four parts: In the first part, each member of the panel was asked to provide a definition of AEC integration. Definitions varied greatly depending on the professional background and perspective of the panelist. Panelists defined integration as: a 'Team Approach' to project execution; leadership and project/program management; either a 'Renaissance Man' master builder or a shared sense of empathy among disciplines; relationship-building; technology-based

Building Information Modeling (BIM); and a reflection of industry trends toward consolidation.

In the second part, panelists provided both driving and preventing factors toward integration. Among the driving factors included: demands of market; client expectations; increasingly complex project; litigation; technology; and re-conceptualization of the meaning of 'value.' Some of the factors preventing the industry from achieving integration included: lack of trained personnel; attitudes of professionals; fragmentation of disciplines in university setting; lack of unifying standards; and fear of technology.

Panelists discussed the general tools that can be utilized to enhance integration in the third part of the workshop. Some of the items discussed included: innovations in procurement and project delivery systems; development of standardized processes; gathering industry feedback on their needs and concerns; and creating an educational environment in which integration is central to learning.

The fourth part included a discussion of the role of Georgia Tech, and other universities, in promoting AEC integration at the college level. Panelists discussed some of the core competencies which were critical for future graduates, including: financial and business skills; problem-solving skills; technical expertise; and more exposure to the various disciplines. Panelists also discussed some of the specific ways Georgia Tech can move toward a more integrated curriculum, including: development of jointly-taught courses; joint lecture series with College of Engineering; open dialogue with the College of Engineering on strategies for closer cooperation; and development of the first graduate degree for Professionals in the Built Environment (MBA, in partnership with College of Management).

After the workshop in the Spring of 2007, the CoA conducted a review process that culminated in a strategic emphasis on interdisciplinarity. This emphasis would allow expanded focus on areas such as green buildings, alternative energy, healthcare, digital design and information technology. It was envisioned that the graduates of the resulting programs would have leadership and problem-solving skills of great value to industry and that faculty would have the resources to pursue interdisciplinary research areas. The changes under consideration would create an undergraduate experience that integrates core requirements with new content areas and modes of teaching and learning (Atlanta Journal Constitution, 2009; College of Architecture News Release, 2009a).

Initially, the CoA planned for the creation of a Bachelor of Science in Design degree with designations in core areas in the CoA such as Building Construction, Architecture, Industrial Design, and others. After the strategic plans were announced, a petition was posted on-line to collect signatures of those in disagreement with the vision of the College (On-line petition, 2009).

On August 19, 2009 the CoA announced the creation of a steering committee to oversee the incremental changes to the curriculum. The steering committee would be tasked with conducting market research including job placement statistics and alumni focus groups; assessing and preserving core disciplinary skills; and assessing options, including an integrated curriculum that is complementary to current academic offerings in the CoA (College of Architecture News Release, 2009b). One month later the CoA expressed that the changes to the undergraduate program would not include

the elimination of any of the existing degrees as pointed out by the on-line petition circulated since the month of July, 2009 (College of Architecture News Release, 2009c).

In order to understand the reasons for the reaction to the CoA's plans for the undergraduate program, an analysis of data collected from the On-line petition is presented in subsequent sections. The need and challenges of such an endeavor are studied through an analysis of data collected from various sources. A survey of students and Alumni at Georgia Tech, industry groups, and students at a close-by university with similar programs to the ones involved at Georgia Tech was conducted.

Methodology:

In order to explore the challenges and opportunities for interdisciplinary AEC education, data was collected from a survey among students and alumni of the Georgia Institute of Technology, Southern Polytechnic State University, and Georgia Southern University in the state of Georgia (these three Universities represent all the AEC programs in the state). Data was also collected from an informal web-based petition pursuing reconsideration of the CoA plans.

The Survey Instrument: The survey instrument was distributed via the Survey Monkey website to a target population of approximately 3448 subjects as shown in Table 2. The response rate is estimated to be 6.64% not including a few faculty and alumni who responded to the survey.

Table 2. Approximate respondent population (estimated from enrollment at respective institutions)

Institution	Enrollment
Southern Polytechnic State University (Spring 2009) (SPSU, 2009)	
Civil Engineering Technology, Construction Engineering, Construction Mgt/Construction Dev., Architecture/Pre Arch./Pre Design Arch.	1442
Georgia Southern University (Fall 2008) (GSU, 2009)	
BSCET in Civil Engineering Technology, BSCONS in Construction Management	617
Georgia Institute of Technology (Fall 2008) (GT, 2009)	
Architecture, Building Construction, Industrial Design, Civil Engineering	1389
Total	**3448**
Response Rate	**6.64%**

The survey was divided in two sections, respondent's demographic information and respondent's perceptions. The questions in the second section included statement for the respondent to indicate level of agreement using the provided five-level Likert scale. The next sections describe the results of the survey.

Survey Responses: The following sections describe the results obtained from the survey. As shown in Figure 1, students were the largest group of survey respondents with 94.6% of the total respondent sample. Although, there was an interest in exploring the perceptions of faculty and alumni, the low response from these groups did not allow for extensive analysis of this group.

Academic Rank: The academic ranking of participants was mainly in the upper levels

of undergraduate degrees and graduate students at the master's degree level as shown in Figure 2. This may be an indication that issues related to interdisciplinary education may be of interest to more experienced students.

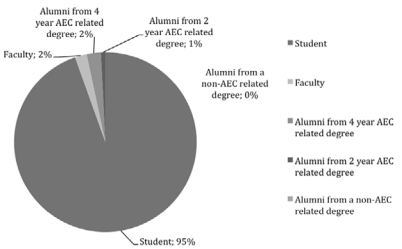


Figure 1. Distribution of Survey Respondents

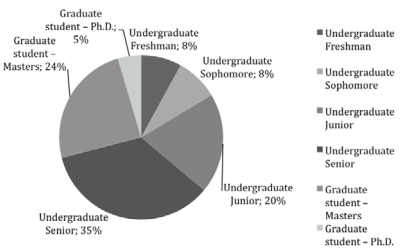


Figure 2. Academic Rank of Respondents

Respondent Age: Over half of respondents (56.8%, n=241) were between the ages of 18 and 24 years. This is representative of the student population who responded to the survey.

Industry Experience: The industry experience of respondents was an average of 3.43 years (n=234).

Work Experience while attending College: The results of the survey showed that a large number of respondents (80.7%, n=202) had some kind of work experience in the AEC industry while being students with 62.4% of those having internship or full-time positions.

Student Competition Experience: A significant number of respondents did not have student competition experience (79.1%, n=215). Of those who did participate in student competitions, the largest number participated in the ASC student competition (7.9%, n=215).

Perceptions about Interdisciplinary Education, Sustainability, Creativity and Technology Use in AEC Education: When presented with the statement; "I feel that my current or past academic training prepared me or is preparing me to work in an interdisciplinary environment", over half of the respondents (69.36%, n=173) agreed or highly agreed with the statement. Over half of the respondents (64.5%, n=173) agreed or highly agreed that their current or past academic training provided them with knowledge about the functions of team members from a professional background different from their own.

Regarding the importance of sustainability in their coursework, 64.16% (n=174) agreed or highly agreed that was important. In addition, 69% (n=174) of respondents expressed to have a deep understanding of the benefits of an interdisciplinary work environment for the sustainability of a project.

A significant number of respondents agreed or highly agreed with the statement "Creative problem solving was or is an important part of my coursework" (79.53%, n=172). Also, a significant number of respondents agreed or highly agreed in that interdisciplinary work environments can enhance creativity of design solutions (92.26%, n=172), as well as solutions to construction related problems (91.07%,

n=172). Over half of respondents indicated that educational information technology was extensively used during their academic preparation (60.46%, n=173).

Regarding the use of educational information technology, a significant number of respondents (75.59%, n=173) expressed that they agreed or highly agree that its use enhances collaboration in a team environment. Over half of respondents (54.6%, n=173) also expressed that they agreed or highly agreed that they felt their academic training is preparing them well to use information technology for information exchange in the workplace.

About the respondent's familiarity with the interdisciplinary education initiatives at Georgia Tech's CoA, the results showed that respondents were not very familiar with almost 30% expressing neither agreement or disagreement and 35.93% expressing disagreement or high disagreement (n=168). Without providing any specific information about the CoA's interdisciplinary education initiatives and considering only the information that respondents may have access through the local media, about half of the respondents (50.6%, n=168) agreed or highly agreed with the interdisciplinary education initiative at GT's CoA.

Respondents agreed or highly agreed (61.58%, n=168) that inclusion of engineering programs in the interdisciplinary education initiatives at GT's CoA would enhance them. More than half of respondents (54.55%, n=168) also agreed or highly agreed that a graduate of an interdisciplinary program from GT's CoA would have good employment opportunities.

The Web-Based Petition

The greatest number of respondents to the on-line petition was from the United Sates (n=546) with 18 being from 12 other countries. The US respondents were distributed among 32 States as shown in Figure 3. Respondents represented a total of 24 disciplines. The disciplines with the largest number of respondents are shown in Figure 4.

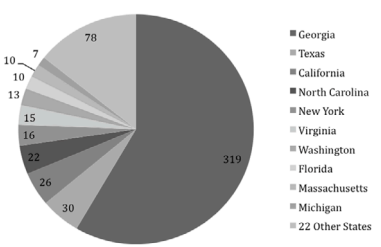


Figure 3. Respondents by US State

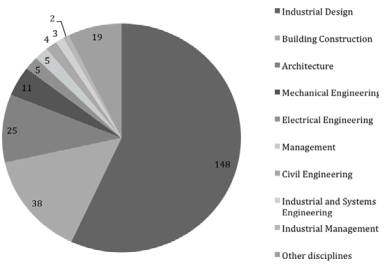


Figure 4. Respondents by Dicipline

The main concerns expressed by respondents to the on-line petition about the interdisciplinary education initiatives at Georgia Tech's CoA included (extracted from the comments posted by respondents on the petition website):

- Graduates will be ***less competitive***, ***less specialized*** for the job market. ***Focus is needed***, CFY (this is the Common First Year, a unique program to GT where students from various disciplines in the CoA take several studio based courses

together) is not good and its more than enough integrated coursework. We ***need professionals***. There are ***no jobs for generalists***.

- ***It weakens all three disciplines*** (lowering the value of undergraduate degrees)
- The three disciplines (Architecture, Building Construction (BC), and Industrial Design (ID)) are ***extremely dissimilar*** (use of different techniques).
- Not at the ***benefit of the student***, but at the benefit of the college tuition profits (Use design thinking rather than accounting thinking).
- The transition ***will surely damage the integrity and the value (discrediting) of the already awarded Building Construction, Arch, and ID degrees***, and will decrease interest in the construction industry.
- We will ***lose the students*** who are interested in the actual disciplines.
- ***4 years is enough to work***, most students want to work after BS.
- It will ***damage their reputation.***
- The fact that ***ID is offered at so few schools*** already really helps keep GT on the map for out of state students.
- More ***management focus for BC.*** A BC student would be better served studying material that is relevant to their field of choice. They should not be forced to spend many hours on studio tasks (mainly charcoal drawings) and being evaluated with arbitrary grading requirements.

Conclusions:

Multidisciplinary collaboration plays a vital role for successful completion of projects in the AEC industry. To meet the growing demands and challenges of AEC industry, an interdisciplinary approach to AEC curriculum design is becoming increasingly relevant. For over ten years, various institutions have experimented with different modes of interdisciplinary learning, but there is still no interdisciplinary curriculum in the AEC education in the US. The recent initiative of Georgia Tech's College of Architecture for an interdisciplinary curriculum was presented as a case study of interdisciplinary education in AEC. A survey was conducted to explore the perceptions about interdisciplinary education, sustainability, creativity and technology use in AEC education by students, alumni and practitioners in the state of Georgia. In addition, an analysis of an on-line petition was performed in order to understand some of the reactions to the CoA's interdisciplinary education initiative.

The results of the survey reinforce the conclusion that interdisciplinary work environments that significantly use information technology have the potential to enhance creativity of design solutions. These work environments also have the potential to enhance solutions to construction related problems as well as sustainability. They also show that use of information technology enhances collaboration and information exchange. It was also observed that the majority of students perceived that their current or past academic training have prepared or will prepare them to work in an interdisciplinary environment. Most of the respondents expressed that including engineering in an interdisciplinary education initiative at GT's CoA would enhance it and that such an initiative could provide them with good employment opportunities.

However the on-line petition of those in disagreement with GT's CoA interdisciplinary education initiative presented a different perspective. There were

many respondents who expressed concerns with lack of specialization, weakening of existing degrees at GT's CoA, the amount of time needed for employment vs. graduate education, and the fundamental differences between the degrees currently offered and that would be integrated.

There is clearly more work to be done to address the needs and challenges of interdisciplinary education in AEC. Georgia Tech's CoA will continue to evaluate ways in which to address those and a continued and in-depth analysis of the process and results will be necessary.

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VIRTUAL CONSTRUCTION PROJECT FIELD TRIPS USING REMOTE CLASSROOM TECHNOLOGY

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ABSTRACT

J. E. Dunn Construction Group and Iowa State University have collaborated in an innovative distance education program. By utilizing a micro-PC, digital camera and hands-free headset and microphone; jobsite personnel at the J. E. Dunn headquarters building construction site transmitted, via wireless technology, video imagery and voice information of real-time construction events to students in Iowa State University's Construction Engineering Program. Remote students seated in a high technology classroom were able to observe and discuss actual jobsite activity as it occurred 225 miles away. A series of "virtual" field trips were conducted covering several phases of the project, including site work, foundations, building structure and interior finishes. One of the virtual tours was led by J.D. Dunn's LEED specialist. In this tour, the guide specifically identified those building components earning LEED points for the project. Students, by and large, were pleased with the virtual site tours as the remote tours were less disruptive to their schedules and accomplished the same educational objective. Although this approach incurred certain technical difficulties, the information technology system performed satisfactorily and demonstrated promise for increased application of virtual construction site tours for many project stakeholders such as owners, architects, engineers, and lender representatives.

INTRODUCTION

No longer must an individual physically travel to a construction project site to observe construction operations. It has been generally believed that only by walking the project could an individual judge the status of the project's schedule, evaluate conformance with safety requirements or understand the unique physical characteristics of a particular construction site or building project. Now with modern communication technologies, virtual visits can be utilized to augment traditional on-site visits and reduce travel costs.

The Construction Engineering Program at Iowa State University in Ames, Iowa has teamed with J. E. Dunn Construction Group of Kansas City, Missouri to leverage information technology to benefit student learning. Construction Engineering students have virtually visited a building under construction to see, first hand, the process of construction. And they never had to leave the classroom! The subject project was the recently completed headquarters building for J. E. Dunn Construction Group located in downtown Kansas City, Missouri. The project includes a 6-story office building of approximately 205,000 gross square feet and an attached multi-level parking garage. This project was specifically selected as it was designed and built to achieve LEED Gold certification through US Green Building Council. When certified, it will be the first commercial office building in the Kansas City metropolitan area to achieve that status (Setzer, 2008).

LITERATURE REVIEW

The most fundamental and widely used wireless communication device is the cellular phone. This common device offers advanced technology beyond simple voice transmission. For example, researchers at the Massachusetts Institute of Technology have collaborated with medical practitioners in the Philippines to transmit X-rays using a cellular phone platform (Denison, 2009). This wireless technology allows experts in distant metropolitan areas to review X-rays taken in remote, rural areas. Without this application of cellular technology, rural patients could not be provided the high level of medical care common to metropolitan areas.

The construction industry has wide application of cellular phone technology, most commonly for verbal communication. But in addition to cellular voice transmission, many construction researchers propose to use wireless technologies, including digital cameras and wireless computers, to observe, review and monitor construction projects. Digital camera technologies and wireless communication infrastructures have proven to increase the efficiency of completing many common project management processes.

Fixed, remote-controlled project site cameras, also referred to as web-cams and surveillance cameras, have become prevalent over the last ten years (Hannon, 2007). Digital cameras are an increasingly common tool for observation, monitoring and

management of construction site operations. The ability to transmit live video images from fixed locations at the project site to a construction company's central office was identified as an application of Internet-based project management systems for the construction industry by Deng et. al in 2001. Their research indicated that at the time of the research the limits of data transmission speed in the available Internet infrastructure did not "generate video-like quality images" (Deng, 2001). These researchers also identified the benefit of improving productivity by analysis of the images recorded through site cameras.

Early research regarding collection of field data using digital cameras was also performed by Liu at the University of Illinois at Urbana-Campaign. Liu developed a prototype information collection device, termed a "Digital Hardhat" (Liu, 1997). This innovative, information technology device included a standard hardhat outfitted with a digital camera mounted above the brim. This hand-free camera allowed transmission of real-time images, audio and video from the project site to remote office. In this experimental model, Wi-Fi technology was employed to transmit data from the hardhat to a server located in the project site trailer. From the site trailer, data traveled off-site via a cabled Internet service.

Researchers at Carnegie Mellon University in Pittsburg, Pennsylvania have also investigated the application of mobile technology on construction projects (Burgy, 2002). They studied certain mobile technologies termed "wearable computers," including lap-top computers, Personal Digital Assistants (PDAs) and Pocket PCs. The proposed application of these IT devices is to collect construction project data by recording information relayed by embedded or attached sensors.

Applications of "active data collection" (Trupp, 2004) has been further explored through research by Trupp et. al. at the University of Illinois. Active data collection is performed when on-site construction personnel manually operate the recording devices. These researchers also envision automated data collection which would not require user interaction, including fixed digital cameras, 3-D laser scanners and RFID-tags. These researchers have suggested that "3D Laser scanning, digital close-range photogrammetry and mobile computing are among the promising data collection technologies" to advance the effectiveness of construction management (Trupp, 2004).

Research by the National Cooperative Highway Research Program (NCHRP) in 2007 reported the advancement of fixed camera systems from either a single camera per project location or independent multiple cameras per project site to the development of "a networked robotic camera system" in which cameras have robotic features and improved image resolution capability (Hannon, 2007).

Silva, et. al. (2008) reported that declining construction productivity is resulting from inadequate supervision. This team researched improvement of project management with a "Virtual Supervision" model using project information obtained by video cameras mounted on tower cranes. The model allows project supervisors to watch construction activities remotely. The anticipated result of this convenient manner to provide construction supervision is improvement of operational efficiency, quality of communication and construction worker satisfaction. These and numerous other research efforts strongly support the continued use of wireless technologies to advance construction.

METHODOLOGY OF VIRTUAL PROJECT TOURS

Off-campus field trips are time consuming and often inefficient uses of students' limited time resources. Field trips may not only result in absenteeism in other classes, but may also cause significant challenges for students with mobility disabilities. Yet, visiting construction projects offers educational experiences for construction engineering students not able to be taught with photographs in textbooks or one-directional filmed media. Virtual project field trips solve the previously noted disadvantages of traditional project tours, and maintain many of the advantages of a real, live construction observation.

Execution of the virtual tour pilot program required the research, selection and integration of information technology devices including a digital camera, voice recorder, and wireless mobile computer. Secondly, software and communication services were researched and initiated to allow voice and videographic information to flow from each mobile device, through a Wi-Fi network and the Internet to its destination of large television screens and speaker system in the high technology classroom. Furthermore, this information network was designed for two-way interaction, allowing students to query the project tour guide and achieving real-time dialogue.

The methodology for this experiment included multiple tours so that "bugs" in the system could be worked out. A series of seven project tours where designated. Following the completion of experimental tours, the tour guides and students were asked to provide feedback on the quality of educational experience, advantages and disadvantages of virtual tours compared to typical on-site field trips, and improvements that could be made to the IT application. This participant feedback provided qualitative data through a sample of convenience.

TECHNOLOGY ELABORATION

Using a handheld camera and head-set microphone, project personnel walk a designated jobsite, narrate, and beam live action back to the classroom in real-time via wireless internet technology. Figure 1 depicts the equipment used for this experiment. Students are able to view the project conditions and converse with jobsite personnel as the action happens, experiencing project management situations as they occur.

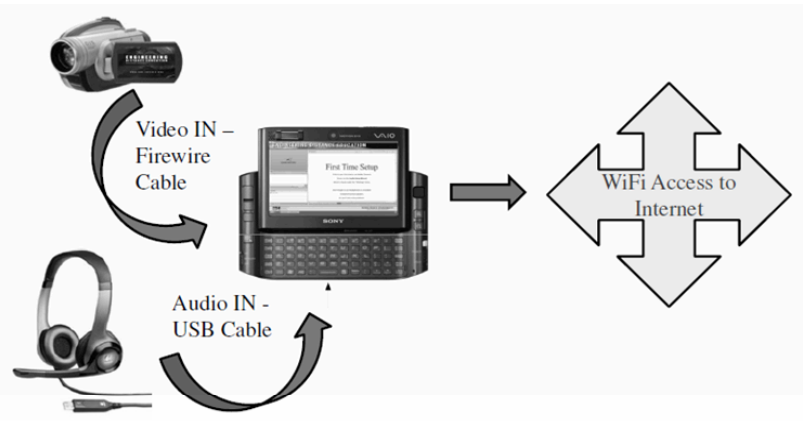


Figure 1: Information Flow Chart and Videography Devices

The remote classroom technology is hand-held and wearable to enable walking, talking work-site lectures over the Internet. The tour guide used a Sony Vaio® UX-390n computer which is similar in size to a portable DVD movie player and designed to be mobile with built-in wireless and cellular broadband capabilities. This micro computer has two built-in cameras for providing live video feeds of the narrator's face or a point-of-view shot of the construction site. The other essential component is a headset/microphone system worn by the construction professional under a hard hat. The headset plugs into the micro computer to enable the two-way audio communication with the remote students attending via Iowa State University's Engineering Distance Education (EDE) online learning system.

At the J. E. Dunn construction site, a wireless LAN system from Trapeze Smart Mobile was deployed to blanket the work-site with Wi-Fi coverage. The last piece of mobile technology is the ubiquitous Sony Handycam camcorder which can be connected to the micro computer to provide long distance shots when heavy equipment and other hazards prevent the instructor from getting close to the construction work zone.

In the classroom, students view a large screen split into sections (refer to Figure 2). On the left, is the live video feed divided between the classroom and job site. On the right, project documents, Building Information Modeling (BIM), drawings, details, specifications and the independent, fixed job-cam can be viewed to illustrate or explain the audio/video portion. An operator monitors the screen from within the classroom.

As demonstrated in Figure 2, in addition to students being able to view actual in situ construction, they can also view at the same time a Building Information Model (BIM) of the subject project. Having both a live image and a BIM model facilitates enhanced understanding and offers easy side-by-side comparison by the students.

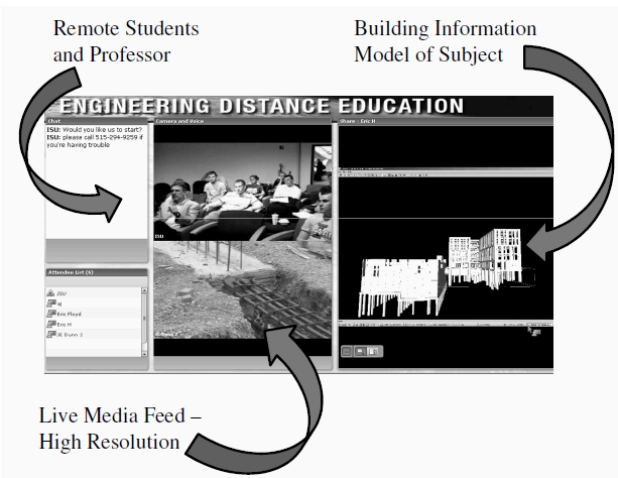


Figure 2: Representative Screen Images comprising the Virtual Tour

The research team's goal from the beginning was to use off-the-shelf technology familiar to the online learning community. Using the *AdobeConnect* web conferencing system as the common platform required that the remote classroom computer be mobile. In the Iowa State University classroom, the equipment included a basic desktop computer, speakers, video projector to enlarge the images coming from the digital camera, and several conference style microphones to capture the student questions. The advantage of using a web-based conferencing platform is that anyone with a computer and Internet connection can join the online class session. For example, architects sitting in offices anywhere could be invited to join the live discussion and display drawings for the live virtual classroom. These web sessions

are captured and archived for later viewing from servers supported by Iowa State University's Extension Information Systems Department.

LESSONS LEARNED

Virtual tours were conducted for students that included five to ten minute segments of audio and video with gaps of similar amounts of time that occurred while the tour guide navigated around the job-site in search of a location that both had Wi-Fi coverage and a construction operation that was of interest for the students. The students were enthusiastic about the opportunity to participate in the experiment and enjoyed the segments of the tour that were transmitted. The consensus was that the concept should be further developed and that virtual tours such as these would be a worthwhile experience, especially if a nearly continuous audio and video feed could be maintained. Positive feedback suggests that students will accept a certain amount of short interruptions in the audio and video feed and some harsh audio in order to have the opportunity of a remote construction tour.

Maintaining a Wi-Fi signal proved more difficult as the building enclosure became partially complete. Strategically placing Wi-Fi antennas to provide complete job site coverage was challenging. This problem was mitigated when the antennas were moved to higher locations, such as the tower crane mast. Even when antenna were placed in the best locations, constant vigilance was necessary to ensure that construction activity did not block the signal or that the antenna was moved to be better location. During virtual tours, when signal was lost, a frustrating amount of time was expended to reconnect the communication link between project site and classroom. These interruptions detracted from the educational experience and lengthened the time required to complete a project tour. This experiment demonstrated that proper antenna placement is a key element to the success of virtual tours if a local area, Wi-Fi infrastructure is used.

At times, a high volume of noise caused by background construction operations and wind caused difficulty for the tour narrator to hear questions from the classroom and also reduced the clarity of audio delivered to the classroom. Unexpectedly for the research team, wind noise detracted greatly from many of the virtual tours. Efforts to protect the microphone from wind somewhat mitigated the problem, but never provided a complete solution. In addition, voice over internet protocol (VOIP) at times delivered harsh audio and latency problems that detracted from the learning experience.

A standard cellular phone was used as an alternate to the head-set microphone and often provided considerable improvement to communication clarity. It also offered the benefit of a separate voice connection to the classroom from the mobile computer connected through the Internet. At times when the Wi-Fi connection failed and the video feed dropped, the use of an independent cellular phone connection allowed the

tour to continue with audio-only delivery until the digital feed could be re-established. Also, the length of time to re-establish the live video link was lessened when the head-set audio device was not used as the total number of devices to be "re-booted" was reduced by one device. While the video feed was interrupted, the cell phone connection offered the opportunity for both the audience and the tour guide to cooperatively engage in trouble shooting. This was especially helpful when it was necessary to establish the Wi-Fi coverage limits of where the video feed could or could not be maintained. When VOIP was used the tour guide often was unaware when the connection to the classroom was lost, much to the frustration of the audience. Based on the experience gained from these test tours, it is recommended to have a back-up audio connection that allows the tour guide to communicate with the audience at those times when the primary connection is lost.

The selected camcorder required operation by hand. At times, however, the tour guide required use of his hands to safely walk the construction site and avoid construction hazards. A hands-free camera, such as hard-hat mounted, would be preferred to hand-held. In such a case, however, the narrator still requires an option to adjust camera settings, such as zooming in on the details of a specific construction activity or as-built condition. In the future, voice activated technologies may offer a solution to this human-equipment interface.

Developing a planned route for the tour is challenging. The tour guide usually knew about the site in detail, has a 3-D 360 degree view of the job site, is geographically-oriented to the surroundings and knows the history of the project. Meanwhile, the students may be suddenly confronted with a narrow angle video view of the details of assembling a constructed facility, possibly before they understand the context within which the details lay. This issue was mitigated by providing students with a map showing the location of the project within its surroundings, a computer-generated rendering of the building, a site plan and a one-page, double-spaced narrative description of the project. Furthermore, it was helpful to begin the tour with wide angle views of the project and its surroundings with frequent references to cardinal directions, the location of nearby landmarks and an orientation regarding the major features of the construction project and their actual location in wide angle views. Subsequent more detailed views were kept in context by occasionally referencing landmarks during the virtual tour. Based on the research team's experience, learning might be further enhanced by giving a brief overview presentation that might include aerial photos of the site, 3-D models, renderings, site plans and floor plans and building elevations.

CURRICULUM DEVELOPMENT

Based upon the success of this pilot program, the construction engineering program at Iowa State University will increasingly implement virtual project tours into its curriculum. Virtual project tours are appropriate components of numerous

construction engineering classes, specifically including construction methods and materials, construction estimating and design/build. In addition to these established classes, a new class on international construction will be offered in the fall of 2010. Virtual project tours, likely predominantly asynchronous, will provide much of the subject matter for the class. These tours filmed in countries around the globe provide access to international construction projects otherwise unavailable to engineering students.

NEXT STEPS

Research and experiment with digital cameras and wireless communication, including this work in virtual project tours, has demonstrated the feasibility of using this concept for construction education. The challenge for construction researchers is to refine the technology with regard to field connectivity, audio quality and virtual tour planning. In addition, it is desirable to develop new practical applications that are consistent with availability of new equipment and advancements in communication infrastructure.

3G cellular coverage is one example of newly available communication infrastructure. This research team is currently modifying the hand-held computer in order to access an AT&T 3G cellular service area directly from the project site in lieu of connection via a project-located Wi-Fi network. We plan to test the transmission speed of media data directly from the hand-held computer to the Internet by cellular service. If the transmission speed is sufficient to support real-time delivery of the audio and video feed, then projects located within any 3G coverage area could offer virtual tours as well.

Background noise reduction is a technology with direct application to virtual tours of construction projects. By the nature of construction projects being both outdoors and involving loud equipment, background construction noises can easily interfere and potentially even inhibit the comprehension of the tour guide's audio information by the classroom audience. Reduction of background noise has an application in hearing aids and hands-free cellular phone devices (such as noise canceling Blue tooth ear-mounted devices). Future research could include incorporation of "smart" noise reduction technology into the apparatus used by the on-site tour guide. It is hypothesized that automatic elimination of background construction and wind noise will significantly improve the clarity of audio transmitted to the classroom and greatly improve the learning experience.

This research group is also testing the benefits of synchronous vs. asynchronous delivery of media from construction projects. Synchronous media is provided live, real-time as demonstrated by the pilot project of the J. E. Dunn headquarters building. With asynchronous delivery of media, the tour is pre-recorded prior to presentation to

the classroom, similar to a traditional film. An asynchronous delivery could offer benefits that are not available with synchronous delivery, such as editing, fast-forwarding, and pausing of the video for discussion and questions. Asynchronous tours could be enhanced by presentation of the pre-recorded tour video by the tour guide. Researchers suggest that the tour guide travel to the classroom to present the pre-recorded video to the students. Although not fully virtual, this solution limits travel to one individual from the project site to the classroom in lieu of an entire classroom of students from classroom to project site.

CONCLUSION

The virtual project tours described in this paper were developed with the purpose of educating construction engineering students who could not easily take a day off from classes and travel to a distant job site. These tours constituted a pilot program through which various information technology equipment and communication options were explored. This experience has proven that modern videography equipment and communication technology allow, in concept, for onsite construction professionals to conduct real-time, virtual construction project tours. These results provide the basis to explore further applications for virtual tours that may be useful to other construction project participants.

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A Case Study for Integrating Lean Six-Sigma and RFID Applications in Construction Processes through Simulation Approach

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Abstract:
Various attempts have been made to apply Radio Frequency IDentification (RFID) technologies to current construction operations and processes; however, RFID applications have still required considerable investments and efforts to be successfully applied in the real construction projects. This paper examines the RFID technology applied to construction projects. A simulation model is developed to quantitatively evaluate the possible productivity benefits of RFID in construction. The model is based on the case study of a real construction project where the critical points of economically feasible solution for RFID application can be searched variable depending on the costs of RFID tags and RFID readers The simulation model also compares performances to apply RFID applications before and after. The results of simulation showed that RFID technology is effective for enhancing the project performances improvement at the operation and process level by reducing cycle time, decreasing queuing time, and improving other benefits including reliability of construction operations compared to invested costs. The results, however, also indicated that RFID application needs for further analysis in view of assessing qualitative aspects as well as implementation obstacles, based on more broaden case studies.

Introduction

Construction productivity has declined and project performance has recently been a major issue in the construction industry. Productivity measurement has focused on

efficiency, which is the ratio of the effective or useful output to the total input in a project (Klanac and Nelson, 2004). In contrast, little has been done to hence the reliability of a process performance, which is the controlled defect rate to maintain a high-standard quality level through six sigma principle (Han et al 2008). Therefore, it is necessary to consider both quantitative and qualitative aspects and to optimize the work conditions improve performance, and build strategies to improve productivity in a construction work. In particular, the qualitative level of material management is a critical factor influencing total project productivity; in other words, the performance of a construction process can be enhanced when both the efficiency and the reliability of material management are insured.

To achieve this objective, many researchers and project managers have sought to improve project performance by applying emerging technologies to current construction operations and processes. In particular, Radio Frequency Identification (RFID) is a branch of automatic identification technologies using radio frequencies, which uses read/write transponders that are able to capture and transmit data in harsh work spaces (Jaselskis et al. 1995). In construction projects, lots of materials and components are confined in a limited space, and construction work processes are complex and operated concurrently. Therefore, tracking the location of materials on a construction site has a direct impact on project performance (Song et al 2006). By improving the resource tracking process, RFID technology is able to provide efficient communication between work processes and to improve the integration of functions in material management. However, construction work sites are complex to formalize and construction operations and processes are various according to a project. Therefore, the RFID application should be customized to a construction work site respectively. The purpose of this research is to establish a systematical framework, in which both quantitative and qualitative aspects are considered when integrating lean six sigma approach and RFID applications in construction industry. Through this framework, this study analyzes the benefits of RFID applications when integrating lean six sigma approach to improve performance of construction operation process.

Recent Applications of RFID Technology in Construction Industry

In the mid 1990s, research on RFID technology in the construction industry began. Jaselskis et al. (1995) first proposed its potential applications in the construction industry. They discussed three potential construction applications for RFID technology including concrete processing and handling, cost coding for labor and equipment, and material control. Jaselskis et al. (2003) proposed a RFID application idea and conducted pilot tests in a refinery project to learn more about RFID and its applicability to the material procurement process on a construction site based on the information gathered from a construction industry-RFID supplier workshop. They derived potential applications from four groups in the workshop: engineering/design, material management, maintenance, and field operations. Recently, the ERABUILD (European Research Area on Sustainable Construction and Operation of Buildings) (2006) conducted research to identify the applications of RFID technology in the current and future construction industry. This research was based on interviews and workshop surveys, and suggested SWOT (Strength/Weakness/Opportunity/Threat) analysis and strategies, and RFID roadmap in the construction industry. Most recently, Chin et al. (2008) proposed the strategy and information system to manage the

logistics and progress control of structural steel works under the integrated environments of RFID and 4D CAD (four-dimensional computer-aided design) technology. They provided the three critical factors for RFID applications in the construction process such as technological availability, domain applicability, and information management strategy. In spite of intensive and hard efforts of researchers during past decade, however, most RFID studies have mainly focused on the technical applicability of RFID on the construction industry. Therefore, the studies have been limited to the assessment of RFID benefits when integrating lean construction principles and six sigma approaches on construction processes.

Lean Six-Sigma Approach for Improving Performance in Construction Process

The concept on combining of the lean manufacturing principle and six sigma approach has been addressed in manufacturing industry for both productivity improvement and quality improvement at the same time. The previous studies in manufacturing industry examined that performance can be improved through incorporating lean manufacturing system and statistical tool (DFSS 2002) and that integration of both lean and six sigma principle application can lead better performance (Kroslid 2002). In construction industry, there also have been limited attempts on the combination of the lean construction and six sigma principle. Abdelhamid (2003) proposed the conceptual six sigma approach in lean construction using the lean project delivery system developed by Ballard (2000). On the other hand, although the lean construction considering production as a flow has been adapted to eliminate waste in workflow (Howell and Ballard 1994; Howell 1999), it has not been obvious that the veiled procedure of how to measure the level of defects in work process. In addition, the concept of near zero inventory in JIT (Just In Time) philosophy has been confront with the questions of many researchers about the size of inventory buffers to achieve the best performance in a volatile and uncertain construction environments (Han et al., 2008). In particular, it has been known as productivity can be deteriorated when inventory size and time lag became zero (Horman and Thomas, 2005). Based on previous studies, Han et al. (2008) suggested an approach for combining lean and six sigma principle based on evaluating the quality of the current operation and quantifying the definite goals of improvements for the targeted operation so as to control the critical sources of variability in construction operation. They proofed the benefits of combined lean six sigma approach using simulation tool. To achieve the goals, they adopted the process capability index (C_p) as the six sigma principle performance indicators using critical total quality (CTQ). The process capability index (C_p) can be calculated as the difference between upper specification limit (*USL*) and mean of the data (*MEAN*) divided by 3 times of standard deviation of the data (*STDEV*).

$$C_p = \frac{USL - MEAN}{3 \times STDEV}$$

If only *USL* given, the sigma can be defined by 3 times of C_p.

$$\sigma = 3 \times C_p$$

Using this indicator, Han et al. (2008) developed the basic framework for the six sigma application to construction projects. They applied the six sigma principle concept to the construction process control through CTQ input, DMAIC (Define-Measure-Analyze-Improve-Control) procedures, and output measures. They

considered the six sigma principle's statistical definition associated with minimizing the defect rates through a control of CTQ. Based on this consideration, the modified DMAIC in a six sigma principle was provided to fit in the construction operations. In addition, the input indices and subsequently measures the sigma level of CTQ was defined. This basic framework for combining the lean construction and six sigma principle became a meta-framework of this research.

Systematic Framework for Integrating Lean Six-Sigma and RFID Applications

This paper presents a systematic framework to the guidelines for implementation of RFID application integrating lean six-sigma. To take an advantage of the lean six-sigma principle, the RFID application can be applied to the construction process on the lean construction environments within basic framework of CTQ inputs as performance indicators, six-sigma application procedure based on DMAIC procedure, and indices of performance improvement as output measures. Thus, this research adopts the basic framework for integrating lean construction and six-sigma principle to construction projects developed by Han et al. (2008). The framework is appropriately modified to fit in a construction process using RFID technology under the lean six-sigma environment. As shown in Figure 1, the systematic framework for integrating lean six-sigma and RFID applications in the construction process is developed.

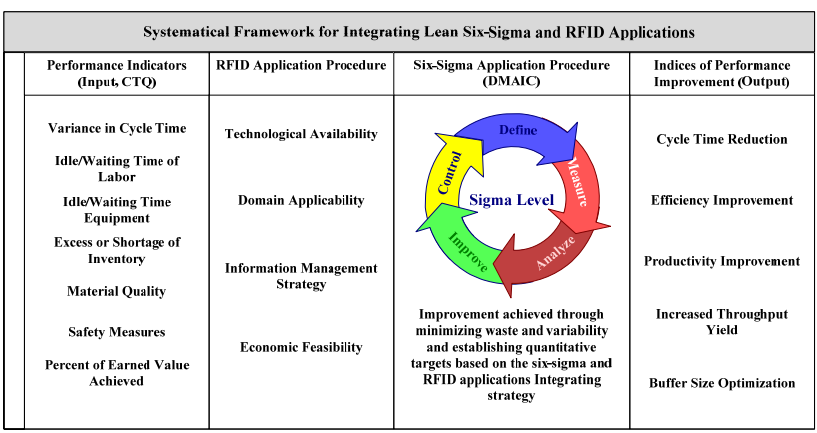


Figure 1. Systematic Framework for Integrating Lean Six Sigma and RFID Applications

The RFID application procedure requires four main considerations for applying RFID application to the construction process: technical availability, domain applicability, information management strategy, and economical feasibility. Technological availability, domain applicability, and information management strategy have been addressed as a critical factors in RFID applications in previous studies (Jaselkis and El-Misalami, 2003; Chin et al. 2008). In particular, economic feasibility of RFID applications should be defined to verify the cost effectiveness of RFID technology in construction process.

Case Study: Simulation of Iron-Reinforced Bar Assembling Process

To show the benefits of RFID application with integrating lean six-sigma approach, this study simulated the iron-reinforced bar assembling process for analyzing the effects of RFID applications under lean six sigma environments when RFID applications are applied or not. This assembling process is the building process of 765kV power transmission lines including site mobilization, foundation, steel tower assembly and erection, and attaching a power line to a tower. In this research, the assembly process of iron tower is focused for case study. This process was committed by 13 crews including tower assembling engineers, tower erecting engineers, helpers, and crane operators. In particular, the maximum size of the storage for iron bars was less than 20t due to the limited site accessibility in the harsh environment. The field data of the target process was collected during 10 working days as shown as Table 1.

Table 1. Field Data of the Target Process

Field data	Values
Committed workforce	13 crews
Current storage weight of iron bars	8.4t
Maximum of the field space to store iron bars	less than 20t
Cost to store 1t of iron bar	$25/day
Delivery and other process cost for iron bars	$6/t
Cost for extending storage space exceeding current capacity	$365/t

Based on this field data, the discrete event simulation models was developed through Extend® based on the simulation model proposed by Han et al. (2009). This simulation model is designed to examine the combination effect of RFID and lean six sigma principle, and to explore the optimal economically feasible solutions to apply RFID applications to a construction process under lean six sigma environment. Thus, the simulated main work process if iron bar assembly consists of delivery of iron bars to the storage area, classifying steel member, moving steel member to the specific location, and assembling each part. Figure 2 shows a part of the Extend model for this process.

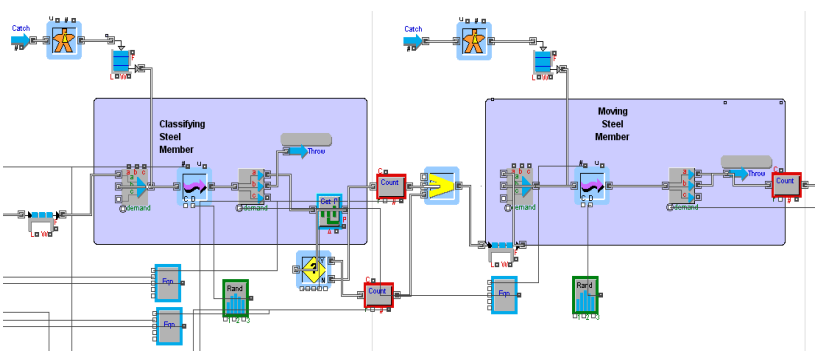


Figure 2. Part of Extend model for the iron bar assembly process

Assumptions for RFID application procedure

The RFID application procedure identified technical availability, domain applicability, information management strategy, and economical feasibility and assumed to develop adequate simulation model based on the previous study (Chin et al. 2008).

1) *Technological availability*: RFID tags are assumed as general 125 kHz passive type and RFID reader is assumed as CF slot and stationary reader which has reading distance with 3 cm.
2) *Domain applicability*: Tracking targets are iron-reinforced bar with metal and magnetic substance and read-only tag and portable and fixed reader is used.
3) *Information management strategy*: Material management of iron bars in the inventory committed by crews of the contractor.
4) *Economical feasibility:* Regarding economical feasibility of RFID application, four input components are assumed such as unit cost of RFID tag, quantity of RFID tags, and effects of RFID application in the activity level. The target quantity of iron bars to be installed in this process is assumed as 500t. In addition, the unit price of RFID tag with chip is $5 per card and the unit price reader is $800 per reader. The time saving of RFID application is assumed as 28% in the process time. Thus, this process is deemed to require 3 RFID readers and one RFID tags per 1t of iron bars.

Simulation Results of Case Study

The simulation results show that the productivity and sigma level of cycle time can be improved in the RFID applied process rather than RFID not applied as shown in Table 2. When comparing the impacts of RFID applications in the As-Is process, the productivity increases from 0.049 to 0.052 (6.1% increases). On the other hand, the cycle time of the process is almost no change and the sigma level of cycle time (CTQ) decreases by RFID applications without any process improvement. That is, the RFID applications without any lean construction treatment are difficult to improve the reliability of work process.

Table 2. Performance by applying Lean Six Sigma and RFID

		Lean Six Sigma Applications		
			To-Be process	
RFID Applications	Performance Indices	As-Is Process	Process Modified	Buffer Size Modified
RFID Not Applied	Buffer Size	8.4	8.4	11.5
	Productivity (t/min)	0.049	0.052	0.055
	Cycle time (min)	162	150	154
	Sigma level of cycle time (CTQ)	1.41	1.72	2.58
RFID Applied	Buffer Size	8.4	8.4	11.5
	Productivity (t/min)	0.052	0.057	0.058
	Cycle time (min)	162	145	153
	Sigma level of cycle time (CTQ)	1.17	1.77	1.84

When comparing the impacts of RFID applications in the process-modified To-Be process, the productivity increases from 0.052 to 0.057 (9.6% increases) and the CTQ increases from 1.75 to 1.77 (2.9%). Moreover, when comparing with simulation results between RFID applied and process-modified To-Be process and basic As-Is process, the productivity drastically increases from 0.049 to 0.057 (16.3% increases)

and the CTQ increases from 1.41 to 1.77 (25.5%). These results imply that both the productivity and reliability of the process can be enhanced by RFID applications under lean construction environments as shown in Figure 3.

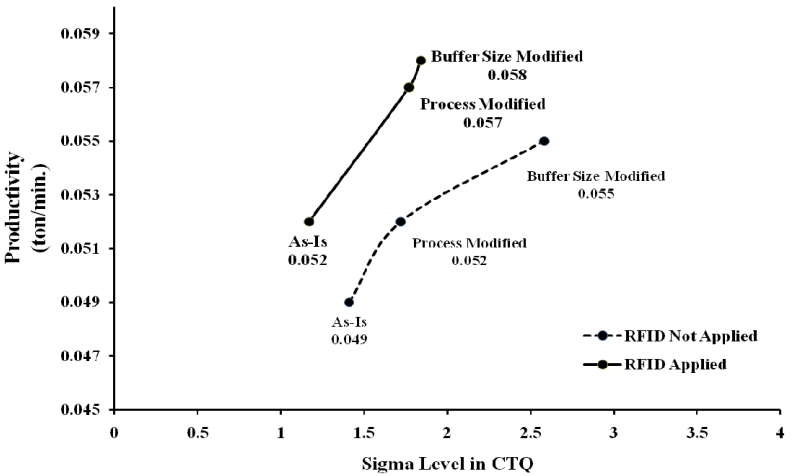


Figure 3. Productivity Improvement by Sigma Level in CTQ

When comparing the impacts of RFID applications in the buffer size-modified To-Be process, both the productivity and the CTQ in the process with both the lean six sigma and RFID applications increase little more than that with only lean six sigma applications. That is, the impact of RFID applications under the inventory management through the control of buffer size is not too much. Thus, it is necessary to search the optimal buffer size to maximize both productivity and reliability of the work process.

Table 3. Process Cost by Lean Six Sigma and RFID applications

		Lean Six Sigma Applications		
			To-Be process	
RFID Applications	Performance Indices	As-Is Process	Process Modified	Buffer Size Modified
RFID Not Applied	Production Cost (US$/10days)	9,400	9,900	11,900
	Additional Storage Cost (US$/10days)	3,500	3,600	5,600
	Throughput (t/10days)	236	252	268
RFID Applied	Production Cost (US$/10days)	9,800	10,400	12,005
	Additional Storage Cost (US$/10days)	3,596	3,740	5,657[a]
	RFID Installed Cost(US$/10days)	3,660	3,780	3,790[b]
	Throughput (t/10days)	252	276	278

[a] Additional cost of US $2,157 for increasing buffer size from 8.4t to 11.5t (3.1t) consists of: (1) storage cost for additional buffer = 3.1t × $25/day × 10days = $775; (2) the cost for extending a storage area = 3.1t × $365 = 1,130, and (3) delivering and other processing cost for producing more throughput (278 - 236 = 42t) = 42t × $6/t = $252 (all in US dollars)

[b] RFID installed cost of US $3,790 for installing 3 readers and one tag per 1t consists of: (1) the cost of 3 RFID reader = 3 × $800 = $2,400; (2) the cost of RFID tags installed during 10days = 278t × $5/t = $1,390 (all in US dollars)

Table 3 shows the process cost that are the sum of the production cost and the additional cost, including the additional storage cost and RFID installed cost in each condition: (1) RFID-applied As-Is process increases 32%, (2) RFID-applied and process-modified process increases 38%, (3) RFID-applied and buffer size-modified process after process-modified increases 66%. Thus, the cost effectiveness of RFID applications needs to be verified for economical feasibility.

Critical points of economically feasible solution for RFID applications

For taking advantage of RFID applications under lean six sigma environments, the economical feasibility of RFID applications needs to be verified on the basis of the simulation results of the work process. Table 4 shows the comparison of total process cost by each application case on the process. The goal of the process is defined as the installation iron bars of 500t for assembly of the transmission tower. To reach this goal, the basic As-Is process requires the total process cost of 28,380 US dollars and 22 days of the estimated duration. The only lean six-sigma applied process requires 27,000 US dollars of total process cost and 20 days of estimated duration. The only RFID applied process requires 31,692 US dollars of total process cost and 20 days of estimated duration are required. Finally, the process integrating lean six-sigma and RFID applications requires 30,352 US dollars and 18 days of estimated duration. For the economical feasibility of RFID applications, however, the critical points of economically feasible solution needs to be identified.

Table 4. Comparison of Total Process Cost by Applications

Items	As-Is process	Lean six sigma applied	RFID applied	Lean six sigma + RFID applied
Target quantity to be installed (t)	500	500	500	500
Available throughput (t/day)	23.6	25.2	25.2	27.6
Estimated Duration (days)	22	20	20	18
Production cost (US$)	20,680	19,800	19,600	18,720
Additional storage cost (US$)	7,700	7,200	7,192	6,732
RFID installed cost (US$)	0	0	4,900	4,900
Total process cost	28,380	27,000	31,692	30,352

To be economically feasible of RFID application under lean six sigma environments in this process, the RFID installed cost should be less than 2,928 US dollars (= US $30,352 – US $28,380). The following formula on the relationship between the unit price of reader and tag of RFID can be obtained.

$$3x + 500y \leq 2928$$

The unit price of RFID reader is presented by x and the unit price of RFID tag is presented by y. The constrains of unit price of RFID reader and RFID tag should be less than current unit price of those RFID applications.

$$0 \leq x \leq 800\,,\ 0 \leq y \leq 5$$

Figure 4 shows the critical points for economically feasible solution for RFID applications and the area of possible combination of unit price of RFID applications. The points on the area resented by the formula mean the possible combination of unit price of RFID reader and tag to obtain the economical feasibility of this process. From the relationship of unit price of reader and tag, the following implications can be known. The unit price of reader needs to lower to 143 US dollars when the unit price of tag is fixed, while the unit price of tag need to lower 1.06 US dollar when the

unit price of reader is fixed. If the reduction rate of the unit price of RFID reader and tag is same under bulk manufacturing environments, the possible unit price of reader and tag can be 478 and 2.98 US dollars. This means that the unit price of RFID reader and tag should be less 40% than the current unit price to obtain the economical feasibility.

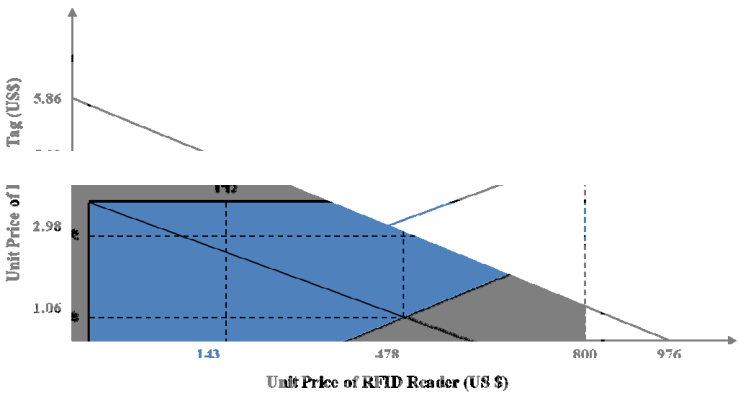


Figure 4. Critical Point of Economically Feasible Solutions for RFID Applications

Conclusions

This research proposes the systematic framework for integrating lean six sigma principle and RFID applications and simulates the construction process to examine the combination effects of those applications. Lean six-sigma principle and RFID technology have been shown to improve performance of a construction process by researchers. When these principles are integrated and applied together, it is shown by process simulation models based on the systematic framework that these principles can have drastic effects on improving performance of the construction process both quantitatively and qualitatively. In the quantitative aspect, the productivity can increase and cycle time can be reduced. In qualitative aspect, the reliability of process capability variation within six sigma level can be controlled and assured. Finally, it is examined that the unit price of RFID applications should be lower than the current unit price to gain the economical feasibility of RFID applications. This research gives the guideline to improve performance of the construction process through integration of lean construction, six sigma, and RFID application. Many researchers and practitioners can be allowed to understand the integration effects of lean six sigma and RFID applications. In spite of merits of this research, there are some limitations. First, this study mainly considered unit price of RFID tag and reader; however, indirect costs and other possible extra costs associated with RFID applications need to be identified and considered to get more realistic optimal solution. Second, field experiment needs to be conducted based on this systematic framework and the simulation results in order to verify the benefits of integrating lean six sigma and RFID applications, the simulation models. Lastly, the impact of buffer size is not significant in the process integrating lean six sigma and RFID applications. Thus, the

buffer size needs to be optimized to maximize both productivity and reliability of the process capacity variability. Based on these limitations, future research will focus the analysis of another construction work process using the systematic framework based on the real data of field experiments and conduct the optimization of the buffer size when RFID technology is applied under lean six sigma environments.

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A Simulation Driven Visualization Framework for Construction Operations : Development and Application

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Abstract
Simulation is a relatively new area of engineering research, whose implementation in day-to-day construction industry activities continues to lag behind research efforts. It is widely viewed that the lack of a visualization component in construction operations simulation contributes to this low level of adoption within the industry. This paper discusses the development of a framework for simulation visualization and the implementation of this framework in modeling a real pipe spools assembly yard and pipe modules site installations. The framework can be used to better represent spatial data in simulation. The framework is developed through a distributed simulation based approach using High Level Architecture (HLA) standards. The paper demonstrates how this research can benefit construction through a real case study.

Introduction

Visualization in general, and particularly in construction projects, is a convenient and intuitive way of conveying project information among various project parties. Recently, construction management researchers have been trying to add a visualization component to construction operations simulation models in order to make these models more intuitive and to enhance decision making in construction projects. These researchers argue that the construction industry has not made optimum use of simulation techniques. Current construction operation simulation models are limited in terms of representing construction sites' spatial data and layouts. This paper explains the development of a framework for construction operations simulation visualization, based on the HLA standards for distributed simulation.

The HLA based Simulation Visualization for Construction Operations framework (HSV) aims at facilitating and improving decision making in construction projects by providing a better representation of construction sites' spatial data among other factors in construction operations environment, that are poorly depicted by mere simulation techniques inside the construction operation simulation models. This indirectly enhances the utilization of simulation models and techniques during decision making in real day to day construction operations.

The paper starts by giving a quick review of the simulation visualization research in the construction research literature. This will be followed by an explanation of the framework, the way it is developed and its components. The features which make this framework distinctive among other simulation driven visualization mechanisms or frameworks will also be emphasized. An experiment in which the HSV framework was implemented to visualize some of the simulated industrial construction processes of pipe modules' assembly and field installations in a real module yard and construction site respectively is demonstrated to assess the capabilities of the framework. Future developments of the framework and the way it is expected to benefit the construction industry will be discussed. Finally, an evaluation of the HSV and its potential will conclude this paper.

Simulation Visualization Mechanisms & Limitations

Simulation is defined as the process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behaviour of the system or evaluating various strategies for the operation of the system (Shannon, 1975). The strength of simulation is that it can be used to test the outcomes of various scenarios on the simulated system rather than giving an optimum mathematical result, as it is the case in mathematical optimizations. Most studies stress the fact that simulation is not used to its maximum potential in the construction industry (Ioannou and Martinez, 1996; Kamat and Martinez, 2001; Huang & Halpin, 1994; Tucker et. al., 1998).The reasons behind that are:

- Most simulation models show results in statistical and text format, which has caused simulation to be perceived in the construction industry as a "black box" where statistical text and graphics are outputted based on certain input.
- The current simulation models do not consider the transformation of space that results from the evolution of the constructed product (Kamat and Martinez, 2001).

In order to overcome the limitations of current simulation and to encourage its application in the construction industry, SDV (Simulation Driven Visualization) evolved as a way of incorporating animation with simulation to provide better understanding to the end user and to represent construction site spaces in simulation. Also, SDV mutually addresses the limitations of using standalone animation or simulation systems. There are "commercial off the shelf" (COTS) SDV packages in the market, including AutoMod® and Quest®; however these SDV COTS packages concentrate on manufacturing operations only, not construction ones. These COTS

are generally unable to effectively handle the additional complications introduced by the changes in the geometry of the construction site as work progresses and using them to model and animate construction operations requires a radical change in the model conceptualization and the thought process followed by construction model developers (Oloufa, 1993; Tucker et al., 1998; Kamat and Martinez, 2008). Another visualization and CAD package commonly used in the construction industry is CATIA®. Although powerful on the CAD side, it has limitations on the simulation side of processes. CATIA offers a better solution for 4D modeling—final product development modeling—but not for construction processes simulation. It is fair to say that products like CATIA inherit the pros and cons for standalone animation systems that are not based on simulation engines.

The first construction simulation tools to adopt graphics were introduced in the early 1980s (Rohrer, 2000). This was done by linking construction simulation packages to animation, to achieve a post-process playback of the simulation (Halpin and Woodhead, 1976; Kalk and Douglas, 1980; Paulson et al., 1983). The "Utopian Framework" for earth movement operations was a good example of this graphic animation (Oloufa and Crandall, 1992). Another attempt was to extract product information from CAD design into simulation through the PSE (Product-oriented Simulation Environment) (Xu and AbouRizk, 1999). This was followed by attempts to display simulation results in statistical graphics as a form of visualization (Huang and Halpin, 1994; Hajjar and AbouRizk, 1999). This category of simulation visualization had its own disadvantages: construction planners and analysts, who are typically well-versed in actual construction operations, are reluctant to base their decisions solely on the statistical text and graphical chart output provided by most simulation systems (Ioannou and Martinez 1996).

Recent research in construction operations SDV involved the use of construction operations simulations' resulting trace files to invoke a post-simulation animation (replay) of the simulation. This included the Dynamic Construction Visualizer (DCV) and Visualization of Simulated Construction Operations (VITASCOPE) by Kamat and Martinez in 2001 and 2004, respectively. Since then, all work in Construction Operations SDV has been contributing to the development of VITASCOPE. This mechanism using simulation trace files is a post-processing SDV mechanism and depends on tightly coupled simulation and visualization engines. Also, the information in these mechanisms flow one way from the simulation to visualization component.

HSV Framework

The proposed HLA based Simulation Visualization for Construction Operations (HSV) framework is based on distributed simulation HLA standards. Distributed simulation is a technology that enables models to be linked together over computer networks so that they work together (or interoperate) during a simulation run. High Level Architecture (HLA) (IEEE 1516.2000) is a set of standards that regulates distributed simulation development (Taylor et al., 2003). In HLA, each simulation is connected to the other through a Runtime Infrastructure (RTI) software. The simulations or models connected to the RTI are called Federates. A federate is not

necessarily only a simulation model, but it can be any software, hardware or even a human player (user-in-the-loop as referred to by HLA distributed simulation terminology, Rycerz et al., 2007). RTI facilitates communication between federates and performs time management of the simulation. Another important component of a Federation (collection of federates) is the FOM (Federation Object Model) which defines all the entities produced by the various simulation federates during the simulation run, state attributes for those entities and most significantly records which federates will update those entities' attributes (publish them) and which federates will merely read them (subscribe to them). For example, in the HSV, federates responsible for the visualization only subscribe to certain attributes of certain entities, while simulation responsible federates can write and read (publish and subscribe) these attributes. On the other hand, for future developments of the HSV, the visualization components (federates) will also publish certain simulation objects' attributes when it starts communicating back with the simulation.
Figure 1 shows the HSV concept, typical components and communications between the visualization federate(s) on one hand and other functional/simulation federates on the other hand.

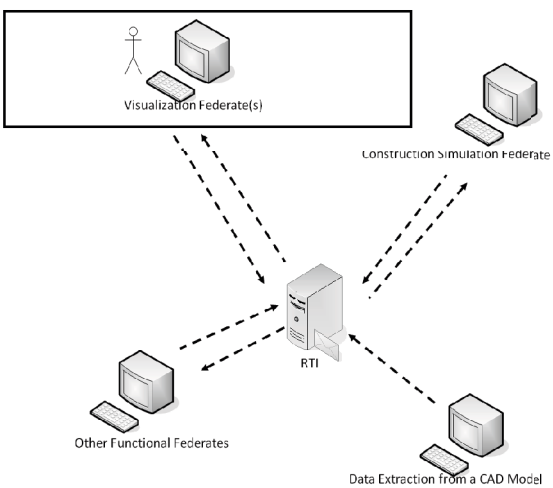


Fig. 1 HSV framework typical components and communication

As it is shown in figure 1, the framework is made up of the following components:

Visualization Federate(s) and its/their User Interface(s): Communicates with the source simulation or any other federate. It depicts the construction operation simulation concurrently as the simulation time advances to reflect what is going on in the simulation instantly. Developments are underway to allow the user to update the simulation during its run through the visualization component.

Source Simulation Federate(s): That is where the simulation of the various construction processes takes place. Also, simulation time advances in these federates. They connect to their respective viewer federate through the RTI.
Other Functional Federates: For example a Databases Federate or a CAD Model federate used to extract the simulated objects' attributes values to update them during the simulation run.

As it is shown in figure 1, all communications between the various federates go through the RTI using predefined HLA protocols. Federates simulating various construction processes can be added/removed to/from the federation. Visualization federate(s) can be connected to allow simultaneous visualization of various simulated construction operations. This visualization is concurrent with the simulation and not post-simulation, which allows the decision maker to see the simulation as it is happening and make more educated decisions by understanding spatial related aspects and logic of the simulation process through the visualization component. Figure 2 below explains- at the conceptual level- the difference between post-run visualization mechanisms and the developed HSV.

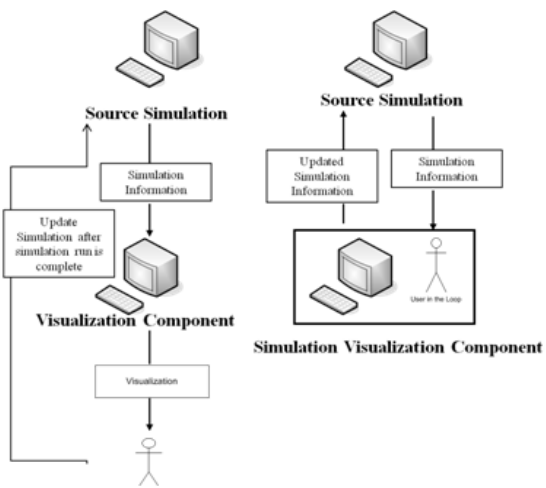


Fig 2. Conceptual differences between post-run visualization mechanisms (left) and the developed HSV framework (right)

In the post-run construction simulation visualization mechanisms (shown in figure 2-left), the decision maker simply watches a post-simulation recording of the simulation events. Also, the tight coupling between the simulation and the visualization components requires more effort for developing both. On the other hand, the HSV

framework (figure 2-right), gives more freedom in choosing the visualization component to connect to the source simulation. For example, three different experiments were carried out using three different platforms as visualization components inside the HSV framework; AutoCAD Civil 2009® for data extraction into the simulation, TrueVision® 3D engine to visualize a simulation of bidding processes in the construction industry and finally Blender® gaming engine as the visualization component in an industrial construction simulation federation. These experiments demonstrated the flexibility that is inherited in this framework. Inside the HSV, the developer can choose the visualization engine that would fit his/her needs either by using an engineering application such as AutoCAD to extract data into the simulation component, or by opting to visualize the construction operations that will take place through more flexible 3d engines or having both at the same time. The framework has this flexibility inherited in it due to the underlying HLA distributed simulation standards. The following sections describe one of the experiments mentioned earlier in more details.

Visualization of industrial construction simulation

The simulation mimics the process of pipe modules manufacturing, starting from the pipe spools fabrication process going through the various stages of the modules assembly at the module yard up to the final stage of installing these completed modules on site. The spools fabrication involves the processes of pipe cutting, fitting, welding and testing. The completed spool is then passed to module yard. In the module yard, each module is assembled at a predefined bay. The pipe spools that compose this module are moved to this bay where the assembly of the spools into the module takes place. Once the module is complete it is transported to site. Site construction sequence depends on the modules installation program (schedule) and if its predecessor has already been installed in its final location at site or no. In this simulation, each of these phases is represented by a certain federate. Visualization of processes in two of these phases is achieved through two separate federates. The architecture of these federates in relation to the whole federation is represented in figure 3. Communication between visualization federate and the federation is enabled through a number of layers.

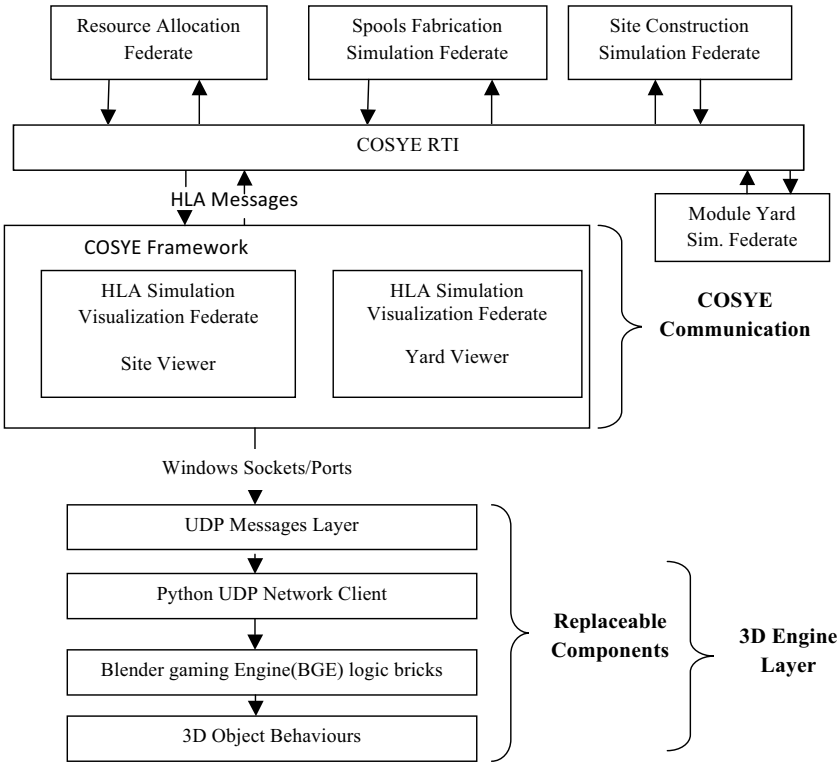


Figure 3 Framework used in simulation/visualization of pipe modules assembly and their site installation

The first layer consists of the following:

- Simulation Federates: Where all the simulation of the various spool fabrications and spools assembly takes place. These federates produce the statistics needed by decision maker. Spool Fabrication Federate, Site Construction Processes Simulation Federate and Module Yard Simulation Federate are shown in figure 3.
- Other Federates: Resource Allocation Federate is responsible for allocating the various cranes to lift/move certain modules to their final location on site. Cranes are assigned to modules based on the cranes availability and their fitness to handle that module.
- Visualization Federates: Federates that read (subscribe to) the objects' (cranes and Modules) attributes and detect changes in these attribute values and communicate these attribute values with a secondary layer of the framework that contains the visualization engines.

The second layer consists of the visualization engines, which were based on Blender Gaming Engine® in this experiment. Two screens are provided for the user to interact with; one showing installation of modules at their final location on site and the other showing modules assembly progress with simulation time in module yard before transporting it to the site.

The two visualization federates subscribe to the attributes related to modules' locations and percentage completion in the FOM of the framework. These attributes are published by the simulation federates. Once the attributes are published, the viewer federates read them and send a message containing the module unique identifier (module ID), module state and its percentage completion to the Blender Gaming Engine (BGE). The communication between the Viewer Federates and the BGE takes place through a User Datagram Protocol (UDP) similar to a client-server connection that is used to send messages between various systems on a network. The server part on the Blender' side is based on a Python API. This API controls the 3D movement and displays it on the screen as the simulation proceeds.

The visualization federate provides the following:

- The logical sequence of modules installation on site (for example the top module can't be installed without the bottom installed first or the middle module cannot be installed before the left/right module's installation). This can't be understood by merely looking at the simulation results.
- The progress of modules assembly together with the bay it is assigned to, so the user can know the bay occupancy schedule during the course of the assembly process.
- A check for the logical flaws in the processes simulation. For example if a module appears in the visualization to be installed before its predecessor is in place, then there is a delay in the assembly/installation of the predecessor module, this means that there is something wrong in the manufacturing schedule of the modules in this case.

Figures 4-1 & 4-2 show some screenshots from the visualization engines and viewer federates implemented in the industrial construction simulation visualization using HSV framework:

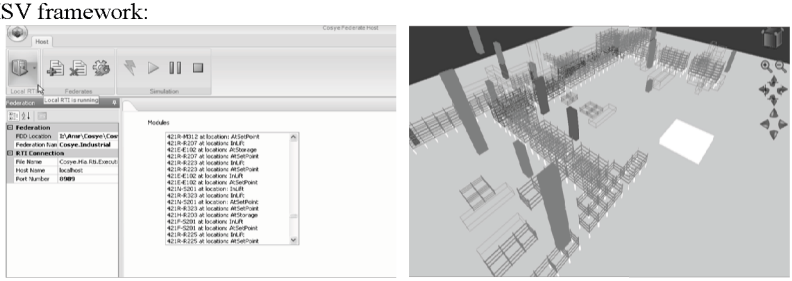


Figure 4-1 Site Viewer Federate and Site Visualization using Blender®

Figure 4-1(left) shows the message in the list box which is sent to the Blender, it simply tells the BGE® (Blender Gaming Engine) to recall a certain module using its module unique identifier, followed by its location on site. Once a module is "At Set Point" then it appears in its predefined location based on the design drawings.

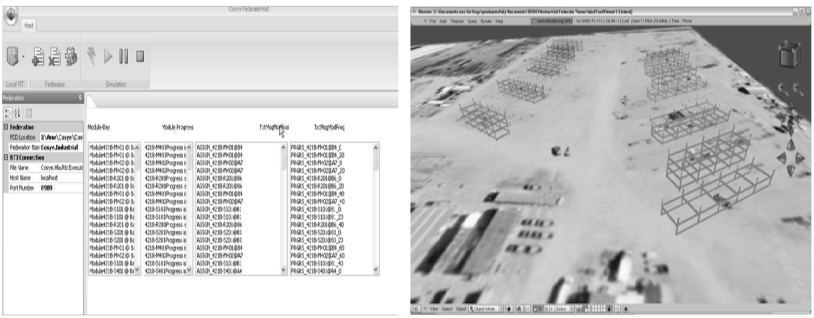


Figure 4-2: Yard Viewer Federate and Yard Visualization using Blender®

Figure 4-2 (left) shows the message sent to the visualization BGE. One message which is in the list box called "Module-Bay" which tells the visualization engine which module goes to which bay based on the simulation. The other message contains the changes in percentage completion of a module during the simulation run

Future Developments:

Currently, development is in progress to make the visualization engine on the second layer of the framework communicate back with the simulation federates, so that a user can update the simulation during its run through the 3D visualization engine. Also, work is in progress to utilize this framework to assist in dynamic site layout planning by defining the logical obstacles on site and deciding on crane paths.

Conclusion:

This paper presented a prototype framework (HSV) for construction operations simulation visualization using distributed simulation approach. The framework is characterized by a loose coupling between the simulation algorithm and the visualization mechanisms. It separates the simulation and visualization components from each other, which removes any compromises on the strengths of any of them. This separation also provides more flexibility and allows the framework to be used to view a wider spectrum of construction operations by enabling the addition or replacement of the simulation/viewer federates or the 3d engine. The HSV framework's potential has been put to test in experiments. A sample case for visualizing industrial construction simulation is presented, and shows the ability of using the proposed framework to harness the power of existing 3D engines.

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An Integrated System to Select, Position, and Simulate Mobile Cranes for Complex Industrial Projects

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Abstract

Determining feasible mobile crane configurations and positions on a complex industrial construction projects that are free of spatial conflicts and the subsequent scheduling of the lifts is important to the productivity and safety of a project. This paper focuses on the integration of a crane dimensional and capacity database with a project's lifted object information to select and position the cranes and then utilize expert knowledge to simulate the heavy lift plan. The system uses dimensional and coordinate data instead of CAD software for computation of crane position areas amongst known obstructions and boundary limits. The crane position area is specific to a crane model and identifies where the center of rotation of the crane can be placed without having any part of the crane body contact the known obstructions and boundary limits. This analysis is performed for multiple cranes and lifted object scenarios to develop a list of possible options. Schedule date constraints and logic are used to simulate and optimize the schedule and crane selection. This provides the practitioner with an effective planning tool to select, position and schedule cranes.

Keywords

Mobile crane; site layout; Heavy lift planning; simulation

Introduction

Construction of a heavy industrial project utilizes expensive mobile cranes to lift

large and heavy pieces of equipment and modules. Due to the magnitude of such large projects and the fast tracked nature of the project, the analysis and selection of mobile cranes is often performed during the pre-construction phase where limited data is available. Plot plans, usually in 2D CAD format are available along with a list of equipment including their weights and dimensions. Some preliminary elevation views of the project may add the third dimension to the project. Historical knowledge of similar projects is sometimes used to assist in the analysis. Complete 3D models are not available until later in the detailed design phase of the project.

To perform the analysis, the experienced lift engineer identifies the piece or pieces of equipment or module that will likely establish the size and configuration of the crane. As is common in the industry, the minimum and maximum radius circles area placed around the center of the object on a plot plan using the object weight and crane capacity as the criteria. The overlapping areas between the crane radius circles for various objects represent is analyzed for optimum crane location based on various criteria [Lin et al. 1996]. The crane position is normally chosen manually by the lift engineer, and a preliminary lift study is developed. This preliminary lift study contains information such as the crane configuration data, crane capacity, load information, percent of crane capacity, layout drawing of the crane on the project, and usually a 2D elevation view where the boom clearance is checked against the object and obstructions. Custom spreadsheets may also be used as a quick method of determining boom clearances.

Use of 3D project models and insertion of crane models to check for clashes have become more common recently due to technological advancements. Some authors have developed a database to house crane dimensions and load capacity information [Al-Hussein et al. 2000] and have developed an algorithm to determine the most suitable crane configuration [Al-Hussein et al. 2001]. Software has also been developed by manufacturers as well as crane and construction companies that access dimensional and crane capacity data to select a crane for insertion into a 3D model but requires user defined crane positions and object trajectory paths. Developing the proper position of the crane body and analyzing the movement of the crane boom is a challenging process that some professionals dealt with for two crane lifts [Smith 2006] using a heuristic search solving three problems with increasing levels of complexity or using a digital plan and simulating the construction operation. Time animation of crane lifts is also achievable through programs in the market with some customization.

These developed programs are typically performed for a single crane lift of one object. Schedule and crane cost optimization, if performed, and cost analyses are usually done separately and manually. Automation and optimization of the schedule, crane selection logic, and crane location are not integrated into these programs.

Few experienced lift engineers have sufficient knowledge or time to integrate the functions of lift analysis into an automated crane positioning, clash detection, logic of crane selection, construction simulation, and schedule and cost optimization program.

Without this functionality, the analysis for all objects and possible crane configuration and locations would be time consuming, thus are not analyzed in entirety.

Researchers employed various mathematical representation techniques to optimize the layout planning methods, namely hybrid artificial intelligence components where a knowledge based database or a fuzzy quantifier played a critical role [Beltagi and Hegazy 2001] and such recent developments in lean theory [El-Ganainy et al. 2007] allowed for better planning in space optimization. Computation based on symbolic model formulation used the input condition that is governed by the positions of facilities relative to the crane [Choi and Harris 2001]. In the construction industry, mathematical algorithms are recognized as a powerful tool for optimization process operations. They are well known and recognized but not easy to develop like in other industry field such as in electrical works. Multi-tasking operations, complex spatial movement of the all construction equipment and materials are complicated to model and analyze. Despite the difficulties, some authors try to model and solve decentralization design problems for a satellite system [Murase et al. 2005]. They show mathematically the challenges created by having multi-objective subsystems, where a method based on set-based design alleviate some of these challenging issues. Others determine possible locations of mobile cranes based on discrete-event simulation incorporating dynamic behaviors of cranes [Tantisevi and Akinci 2008] or concentrate on crane/space scheduling issues [Zhu and Lim 2005; Zouein and Tommelein 2001]. Solutions to spatial collision or interferences problems evolve where the collision detection algorithm is developed for virtual reality applications [Takemura et al. 1998].

Research objectives

This paper focuses on integrating a mobile crane selection and positioning with simulation to plan and schedule the various lifts based on knowledge based heuristic rules. The approach uses data centric mathematical computation of the crane position areas. The crane position area is specific to a crane model and identifies where the center of rotation of the crane can be placed without having the crane body contact the known obstructions and boundary limits. This analysis will be performed on multiple crane and lifted object scenarios. The crane positions areas are partially optimized to points to develop a list of possible crane configurations and their positions. The lifted object delivery dates, resource and schedule constraints, and the list of crane options are used to simulate and optimize the heavy lift program. Post analysis animation is used to visualize the results.

Methodology

In order to develop the framework to support computational analysis of lifting multiple objects for multiple crane configurations, data must be made readily available. There has been considerable effort in entering crane dimensional and capacity data into the industry company database (see figure 1). It currently contains 312 cranes, 25735 crane configurations, and 390,000 capacity entries. Along with the crane data, project specific information is needed to identify the lifted object

information such as dimensions, coordinates, weights, elevations, dates, and crane selection logic. This data is entered manually into the database or through a customized interface within AutoCad that links to the project database (see figure 1).

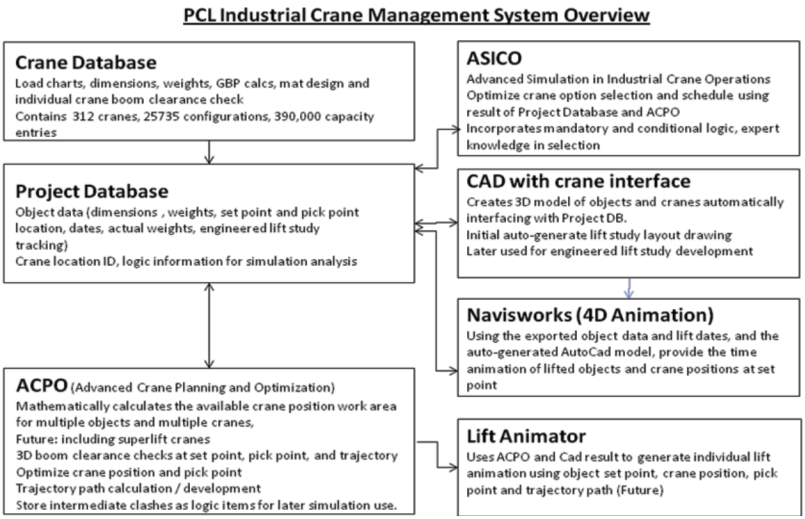


Figure 1 PCL Industrial Crane Management System Overview

The Advanced Crane Planning and Optimization (ACPO) research project noted in figure 1 encapsulates the field operation and engineering expert knowledge with the company's crane database to provide lift engineers with an automated project crane selection, positioning, and 3D trajectory analysis. This decision support system employs advanced mathematical theorems to solve static and dynamic spatial tasks. It lists all available crane options providing the crane configuration, crane location, and pick point that meet the required spatial and capacity constraints. The first part of this process will be described in this paper.

The resulting crane options developed by ACPO are accessed directly by ASICO (Advanced Simulation in Industrial Crane Operations) to use expert knowledge in selecting the best crane configuration and location based on given schedule and logic constraints. The result of this second decision support system will provide the best suitable crane and respective lift date for each object as calculated by the simulation model. The post simulation schedule is then visually presented using the CAD model of the project. This CAD model can be auto generated from the database or obtained directly from the engineering company. The project 3D model and developed crane models are imported into an off-the-shelf animation software (Navisworks) using the dates from the simulation to provide a 4D animation of the project heavy lift schedule.

Development of the Crane Position Area

A 3D model of the project is usually not available during the preconstruction phase of a project. Utilizing the available two dimensional plot plan of a project, the object and boundary data is entered either manually into the project database or through a custom CAD interface that is linked to the project database. The object and obstruction dimensions, 3D coordinates, object type, and weight are entered in the CAD interface as shown in figure 2 below:

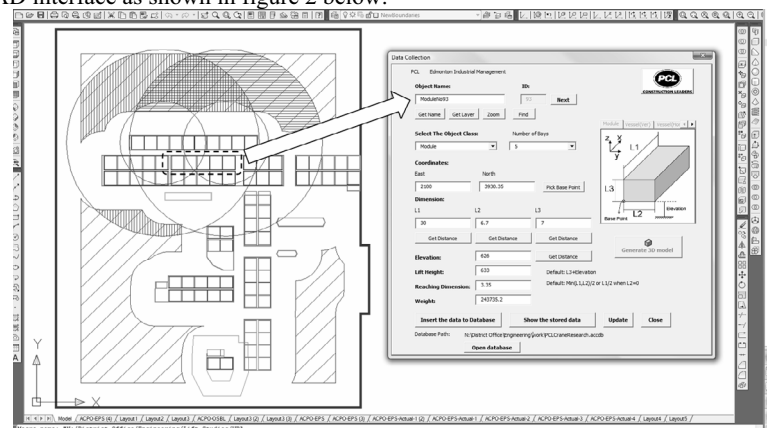


Figure 2 CAD Interface for entering Object Data into the Project Database

The project database contains lifted object data, list of desired cranes, date constraints, lift study tracking, scheduling logic criteria, transport and storage data, and activation of the simulation engine. A screenshot of the project database interface is shown in figure 3:

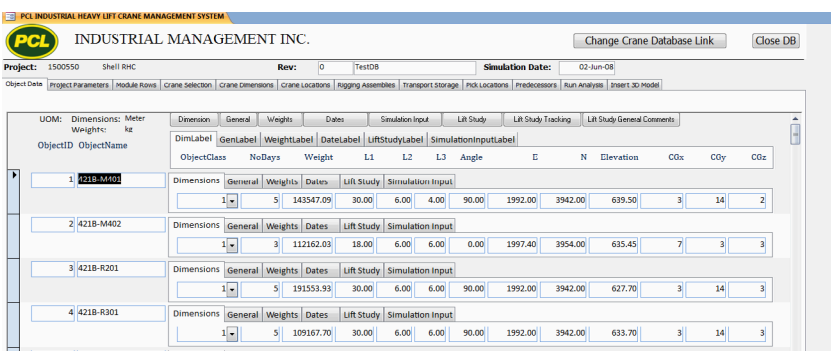


Figure 3 Project Database Interface Screen

To develop a 3D model, these objects are auto-generated through code programmed in AutoCad using information from the project database. This 3D model is also used for developing lift studies.

To further define the first part of ACPO, the crane body work area is calculated by a series of algorithms using data residing in the databases. The project plot plan is divided into several areas. The first is to define the outside boundary limit/s representing the physical outside boundary of the available project construction area. The area occupied by existing obstructions or other construction activities inside the boundary limits are determined next. The area between these two represent where the physical body of the crane can reside. An offset dimension is required from the crane's center of rotation in order to define the crane body work area. This offset is the mobile crane's tail swing or the outrigger diagonal dimension plus an additional safety buffer clearance dimension (see Figure 4 and 5).



Figure 4: Crawler Crane Tailswing

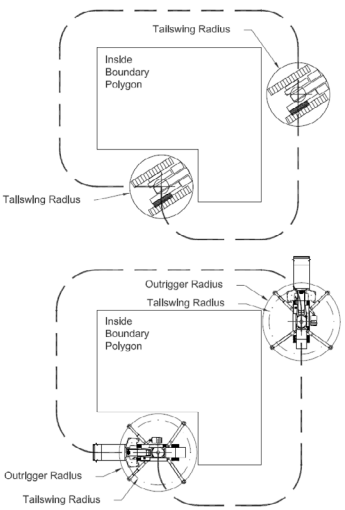


Figure 5: Offset from Crane's Centre of Rotation

The issue of using a crane with superlift will be dealt with in a future paper. This method of determining the offset can be used for any 2D geometrical shape and stores the data for further analysis. The following Figure 6 describes this phase.

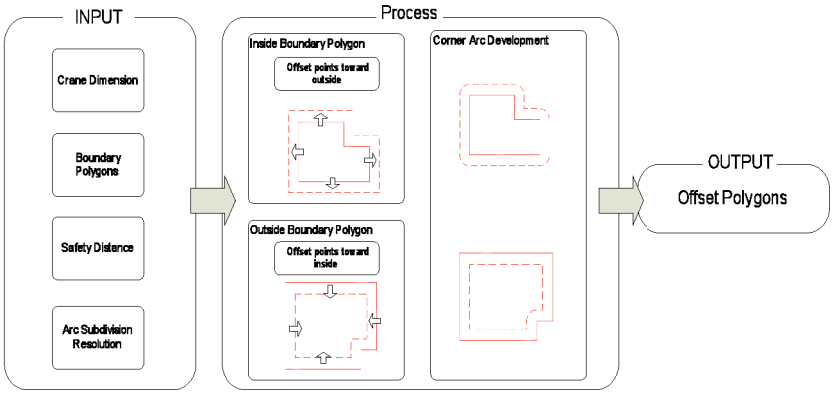


Figure 6 Crane Body Work Area Development Flowchart

An example of a project where this methodology was implemented is shown in figure 7. The crane body work area is clearly seen, and represents where the centre of the crane can be placed knowing that the tailswing rotation of the crane will not come into contact with either the interior or exterior boundary limits.

The crane body work area noted above does not take into consideration the weight of the lifted object and the corresponding minimum and maximum radius that the specific crane configuration can handle. As is common in the industry, the minimum and maximum radius circles area placed around the center of the object. The overlapping areas between the crane body work area and these radius circles represents where the crane can make the lift based on capacity. The crane capacity data and minimum and maximum radius is obtained electronically from the crane database for the corresponding crane configuration selected in the project database. The boom clearance and trajectory check is also performed at specified intervals around the perimeter of the crane position work area and is reduced accordingly to reflect the specified criteria. These calculations, though not described in detail in this paper, are performed using algorithms without the use of CAD software. The crane position area analysis is done for every lifted object entered in the project database. The result is exported into CAD for visualization and shown in figure 8. Area 'A' is the crane position area for object 1 whereas area 'B' is for object 2. Area 'C' is the area where both objects can be lifted with the same crane.

It is important to note that the chosen methodology is based on areas, and not on a grid system. Defining the crane position area is useful in various stages of development to show the available crane position area for specific objects, for overlapping areas for crane position optimization, and to validate the final chosen crane positions. It is also useful when meeting with site personnel to visually represent the feasible crane options.

Determining the best specific crane locations within the areas can utilize methodologies similar to [Lin 1996] that uses various criteria to evaluate the options. When multiple crane configurations, crane locations, and objects areas are analyzed, several thousand options are generated. This would be hard to achieve without integration of the various system and the automation described above. The resulting crane options are then analyzed by ASICO, a simulation based program which determines schedule the cranes and objects using the best option based on date and heuristic expert knowledge criteria. The schedule data result of the simulation is passed to a software program (Navisworks) that creates a 4D animation of the project using the auto generated 3D model developed from the object data in the project database. A time snapshot of this animation is shown in figure 9:

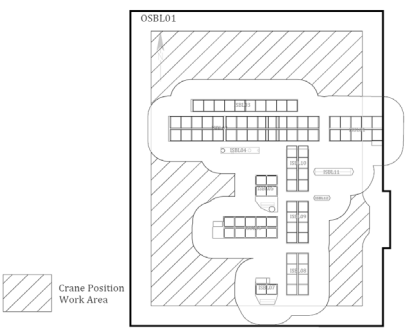


Figure 7 Project Crane Body Work Areas

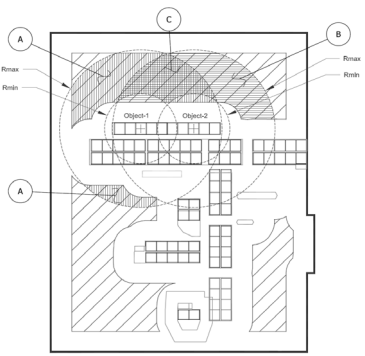


Figure 8 Crane Position Area for given objects

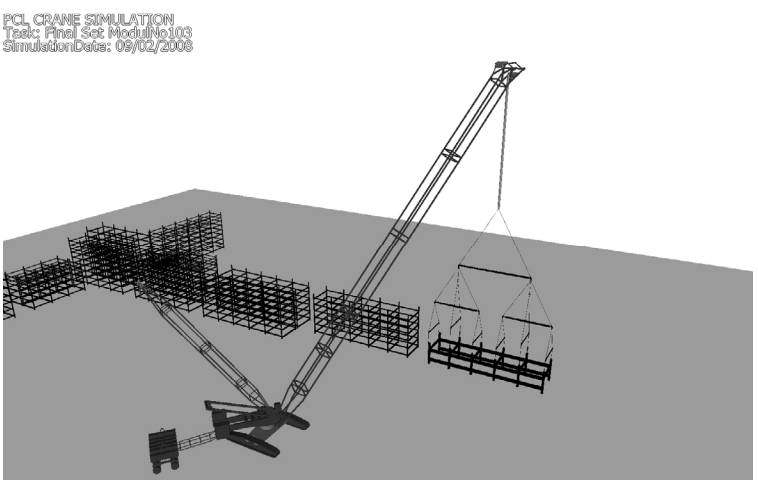


Figure 9 4D Animation Snapshot of Crane Heavy Lift Analysis

Conclusion

Heavy industrial projects involve complex analyses to determine the crane selection, the positioning of the crane, and the scheduling of lifts. Without automation and integration, this analysis is heavily dependent on experienced lift engineers who choose the crane and position based on intuition and experience, and do not check every possible alternative. To overcome these limitations, a methodology and program was developed to integrate the crane data, project information, CAD model, expert knowledge, and simulation to provide all the possible crane and location options based on given criteria, and subsequently optimize the selection and heavy lift schedule.

The developed crane database contains dimensional and capacity information, and the project database provides object dimension, coordinate, weight and date information. This information is accessed by the ACPO (Advanced Crane Planning and Optimization) program to calculate the crane position areas specific to a crane model and identifies where the center of rotation of the crane can be placed without having the crane body contact the known obstructions and boundary limits. The overlapped areas are then optimized to provide a crane position point. The result is a list of crane options (configuration and location) for each lifted object that takes into account all the spatial and capacity constraints. Such an extensive list of crane options could not be practically developed using traditional methods that rely heavily on the practitioners' intuition and experience. The list of crane options is analyzed by ASICO (Advanced Simulation in Industrial Crane Operations), is a simulation based model to optimize the schedule of cranes and object placements based on heuristic expert knowledge logic. Its output together with the auto-generated 3D model is then visually represented in a 4D animation for an easily understandable project execution plan. This integrated system is a useful decision support system for lift engineers and project personnel to effectively manage the heavy lift program of a complex industrial project.

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An Optimization Model for Dynamic Multi-project Environment in Construction

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Abstract
This paper introduces a mathematical model and an optimizer to optimize dynamic variables of construction operations in multi-project environment. Vulnerable nature of construction schedules, resource limitations, multiple objectives, project uncertainties, business priorities and other inevitable constraints make the operations very challenging. The ultimate outcome of the model is to improve construction business efficiency and productivity in terms of profitability and resource management. The model consists of two main components; theoretical model and an optimizer. The first part is the formulation of the theoretical model considering all the multi-objective variables using mathematical descriptions, assumptions and equations. The second part is the solution using special purpose discrete-event simulation and genetic algorithms (GA). An example with real life project data is presented to demonstrate the application of the proposed model. The results offer the best solution for conflicting objectives of minimizing multi-project schedules, maximizing resource utilization and maximizing the profit while satisfying all the imposed constraints.

Introduction

Research study shows that 90% of all projects, by value, are carried out in multi-project context (Turner 1993). In contrast, the vast majority of practical and theoretical developments on project management have been related to single projects considered in isolation (Evaristo & Fenema 1999). The current demand for higher quality of living and greater technological development has meant that large construction projects are increasing in number and complexity year by year. Many problems and issues associated with multi-project environment (MPE) are documented in literature. Some of the very common issues are as follows:

- Getting attention from senior management (Olford 94; Lycett et al 2004)
- Resource management (Dumond&Dumond 93; Olford 94; Payne 95; Eskerod 96)
- Establishing a good and dynamic scheduling (Olford 94; Payne 95; Wang 2005)
- Effective communication and coordination (Olford 1984; Ferns 1991)
- Risk management (Eskerod 1996)
- Management structure for MPE (Merwe 1997)

In a MPE, the management of engineering and construction companies are interested in (1) taking care of all the projects in different phases (e.g. a number of projects are under construction, some of them are waiting for start, while others are in bidding stage and quite a lot of projects are in conceptual stage); (2) having a structured approach for taking "go" or "no go" decisions during project selection; (3) looking for an optimum (better solution within the feasible zone) program schedule that incorporates major decision variables of the company, project delivery system, individual project objectives, driven factor and priority; (4) dealing with uncertainties; and (5) monitoring the projects by preparing checklists and reports regularly related to site and management issues for improvement. They also want simultaneous solution or optimum solution for multi-objectives problems e.g. timely completion of all the projects on one hand and effective utilization of available resources on the other hand.

The goal of the study explained in the paper is to develop an integrated optimization model based on simulation and genetic algorithm (GA) with an aim to address and answer the questions as mentioned above. The paper demonstrates the optimization methodology with an illustrative example of ten building construction projects. The model can be applied to any construction projects with minor modifications of the parameters and constraints as suitable to.

Previous Studies

The previous studies related to MPE are explained under the following four categories.

(a) Multi-project management critique

Table 1 illustrates relevant past researches on the multi-project environment and respective management issue addressed by them. It is readily apparent that a few attempts were made for solving optimization problem. Most of the researcher considered one or two issues in isolation for managing multiple projects. Kandil (2005) developed an advanced multi-objective optimization model for highway construction. The problem was to minimize construction time & cost, while maximizing its quality. In their study, Wang & Schonfeld (2005) introduced a methodology for evaluating waterway systems and optimizing the selection and scheduling of interdependent projects by using simulation model (for assessing waterway system performance) and genetic probabilistic model, in which, its application is limited to interdependent projects in large waterway networks. The optimization model developed by Wiley et al. (1998) focused to the initial design and development of multi-project programs. Their intention was to provide the program

manger with a vast array of alternatives to investigate different options in designing and initiating multi-project programs.

Table 1: Recent past research in the multi-project management

Author	Management issues					
	Planning	Sched.	Res.Mgt.	Control	Cost	Opt.
Dumond & Dumond, 1993			X	X		
Ferns, 1991	X					
Fatemi & Ashjari, 2000		X	X			
Kandil, 2005		X			X	X
Lycett, 2004	X					
Maio et al., 1994	X			X		
Merwe, 1997				X		
Olford, 1994	X					
Payne, 1995	X			X		
Wang & Schonfeld, 2005		X				X
Wiley et al., 1998	X					X

(b) Mathematical model for construction operations of MPE

There is lack of evidence that any mathematical model developed for solving multi-objective optimization problem in construction. However, mathematical modeling technique has been applied in many areas for resolving various real life problems for many years. Alattar (2003) developed a mathematical model to optimize for container terminal operation. The approach was to develop an integer program using set theory and partitions. He considered two objective functions, the waiting time for vessels and the waiting costs for container. The ultimate goal was to minimize for these objective functions. Maji (2008) developed a GA based multi-objective algorithms for highway alignment design optimization.

(c)Advancement of simulation in construction

Construction simulation was first introduced by Halpin in 1973 with the development of CYCLONE modeling methodology. It was a construction-specific process simulation technique with a small abstract set of modeling elements. There have been a few significant developments in this area since CYCLONE. They include: simulation model for earthwork operation, tower crane operation, concrete pouring, PERT scheduling, etc using Simphony environment (Hajjar & AbouRizk 1999). Most of the templates focus a specific area of construction operation rather than overall optimization. Another study by Lee and Miller (2004) for multi-project management focused on developing a simulation model using system dynamics principles. Their model was designed and applicable only for the software industry. A little evidence

was found in the literature where researchers attempted to develop simulation model for analyzing multi-project schedules of construction in MPE.
(d) Genetic algorithms based optimization models
A number of research efforts have developed genetic algorithms that search for optimal solution. Li & Love (1997) formulated time-cost trade-off problem as a single objective optimization problem. Zheng et al. (2004) developed a genetic algorithms-based approach for time-cost optimization. The objective functions were minimizing duration and project cost. Hegazy and Kassab (2003) presented a new approach for minimizing cost applying flowchart based simulation tool and GA. The model was used to determine the least costly, and most productive amount of resources that achieve the highest benefit/cost ratio. Marzouk and Moselhi (2004) developed a framework using computer simulation and genetic algorithms for minimizing time and cost of earthmoving operations. All of these models were mainly intended and applicable for single project environment.

The simplified objectives of the study current study are:

1. develop an influence diagram for MPE
2. identify and prioritize the factors related to optimization of schedules, resources and business decisions in the MPE
3. develop an optimization framework and methodology
4. develop a theoretical model to formulate multi-objective problem in terms of mathematical equations and algorithms
5. develop a simulation model for analyzing multi-project schedules, and
6. develop a GA-based optimization model for solving multi-objective problems.

Optimization Methodology
The optimization model was developed on the basis of conceptual framework as shown in Figure 1. The model has two main parts: (1) the "theoretical model", and (2) "solution procedures" or optimizer. Again the theoretical model can be divided into three components such as (i) problem definition, (ii) algorithms formulation, and (iii) mathematical solution. On the other hand, the solution procedures consist of seven components such as (i) input database, (ii) the simulation model, (iii) simulation output, (iv) the genetic optimization model, (v) integration of GA model and the simulation model, (vi) the GA model output (optimal solution), and (vii) model validation.

Part 1: The Theoretical Model
The purpose of the theoretical model is to define a construction multi-objective problem in terms of algorithms and find mathematical solution. Due to page constraints of the paper, detail discussion will be limited to deriving relationship equation between two key decision variables (project duration and resource requirement) of the theoretical model. The word "project duration" means here the time required (in months) to complete the construction work of a project and "resource" means the manpower resource required (in number) for a project and directly deployed by the general contractor.

a) Objective – mathematical modeling of a multi-objective problem in construction including defining the research question, identifying and quantifying factors/variables, setting mathematical assumptions and developing mathematical relationships for objective functions, variables (e.g. time-resource relationship, project cost break down), and constraints.
b) Approach – multi-objective optimization using set theory, series expanding (Binomial theorem), derivatives (Calculus) and discrete algebraic equations.
c) Deliverables – a mathematical model for constr. multi-objective problem.
d) Results/outcome – mathematical optimum solution to the problem.

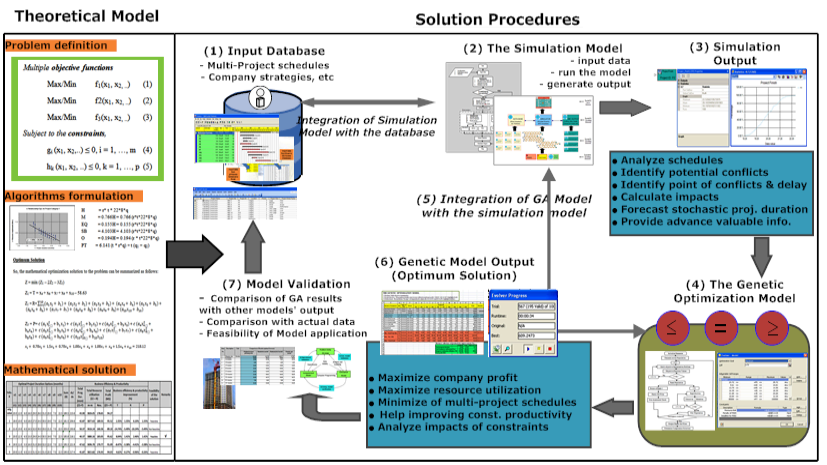


Figure 1: Conceptual framework of the study

Deriving relationship between project duration and resource requirement

Project duration (t) and resource requirement (r) are the two key ingredients of the proposed optimization model. These two variables are very critical for the success of any project. There is lack of evidence in the literature where mathematical relationship was derived between t and r for a typical high-rise building construction. Following is the brief description of formulating this relationship.

"Work" can be defined as the time required for completing a task or assignment.

So, Work = Resource assignment * Time required = Or, $W = r * t$

Assuming that W is constant for a specific project/work package.

i.e. $r * t = \text{Constant}$ i.e. **$r = \text{Constant} * 1/t$**

That means if duration of a project decreases then resource required normally increases and vice versa. However, the rate of change for increase or decrease will not be the same for all type and size of project. A number of similar nature and type of projects were investigated to derive a suitable relationship between time and manpower resource requirement. Necessary data were collected from three leading

construction companies as mentioned in the acknowledgement section using the questionnaire survey form shown in Table 2. The data were then analyzed and graphed for developing the t-r equation. Figure 2 illustrates the time-resource graphs for one of the five categories of high rise building construction projects with duration of 9 months. The nature of graph was found close to linear although not totally linear. From practical point of view, a linear regression line was considered that builds the equation for that particular category. The x and y-axes represent the duration and resource requirement for completing the project respectively. It is noticed that time and resources are inversely proportional to each other i.e. if the value of one variable decreases then the value of other variable increases.

Table 2: Questionnaire survey form for collecting project data

Project Resource Allocation Data (only for building construction projects):

Project No.	Project Info					Manpower (GC's own staffs)	Remarks
	Brief Description	Duration (Months)	Year of completion	Value (M$)	Self-Perform Trades (Tick as apply)	(Nos.)	
					• Concrete • Formwork • .....?	3-5 6-10 11-15 16-20 21-25 26-35 36-45	

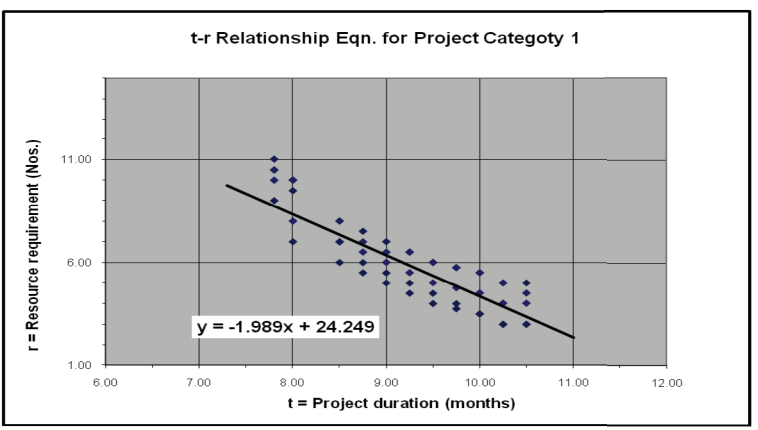


Figure 2: t-r relationship equation for project category 1 (duration ~ 9 months)

Using the graph (Figure 2) and equation, one can find the corresponding value of t and r. For example, if x (project duration) = 9 in the equation then the y (resource requirement) value = 6.348. This information is very important for adjusting the t-r values of projects in searching of optimum solution to business objectives. The building construction projects were divided into five categories. The t-r equations for categories 2, 3, 4 & 5 were derived in the same way as summarized in Table 3.

Table 3: The t-r equations for five categories of building construction projects

Category	Project dur. (months)	t-r equation	Type of project
1	~ 9	**y = -1.989x +24.25**	High-rise building construction
2	~15	**y = -1.034x +26.20**	High-rise building construction
3	~24	**y = -1.318x +47.64**	High-rise building construction
4	~36	**y = -1.436x + 72.40**	High-rise building construction
5	~48	**y = -1.202x + 86.00**	High-rise building construction

Part 2: The Solution Procedures or Optimizer

The solution procedures can be divided into seven components as follows. The outcome of the mathematical model has triggered the road map for finding the practical optimum solution to real life problems, which are described below.

1) Input database – this is basically creating a database collecting all the necessary information e.g. project info, multi-project schedules, resource allocation plan, constraints, and project risks. MS Access® was used for creating this database.

2) Simulation model – this is to develop a discrete-event simulation model and integrating using Simphony.NET environment for analyzing the multi-project schedules. It was designed to simulate the progress of construction work. It has total 16 modeling elements in four levels such as level 1 (root element), level 2 (database, program and simulation output), level 3 (database portfolio, project start, link, work package, project finish, report 1, report 2, report 3 and report 4), and level 4 (risks, constraints and capture duration), as shown in Figure 3.

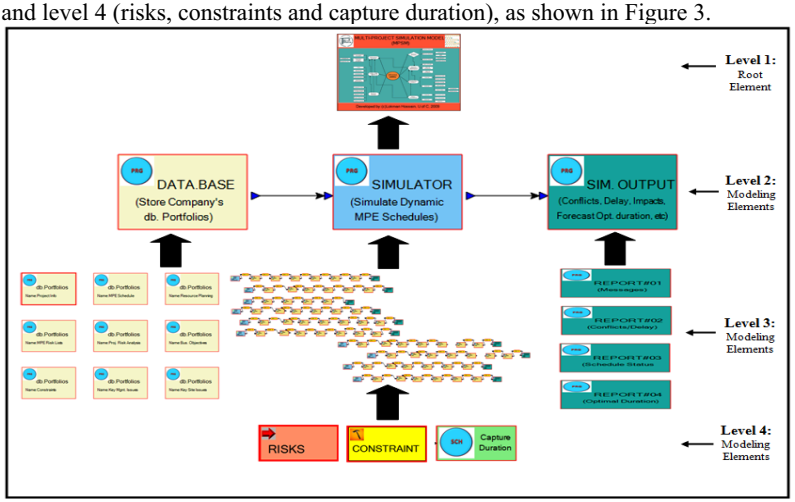


Figure 3: Hierarchical structure with modeling elements of the simulation model

The model was integrated with the database such that many of data can be retrieved automatically from the database into the model. Key input parameters for the simulation model include project info (e.g. project priority, project delivery system, etc), info about project level schedule or bid schedule (e.g. project start, logical relationships among work package, etc), manpower resource required, uncertainty (e.g. description, probability, impact, etc). Some of the uncertainty variables that were considered in the model are a) urgent change order, b) sub-trade's performance, c) shortage of resources, and d) unexpected events. Also these variables were modeled as the sub-model of "project start" modeling element. Interested readers may refer to the paper Hossain & Ruwanpura (2008) for further detail information about the simulation model.

3) Simulation output – The simulation model is designed to generate four different kinds of output – messages for the decision makers, project conflicts or delay, schedule status and optimal duration forecast for projects. Figure 4 shows an example of one of the key output of the sim. model i.e. forecasting stochastic duration for projects given the conditions and uncertainties. Table 4 illustrates the summary of forecast duration (min., most likely, max.) of all individual project.

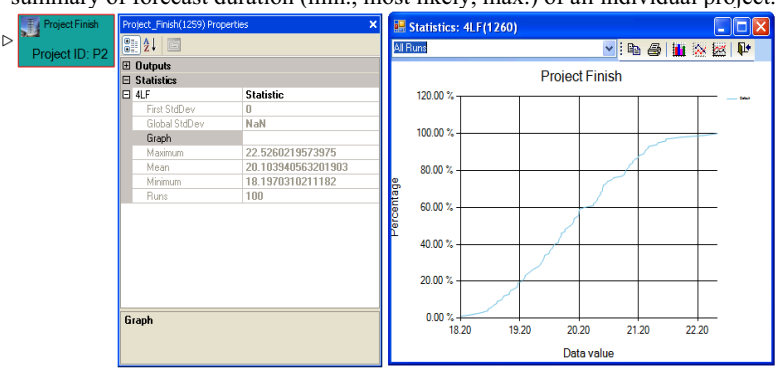


Figure 4: Forecast of stochastic duration for project P2 (statistics and CDF graph)

Table 4: Simulation output – summary of forecast duration for all projects

Project No.	Project ID	STATISTICS Optimal duration (months)		
		Min.	Most likely	Max
1	P2	18.20	**20.10**	22.53
2	P3	10.65	**11.78**	13.21
3	P4	4.22	**6.31**	8.49
4	P5	12.71	**13.94**	15.24
5	P6	21.03	**30.90**	38.09
6	P7	18.37	**24.99**	30.96
7	P10	20.86	**28.81**	34.50
8	P11	12.59	**18.73**	26.18
9	P15	7.77	**8.63**	9.71
10	P17	20.63	**22.68**	25.29

4) Genetic optimization model – the genetic optimization model was designed considering a number of parameters, mathematical equations and constraints for solving multi-objective problem. Mainly company level data and some of the project level data were required to drive this model. The performance of the

model has been demonstrated by solving a problem with three conflicting objectives - (i) minimizing schedules (Z_1), (ii) maximizing resource utilization (Z_2), and (iii) maximizing profit (Z_3). The relative weight for Z_1, Z_2 and Z_3 were considered as 1, 2 & 3 respectively. So the weighted average of objective functions were defined as $Z = \min (Z_1 - 2Z_2 - 3Z_3)$. Input variables considered – project duration (t), resource required (r), cost of manpower, cost of materials, cost of equipment, cost of sub-contracts and cost of overhead. Also in this optimization model, five constraints were considered namely – company resource limit (max = 190 nos.), minimum target profit ($90M), penalty for project P5 if delays more than 16 months, and deadline for project P15 and P17. It has the capability of solving for near optimal solution to any complex problem.

5) Integration of GA model and the simulation model – The GA model was integrated with the simulation model for using the output data shown in Table 4.

6) GA Output – once the problem was defined, the GA model was ready to search for near optimal solution. The results show the optimum values for each of the objective function. It will also indicate the improvement in business efficiency and productivity in terms of schedule, resource utilization and profitability.

Table 5 illustrates the optimum solution for the example problem with ten projects. The compromise optimum values for the objectives functions are T (program duration) = 37.87 months, R (total resource utilization) = 185 nos. and P (overall profit) = $97.29M compared to the original values of 43.90 months, 178.65 nos. and $94.27M respectively. The solutions indicated an improvement in business efficiency by 13.74%, 3.43%, and 3.20% in terms of time, resource utilization and profitability (Please see bottom right hand corner of Table 5).

7) Model validation – The optimization model were validated using the validation techniques of a) data validation, b) conceptual model validation, c) computerized model verification, d) operational validation, and e) comparisons of results with actual project data. Detail discussion is out of scope of the paper.

Table 5: Output of the GA model

	Business Parameters	Unit	Type of Data	Source	Project ID P2	P3	P4	P5	P6	P7	P10	P11	P15	P17	Total	Remarks
10	Orig. Project Schedule	mon	Determ.	P6	20.00	12.00	6.00	16.00	29.00	26.00	31.00	20.00	7.00	22.50	43.90	
11	Orig. Res. allocation		Determ.	Planning	21.28	13.79	12.32	9.66	30.76	13.37	27.88	21.28	10.33	17.99	178.65	3,826.05
12	Original Estd. Profit			Planning											94.27	
13	Project Duration	mon	Stochastic	Sim. output	20.13	11.78	6.23	13.93	30.82	24.96	28.29	18.72	6.99	22.29	41.78	Dec. Variable
14	Manpower Reqd.	Nos.	Stochastic	t-r eqn.	21.11	14.02	11.86	11.80	28.14	14.74	31.77	22.96	10.34	18.26	185.00	Dec. Variable
15	Cost of Manpower (H)	$M	Stochastic	Math. Model	10.47	4.07	1.82	4.05	21.37	9.07	22.15	10.59	1.78	10.03	95.40	Variable
16	Cost of Materials (M)	$M	Stochastic	Math. Model	8.02	3.12	1.39	3.10	16.37	6.94	16.97	8.11	1.37	7.68	73.08	Variable
17	Cost of Equipment (EQ)	$M	Stochastic	Math. Model	1.62	0.63	0.28	0.63	3.31	1.41	3.43	1.64	0.28	1.55	14.79	Variable
18	Cost of Subs (SB)	$M	Stochastic	Math. Model	42.96	16.70	7.47	16.61	87.68	37.20	90.88	43.47	7.31	41.15	391.42	Variable
19	Cost of Overhead (O)	$M	Stochastic	Math. Model	2.03	0.79	0.35	0.79	4.15	1.76	4.30	2.06	0.35	1.95	18.51	Variable
20	**Total Cost**	$M	Stochastic	Math. Model	65.10	25.30	11.32	25.18	132.88	56.38	137.72	65.87	11.08	62.36	593.19	Variable
21	**Total Revenue**	$M	Stochastic	Math. Model	74.92	31.21	14.47	32.22	147.51	68.90	151.45	75.27	14.76	73.77	684.48	Variable
22	**Min. -Total Prog. Dur.**	mont hs	Stochastic	GA model	20.13	11.78	6.23	13.93	30.82	24.96	28.29	18.72	6.99	22.29	37.87	Objective #1
23	**Max. - Res. Utili.**	m-m	Stochastic	GA model	424.92	165.15	73.88	164.32	867.28	367.96	898.91	429.94	72.32	407.02	3,871.70	
24		Nos.	Stochastic	GA model	21.11	14.02	11.86	11.80	28.14	14.74	31.77	22.96	10.34	18.26	185.00	Objective #2
25	**Max. - Total Profit**	$M	Stochastic	GA model	9.82	5.91	3.15	7.04	14.63	12.53	13.73	9.40	3.68	11.41	97.29	Objective #3

Business efficiency & productivity improvement (%)	Original	Final	Improved (%)
Total program duration	43.90	37.87	13.74
Total manpower utilization (Nos)	178.65	185.00	3.43
Manpower utilization efficiency (%)	185.00	185.00	100.00
Total profit ($M)	94.27	97.29	3.20

Conclusions

This paper presents a methodology and tools for optimization of dynamic multi-project environment in construction. First, a theoretical model was developed to formulate the problem in terms of mathematical equations and algorithms. Secondly, a discrete-event simulation model was developed for analyzing the vulnerable multi-project schedules, identifying potential problems, calculating cumulative impacts on project and overall program, and forecasting optimal duration for project completion. The simulation model can be used for any number of projects regardless of project size, type of resources, project delivery system and other business strategies and constraints. Thirdly, a GA-based multi-objective optimization model was developed for solving complex construction multi-objective problem with conflicting objectives subject to a number of constraints. While the theoretical model provided necessary optimization concept and algorithms, the simulation output data provided the basis for optimizing project schedule and resources, the GA-model performed the final part of the optimization to find the compromise optimum solution of the problem.

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BIM-Integrated Sustainable Material and Renewable Energy Simulation

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ABSTRACT

The primary goal of the research is to investigate the discontinuities between current energy modeling tools and the implementation of sustainable features within the models they produce for better envelope design and construction material selection. From previous research efforts, it was discovered that energy modeling has made advances within their integration to early and mid level design phases, particularly through the use of Building Information Model (BIM) and the Green Build eXtensible Markup Language (gbXML) file type. However, it was also discovered that BIM-integrated energy modeling tools are often lacking in their ability to incorporate renewable energy sources such as photovoltaic panels, wind turbine, and geothermal wells. This paper introduces strategies to include such sustainable fixtures to predict energy generation with a case study of Zero Net Energy Test Home(ZNETH). In addition, this paper introduces parametric analyses for better envelope design and construction material selection by analyzing simulated energy consumptions with various parametric inputs, e.g., material types, location, and size.

KEY WORDS

Energy Modeling, Energy Analysis, BIM, Zero Net Energy

1. INTRODUCTION

The University of Nebraska-Lincoln has started an innovative research project to build a Zero Net Energy Test House (ZNETH). The project was started in June of 2008 and is expected to be completed by the summer of 2010. The main objective of the test bed home is to address the best method of designing and constructing houses that has a negligible effect on the environment. Engineering students and faculty from the construction and architecture departments are engaged in the research to address the required specifications and appropriate materials that should allow for a zero net energy scenario. Some of these specifications and materials have been chosen while others are currently under examination. ZNETH has been designed to comply with the frame work of the Leadership in Energy and Environmental Design (LEED) Platinum certification rating from the US Green Building Council's LEED for home requirements.

The ZNETH project has been used to investigate several research objectives. For this paper, the main objective is to address the discontinuities between current energy modeling tools and the implementation of renewable energy features within the models they produce for better envelope design and construction material selection.

2. BACKGROUND

2.1 The Zero Net Energy Test Home (ZNETH)

ZNETH consists of two floors and a basement (Figure 1). Several sustainable systems have been proposed and implemented with this project. Insulated concrete forms (ICF) were installed for the basement walls and the walls at the north, east, and west of the first floor. 2x6 framing with closed cell, soy based spray foam is planned to be used for the south wall of the first floor and all second floor walls. The home is clad with an Exterior Insulation Finishing System (EIFS). In addition, various high efficiency window types were selected to reduce solar heat gains during summer months and heat losses during winter months. Horizontal and vertical geothermal wells were also incorporated into the house's design. The horizontal well was looped at 8 ft deep, and the two vertical wells were drilled to 150 ft. In addition, to lower the energy consumption of heating system, a radiant floor system will be used in the first and second floors to eliminate the use of a furnace for heating the house.



Figure1 Zero Net Energy Test House (ZNETH)

To make the house more efficient and sustainable, a wind turbine and solar panels have been selected as the energy producing resources for this project. It was assumed that the total produced energy from the wind turbine and solar panels would be more than the house consumes. If successful, the unused energy can be sold back to a

power company using a net metering system. The maximum assumed energy produced from the wind turbine is 2 kilowatts-hour (kWh). kWh is a rate of power consumption equal to 1000 watts for one hour. Likewise, a maximum of 2 kWh rate is expected to be produced by the solar panels that were installed on the roof.

2.2 Building Information Model (BIM)

In this study, two different BIM processes were conducted for the ZNETH energy modeling: object-oriented geometric information modeling (e.g., envelop, doors, windows, walls, zones, etc.) with a BIM tool and 3D building energy modeling (e.g., materials, heat resistance, location, weather data, etc.) with an energy simulation tool. The main advantage of using this approach is that the 3D geometric building information is transferred to the energy simulation tool rather than recreating 3D geometric information again from the energy simulation tool.

2.2.1 Energy Simulation Modeling

After examining several energy programs, Autodesk's Ecotect v5.6 was selected for the energy simulation. Ecotect has a variety of energy analysis functions. In 2005, the US Department of Energy examined 20 energy programs to provide an overview of their features and capabilities. Ecotect was defined as a complete building design and analysis software (Crawley et al. 2005). One of the most powerful features that Ecotect offers is its ability to view analysis results in various formats such as graphs, tables, and 3D objects (Riether and Butler 2008). Ecotect is a stand-alone energy analysis program capable of applying energy analyses such as thermal, solar, acoustics, and lighting throughout early design phases. Moreover, Ecotect allows results to be mapped directly over 3D objects, creating a more intuitive design process (Crawley et al. 2005). Ecotect can import and export a number of file formats such as IFC, gbXML, 3DS, DXF, and VRML.

2.2.2 Geometric Information Modeling

ZNETH was modeled using Constructor 2008, which was developed by Vico Software. From the previous study (Cho et al. 2009), gbXML was identified as the most accurate interoperable file format between BIM and energy programs. Figure 2 shows the BIM models before and after the exporting process from Constructor to Ecotect.

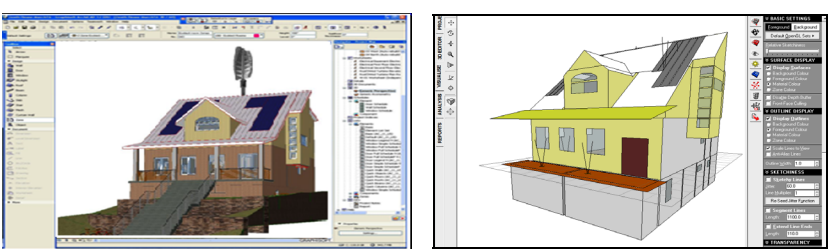


Figure 2 Geometric BIM in Constructor (left) and Exported BIM in Ecotect (right)

3 APPLYING THE RENEWABLE ENERGY SOURCES INTO THE ENERGY MODEL

Ecotect has a variety of tools and functions to perform the required analyses however, there are limitations of modeling the renewable energy resources within the model. For example Ecotect has 1) a limited solar panel tool, 2) no wind turbine tool, and 3) no geothermal system function. The strategies that have been taken in this research to solve those limitations are discussed in the sections that follow.

3.1 Photovoltaic Panels

To calculate the produced energy from the photovoltaic panels (PVs), two data sets have to be available: the electrical efficiency percentage which is unknown in this study, and the available solar radiation for different seasons. Ecotect has a specific tool that operates as a PV where some specifications can be entered manually like the electrical efficiency percentage and space heating. However, the tool does not have an option to calculate or enter the available solar radiation for different seasons. Therefore, the electrical efficiency percentage was calculated using the trial and error method to find the required percentage that would produce the expected energy amount using the average available solar radiation for Omaha Nebraska. That solar radiation was found to be 4.6 hour / day (Radarsign 2008).

3.2 Wind Turbine

The inclusion of a residential wind turbine was difficult to implement into the energy model due to Ecotect's inability to directly incorporate one. To solve this issue, some appliances available in Ecotect have an option of adding daily produced energy. To calculate the daily produced energy of the turbine, the mean annual wind speed of Omaha was assumed as 5.5 miles (8.85 kilometers) per second based on the official Nebraska Wind Resources Record. Then the mean wind speed was used to extrapolate the expected annual amount of produced energy from the wind turbine (Figure 3) (Helixwind 2007). Next, the annual produced energy (1000 kWh/year) was divided by 365 days to produce the theoretical daily energy output of the turbine (2.74 kWh/day). Finally, the obtained theoretical output was tagged to the appliances in Ecotect.

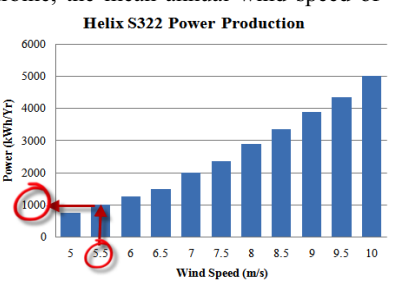


Figure 3 Wind Turbine's Stated Energy Production (Helixwind, 2007)

3.3 Geothermal System

The geothermal system affects two aspects of the energy analysis: the thermal analysis and the energy consumption analysis. Ecotect does not have a function to

calculate the thermal effect or the expected energy consumption of HVAC systems affected by a geothermal loop. To solve these issues, two steps were taken. First, for the thermal analysis, a natural ventilation system was added to each room to mimic the effect of the geothermal and radiant floor systems. Second, TRACE 700, another commercially available software which has a specific tool for the geothermal system, was adopted to calculate the total consumed energy of ZNETH. TRACE 700 can be used to design and analyze building's energy consumption. Extensive information, such as a room's area, volume, location, appliances specifications, schedule, as well as their structural components need to be available to build a model in TRACE 700. The calculation procedures are based on the American Society of Heating, Refrigerating and Air-Conditioning Engineers manual (ASHRAE 1997).

4 ANALYSIS RESULTS

The cumulative energy generated by the PVs and the wind turbine were 2,219 kW/year and 1,000 kW/year respectively. Thus 3,219 kW were estimated as the total generated energy in a year.

By using TRACE 700, the total consumed energy of ZNETH was estimated at12,189 kW/year. Figure 4 demonstrates a comparison between the total cumulative energy consumption (brown line), total cumulative energy production (yellow line) and the total cumulative energy consumption after subtracting the energy production (red line). The graph shows the produced energies from the solar panels and the wind turbine as not being enough to cover the total electrical consumption of ZNETH.

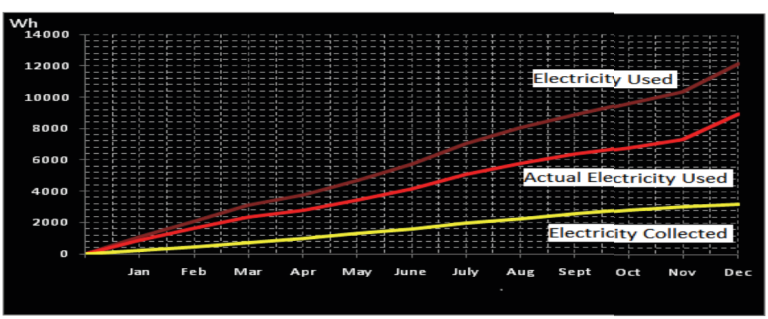


Figure 4 ZNETH's Calculated Energy Production vs. Energy Consumption

5 PARAMETRIC ANALYSES

Examining a number of different design alternatives, especially from an economic perspective, throughout initial design phases help design teams attain a more concise perception of what the most economically and environmentally efficient strategy should be taken. Therefore, theoretical changes have been made to ZNETH's energy model and tested to investigate what the most efficient design of the home could have produced.

First, the overhang width was tested to find the most efficient width that would block the sun radiation during the summer months only. Additionally, some windows have been resized and relocated to increase natural light levels. Second, a model was built similar to the ZNETH, but with the newly proposed design changes. This new model was notated as ZNETH-NEW. A comparison was conducted between the ZNETH-current, which is the as designed model with no changes, and ZNETH-NEW using four different wall material scenarios.

5.1 Resizing the Overhang

A 2.4m width overhang was built atop of ZNETH's front porch as shown in Figure 5. Using Ecotect, a solar analysis was conducted to calculate the total monthly solar radiation transmitted through the front windows of the living room throughout the year, and found to be 139.95 kW/year. The low value indicates that the as-built porch overhang is overdesigned, minimizing the sun's radiation to the front windows during all seasons

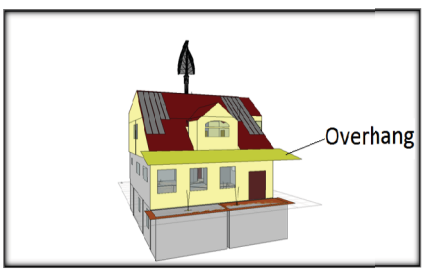


Figure 5 The Transmitted Solar Radiation After Resizing the Overhang

To promote a more practical approach to the amount of solar radiation entering from the main floor's front windows, the overhang width has been analyzed. Through simulations with various sizes of overhang widths, 1.1m was identified as the most efficient overhang size to provide the highest shading percent during the summer months while allowing for a larger amount of solar radiation to enter during the winter, spring and fall months. The simulated total transmitted radiation was 390.10 kW/year. As shown in Figure 6, there is a smaller amount of transmitted radiance through the summer months when using the newly designed overhang. However, there is more radiation during the spring, fall and winter seasons, that helping to increase the heat sources available to this room. Also, the design would reduce the required heating loads, in turn decreasing the total energy consumption of the house.

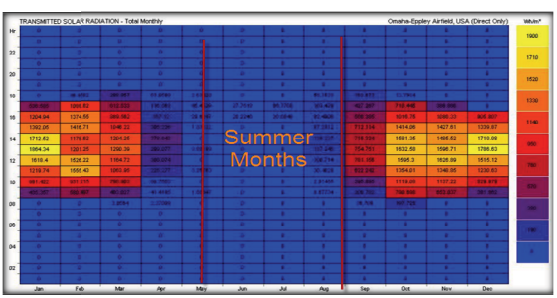


Figure 6 Transmitted Solar Radiation of Optimal Overhang (lighter color shows higher radiation)

Using TRACE 700™, a consumption analysis was conducted to calculate the expected heating load and the total consumed energy of the whole year for the

ZNETH model before and after redesigning the overhang. The heating load needed to regulate the house's temperature has been reduced by 204 kWh/yr. This is because there is more solar radiation entering the living room during winter, fall and spring months. Also, this heating reduction would further minimize the total energy consumption of the house by 189 kWh/yr. Table 1 shows a summary of the analyses that were conducted by Ecotect and TRACE 700 on ZNETH before and after optimizing the overhang.

Table 1 Results of the Overhang Analysis from Ecotect and TRACE (kWh/year)

Analysis type	Before	Suggested design	after	Improvements
Ecotect Transmitted radiations	139.95	Optimizing the overhang for the living room	390.10	250
TRACE Total heating load	2,430		2,226	204
TRACE Total consumed energy	12,189		12,000	189

kWh: Kilowatt-hours

5.2 Resizing Windows

To improve lighting levels on the second floor, three windows in the second floor were enlarged and relocated to allow for more natural light into the house. These windows were selected because they did not have any obstruction that would block the sun light. By using Ecotect, the effect of the day lighting levels was tested before and after resizing the windows (Figure 7). Based on the as-built design, rooms (1), (2) and (3) have an average of 160 Lux, 110 Lux, and 45.5 Lux (lumens per square meter) respectively. By resizing the windows in rooms (1), (2) and (3), the available

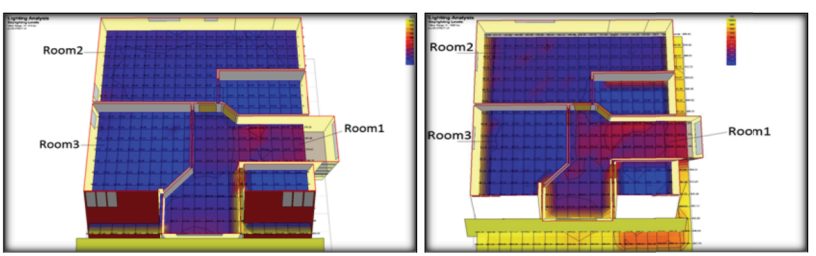


Figure 7 The Daylight Levels as Designed (left) and After Window Resizing

daylight was increased over the previous results by 88.33 Lux.

5.3 Material Selection

After investigating the most efficient overhang size and second floor window size and location, a parametric analysis of materials already being used in the house was conducted using Ecotect and TRACE 700.

The first scenario analyzed was that of the as-built external walls of ZNETH. In the basement Insulated Concrete Forms (ICFs) with an R-Value of 26.34 h.ft^2.^{o}F/Btu was used. While 2x6 stick framing filled with closed cell soy based spray foam with an R-value of 34.55h.ft^2.^{o}F/Btu was used. The second scenario incorporated the use of ICFs in all external walls with the concrete core thicknesses at 4", 6", and 8". The third scenario mirrored that of a typical 2x6 framed home with traditional batt insulation and 8" concrete foundation walls. The last scenario replaces the batt insulation of the framed walls in the third scenario with the closed cell soy based spray foam. The table below summarizes each setup.

Table 2 Summary of the Four Scenarios and Their R-values

	Description	**Floors**	**R-value (ft^2.^{o}F h/Btu)***
Scenario 1	As designed	basement	26.34
		first and second	34.55
Scenario 2	ICF-4"	basement, first and second	26.17
	ICF-6"		26.34
	ICF-8"		26.5
Scenario 3	Typical home insulation (2x6)	basement	12.19
		first and second	21.65
Scenario 4	Closed cell soy based spray foam	basement	22.22
		first and second	34.55

*1 ft² F° h/Btu = approx. 0.1761 K.m²/W

Using the setups above, parameters were loaded into the two energy models and a thermal analysis was conducted using Ecotect, while a total consumed energy analysis was conducted using TRACE 700.

5.3.1 Thermal Analysis

Hourly thermal analyses were conducted to compare the heat gains between the two models. The hourly thermal analysis calculates how much heat is obtained through the wall material on the hottest day in the area, which is July 26th. Table 3 shows the heat gain through the wall materials, in kilowatt-hour (kWh) for ZNETH-current and ZNETH-NEW, under the four scenarios. As can be seen, the ZNETH-current under the first scenario has the lowest heat gain because this scenario has a higher thermal resistance value (R-value). On the other hand, the ZNETH-NEW under all the four scenarios showed a high heat gain because enlarging the windows reduced the thermal resistance (R-value) of the second floor's walls.

Table 3 The Heat Gain Through the Materials in Kilowatt-Hour (kWh)

	Description	ZNETH- current	ZNETH-NEW
Scenario 1	As designed	16.370	26.403
Scenario 2	ICF-4"	17.587	24.778
	ICF-6"	17.257	24.488
	ICF-8"	17.224	24.457

Scenario 3	Typical house	24.755	33.822
Scenario 4	Closed cell soy based spray foam	17.055	26.692

5.3.2 Consumption Analysis

Using TRACE 700, the total consumed energy analysis was conducted to compare the total consumed energy between the two models. Table 4 shows the total consumed energy for the whole year in kilowatt-hour (kWh/year) for the four scenarios. Enlarging the windows of ZNETH-NEW would decrease the R-value of the walls, which would in turn increase the total consumed energy. On the other hand, applying blinds to the windows have a greater effect at reducing the total energy consumption. Additionally, the use of closed cell soy based spray foam in all external walls was found to be the most energy efficient alternative for both energy models.

Table 4 Total Consumed Energy for a Year in Kilowatt-Hour (kWh/year)

	Description			
		ZNETH - current	ZNETH-NEW	Difference
Scenario 1	As designed	12,189	12,478	-289
Scenario 2	ICF-4”	12,325	12,506	-181
	ICF-6”	12,253	12,487	-234
	ICF-8”	12,179	12,439	-260
Scenario 3	Typical house	15,336	15,494	-158
Scenario 4	Closed cell soy based spray foam	12,079	12,417	-338

6 CONCLUSIONS

The ZNETH project has been used as a case study to address the main objective of this paper, which is to investigate the discontinuities between current energy modeling software tools, and to investigate the implementation of sustainable features within the models they produce. While several energy software packages were examined for possible inclusion in this research, Ecotect was selected as fulfilling the research's parameters. Based on research outcomes, the following conclusions were drawn:

1) Ecotect has a variety of capabilities to perform different energy analyses. However, it lacks tools or functions to simulate renewable energy resources. Other programs such as Trace700 or EnergyPlus are required to simulate energy consumption to supplement Ecotect’s limited functions.
2) A wind turbine can be indirectly added to Ecotect models using appliances, which have an option of adding daily produced energy.
3) The geothermal system can be applied only as a natural ventilation system to simulate thermal effects.

For the parametric analysis, two changes were made: resizing the windows and reducing the overhang size. After analyzing all the changes, thermal and energy consumption were compared between ZNETH-NEW and ZNETH-current. The following conclusions were drawn from thermal analysis comparison:

1) For ZNETH-current, the as-designed materials of the exterior walls were sufficient enough to reduce the heat gains during the hottest day.
2) Enlarging the windows would reduce the thermal resistance (R-value) of the walls which increases heat gains.

The energy consumption comparison has shown the following conclusions:

1) Closed cell soy based spray foam as an insulation material for all walls was found as being the best alternative for both the energy models.
2) Enlarging the windows decreases R-value and increases consumed energy.

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EXPLORING THE EFFECTS OF CONTEXT LEVEL FACTORS ON THE STRUCTURAL STEEL FABRICATION SHOP OPERATION

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Abstract

Structural steel fabrication is influenced by both operation and context level effective factors. Usually the mechanisms through which operation level effective factors (e.g. capacity of equipment and operation sequences) affect the fabrication shop are properly documented within a variety of methods such as equipment manuals, job instructions, standards, quality control charts and ISO documents. However, while context level effective factors (e.g. operators' fatigue level and organizational policies) originate from human behavior, usually their enforcing paths are not well understood like operation based effective factors. This issue usually limits decision makers at steel fabrication shops to accept more inaccuracy by ignoring the effects of context level factors during their analyses. In an effort to address this issue, this research attempts to explore the effects of fatigue (as a context level effective factor) and its affecting dynamics within a steel fabrication shop. A hybrid model of system Dynamics and Discrete Event Simulation modeling approaches has been employed as the main tool for the research.

1. Introduction

Structural steel construction is a major part at many construction projects, ranging from industrial projects, such as refinery, petrochemical complex, and power plant, to the infrastructure and municipal projects, such as bridge, stadium, residential building, hotel, and office building. In order to reduce the total duration and cost of the structural steel construction projects, most of structural steel constructors have

either owned the structural steel fabrication shops or established joint partnerships with them. Because of the mobilization restrictions involved in the project job sites, these well equipped fabrication shops carry out many operations for the steel using specialized and more productive stationary equipment. The fabricated steels, then, are shipped to the job sites to get erected in the form of the designed structure.

In addition to the benefits that use of fabrication shops can put in the structural steel construction, it increases the complexity of the structural steel construction projects by introducing an extra phase, i.e. steel fabrication. Furthermore, to be cost effective, most steel fabrication shops concurrently provide fabricated steel pieces for different projects. These all require further managerial efforts for planning and controlling the assigned projects to the fabrication shop.

In order to come up with more accurate planning and control methods for the shop, in this research we are going to explore some feedback loops between operation (or physical) and context (or nonphysical) level of the fabrication phase, which affect the operators' productivities (see [Lee et al. 2007] for more information). Our focus at this part of the research will be more on the feedback loops related to the operators' fatigue and productivity rate at the fabrication shop. We will link these feedbacks to some control policies that fabrication shop managers have, e.g. adjusting the working hour schedule.

A hybrid simulation modeling approach based on System Dynamics (SD) and Discrete Event Simulation (DES) has been proposed for following the effects of made changes to the policies in the fabrication shop operations. This is a modeling approach which utilizes SD for capturing the system behavior at the context level and employs DES for modeling the operation level behavior of the fabrication shop (refer to [Alvanchi et al. 2009] for more information). This hybrid model will make us capable of applying different alternative policies to the fabrication shop and testing the effects of them on the fabrication shop productivity.

2. Problem Statement

In addition to the direct costs of material, equipment and operators, charged to the steel fabrication shop, holding a fabrication shop will add many indirect costs to the fabrication process. These indirect costs load relatively constant amount of money to the fabrication shops. Meanwhile it should be considered that there is always an easy replaceable alternative option to the fabrication shop that is onsite structural steel assembly. As a result, it is very critical for every fabrication shop to keep its capacities busy as much as it can and to maintain its productivity rate at the highest possible level to stay at a competitive price. Therefore, despite onsite construction works, usually fabrication shops run the night shifts as well as day shifts. The prevalent use of overtime in the fabrication shops is also in accordance with such condition. However, the shop managers should also obey the labor codes enforced by the authorities which defines the main bottom lines regarding the working hours (e.g. Canada Labour Code [is accessible at http://laws.justice.gc.ca /en/L-2/FullText.html] limits the total standard and overtime hours to 48 hour per week).

On the other hand, the nature of the work in the fabrication shop requires considerable physical involvement in the work which creates fatigue in the operators

and reduces their productivity. Furthermore, work safety tools, such as boots, glasses, helmets, masks and gloves, amplify the created fatigue and reduce the productivity. These all generate a situation in which the way that shop managers distribute the standard and overtime working hours during the week can play a significant role at the final achieved productivity. Moreover, there are some parameters such as timing and durations of the coffee breaks during the day and the amount of assigned workloads to the stations which can affect the level of the fatigue and productivity at the stations.

In this research we are trying to model the dynamics of the fatigue and productivity in the working stations which also involves fabrication shop managers control policies regarding the operators' working hours. This model will give shop managers the capability of examining the effects of changes to their set working hour policies and making their final decisions based on that. Although this research mainly gets focused on the mutual effects between fatigue and productivity, the fabrication shop operators can also get their benefits since a minimized fatigue level will be another result of this research.

3. Dynamics of the Fatigue in a Station

Reviewing the research efforts on the relationship between human fatigue and productivity, main effective parameters in this relationship can be listed as in below:

- Overtime
- Length of the continuous work and shift
- Time of the work during the day
- Difficulty and special conditions of the work

In this section we are going to portray the dynamics through which these effective parameters affect the human fatigue and productivity in a fabrication shop station. We will first depict the *basic* dynamic model of a typical fabrication shop station and then each effective parameter will be added as a complementary dynamic mechanism.

3.1. Basic Dynamic Model of a Fabrication Shop Station

Figure 1 presents the basic dynamic model of a typical fabrication shop station using stock and flow diagram (see [Sterman 2000] for more information). According to the *committed work* and *fabrication start schedule*, new works are released to the station. These new works are going to be added to the list or backlog of *fabrication to be done* at the station. Existence of any *fabrications to be done* at the station will make the station status busy during the scheduled working hours. The plus sign (+) at the head of the arrow between the *fabrication to be done* backlog and the *station busy status* resembles a positive relation between them, i.e. the more works on the station's *fabrication to be done* list, the busier station will get kept. A busy station will do the work at the *fabrication finish rate* which is calculated based on the station's productivity rate and *number of operators*. As soon as station does the fabrication jobs, the *fabrication to be done* backlog is depleted and it will be added to the *fabrication done* backlog.

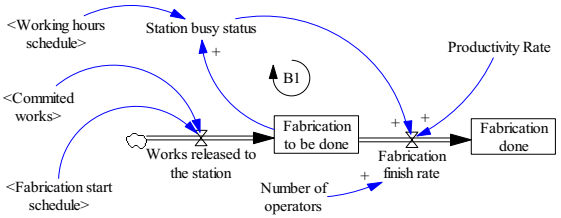


Figure 1. Basic dynamic model of a fabrication shop station

The feedback loop B1 refers to the balancing feedback loop formed by *fabrication to be done*, *station busy status*, and *fabrication finish rate*. The balancing term here refers to the fact that an increase in the value of a variable on this loop would cause a decrease in that variable later on, through the active cause and effect dynamics of the loop. For example on the feedback loop B1, by an increase in the level of the *fabrication to be done,* the *station busy status* will be increased and as a result of that the *fabrication finish rate* will get increased which will result in a reduction at the *fabrication to be done*.

3.2. Dynamics of the Overtime Fatigue

Compared to the standard working hours, overtime working hours during the week will produce more fatigue for the operators. According to the results presented by Sterman (2000), the effects of this overtime fatigue are mainly revealed during the next working week. Feedback loop R1 in Figure 2 represents a simplified reinforcing loop through which the effects of overtime fatigue is conveyed to the productivity rate of the station.

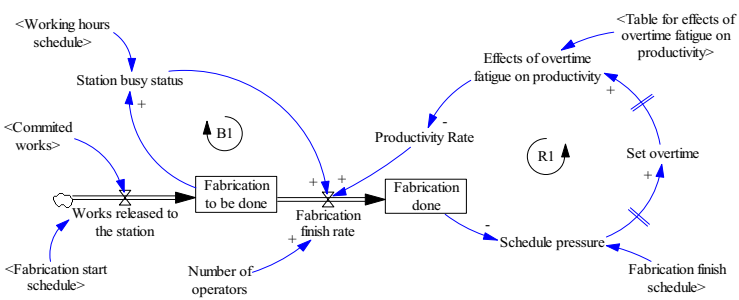


Figure 2. Effect of the set overtime on the work fatigue and productivity rate

In the reinforcing feedback loop an increase in the variables on the loop is a cause for an ensuing increase to that variable in the future. In the feedback loop R1 the schedule pressure is determined as the result of the difference between level of the *fabrication done* and the *fabrication finish schedule*. The minus sign (-) at the head of the arrow between *fabrication done* and *schedule pressure* in the Figure 2 resembles a negative relationship between them, i.e. an increase in the level of the *fabrication done* backlog will result in a decrease at the schedule pressure. An increased schedule pressure may cause the shop managers to increase the *set overtime* for the station.

The *set overtime* hours should be announced to the operators a while in advance to the workers. The double slash on the arrow between the schedule pressure and set overtime in the Figure 2 represents this delay. Based on the set value for the overtime in the previous week and the overtime effects table, *the effects of the overtime fatigue on the productivity* and in the next step the *productivity rate* are determined.

3.3. Dynamics of the Continuous Work Fatigue

Since early 1960's many researchers in the area of ergonomics and occupational medicine have driven various research efforts for deriving the relationship between the human endurance and different levels of workloads (e.g. Rohmert 1973a; Rohmert 1973b; Koparadekar and Mital 1994; Vøllestad 1997; Rosa at al. 1998; Folkard and Tucker 2003; Shih 2007). The results of these research efforts mainly have been used as guidelines or regulations to the work managers to adjust the assigned workloads to their workers. However, in this part of the research we will use these results to investigate the dynamic effects of the continuous work fatigue on the productivity rate at fabrication shop stations.

The reinforcing feedback loop R2 in the Figure 3 depicts a simplified dynamic model for the effects of the continuous work and shift length on the fatigue and productivity rate. Loop R2 starts with a positive relationship between *fabrication to be done* and *station busy status* (which is also in common with the base dynamic model). The value of the *station busy status* (0 or 1) during every period of the time determines the value of *busy time rate* and *idle time rate* flows which adjust the *total busy hours in shift* and *total idle hours in shift* backlogs. At the end of each working shift the total accumulated values at these backlogs gets discharged since the operators in the new shift will receive no effects from the accumulated fatigue at the previous shift. The *effects of continuous work on productivity* can be determined at each period of the time according to its related table and current values of the *total busy time in the shift* and *total idle time in the shift*. At the final step the *effects of continuous work on productivity* will be applied to the *productivity rate* which adjusts the level of *fabrication to be done* and *fabrication done* backlogs.

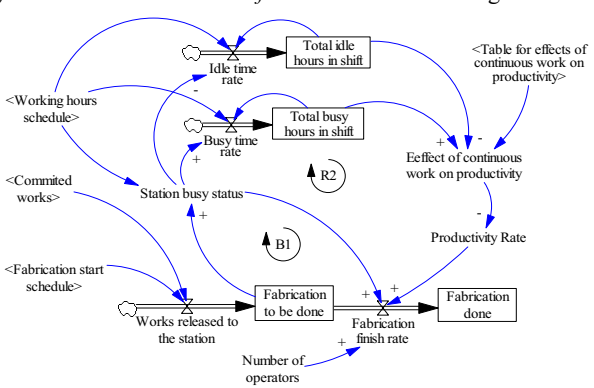


Figure 3. Effect of the continuous work and shift length on the work fatigue and productivity rate

3.4. Dynamics of the Time in the Day and Fatigue

The physiological characteristics of the human force him to not keep an evenly distributed attitude during the day. This issue has been investigated by the researchers in the area of ergonomics and occupational medicine (e.g. Rosa at al. 1998; Folkard and Tucker 2003). In our research we are going to incorporate the achieved results from these research efforts for developing the fabrication shop stations' dynamic model. The effective chain related to the time of the day fatigue has been presented in the Figure 4. Despite the previously mentioned dynamic mechanisms, the *effect of time in the day on productivity* follows a straight line of causes and effects to affect the productivity rate, instead of a feedback loop.

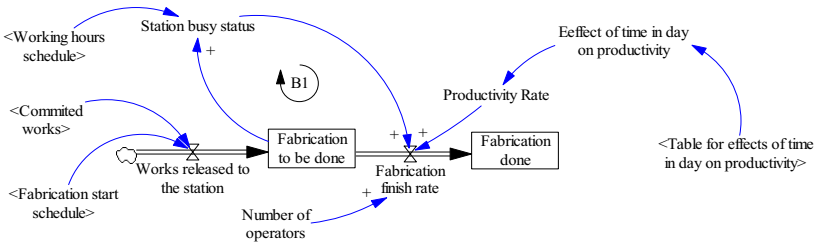


Figure 4. Effect of the time of the day on the work fatigue and productivity rate

3.5. Difficulty and Special Conditions

The presented dynamic mechanisms for the fatigue and productivity rate in the previous sections follow a generic approach which can be applied to different types of fabrication shop stations, e.g. cutting, fitting, welding, and painting. However, it should be taken into account that, depended on the level of physical and mental involvements at each station, the occurred fatigue and productivity rate varies from one station to the other. Furthermore, usually quantified values and curves provided by the researchers have been sampled from special types of works and do not necessarily represent fabrication shop stations' behaviors.

The mentioned issue, more or less, is extendable to many other types of the work for utilizing the provided fatigue data. Though, many research efforts (e.g. Rohmert 1973a; Rohmert 1973b; Vøllestad 1997; Rosa at al. 1998; Shih 2007) have considered different levels of work difficulties in their samplings and have published their results based on these levels. It is significant to know that most of research works have defined the work difficulty level as a percent of Maximal Voluntary Contraction (MVC) which returns to "a maximal exertion of force reported as force (e.g., lb, kg, Newtons) or as a moment around a joint (e.g., Newton-meters, foot-pounds, kilogram-meters)." (Bernard 2006). Thus, one easy way for tuning the provided data to the specific station of fabrication shop (or any other type of work) is to estimate the level of MVC at every station and to develop its related reference tables. In this perspective, every fabrication shop station will have its specified dynamic mechanism and will follow its own behavior as reactions to the applied workload. For example, while, presumably, welding operation requires more level of physical involvement than painting, the estimated MVC level at welding station will

be higher than painting station and the fatigue at the welding station will occur in shorter period of time during its busy status.

4. Fabrication Shop Model

Going one step higher than the station level, a set of corresponding stations constitute the fabrication shop. Within the fabrication shop a station receives steel pieces from previous stations, performs its assigned operation and then sends the pieces to the next stations. Therefore, an appropriate fabrication shop model should be able of concurrently tracking both the interactions at the shop floor and the ongoing dynamics of every single station. In this research we are going to follow the hybrid SD-DES modeling architecture proposed by Alvanchi et al. (2009) for the structural steel fabrication shop model development.

4.1. Hybrid Model Development

The SD modeling approach is the commonly used modeling tool for capturing the dynamics and feedback loops within the systems. As such, the SD modeling approach is going to be utilized as the main modeling approach for capturing the dynamics of the fatigue and productivity rate within every single fabrication shop station. On the other hand, the DES modeling approach is the proper modeling tool that can capture the flow of materials from one station to the other at the fabrication shop floor.

Figure 5 depicts a simplified structure of the hybrid SD-DES model for the fabrication shop. The rounded rectangles at the bottom of the figure linked to each other with straight arrows represent the fabrication shop stations and the flow of material among them. A DES model will capture this part of the fabrication shop. As well, the presented stock and flow diagram at the top of welding station represents an inclusive SD model of the single dynamic models explained in the section 3 which describes the dynamics of the fatigue and productivity rate inside the welding station. This dynamic mechanism works in every station within the fabrication shop.

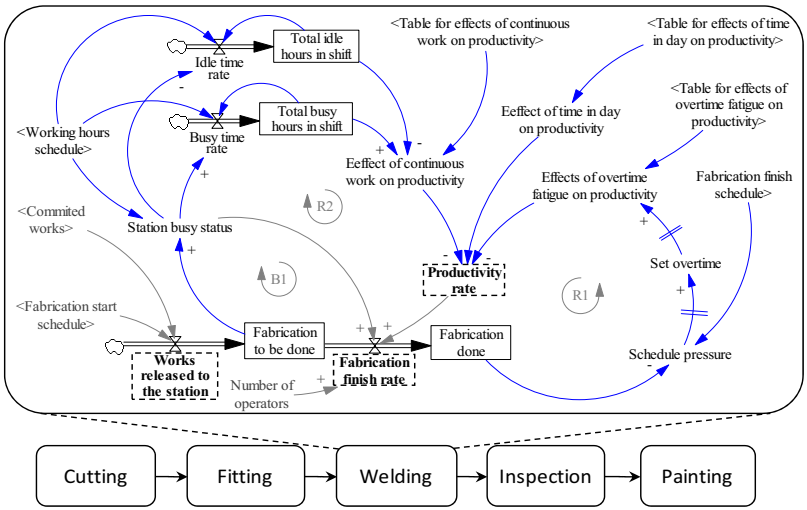


Figure 5. Hybrid SD-DES model of fabrication shop

Three main contact points between SD and DES models have been highlighted in a dashed rectangle with a bold font in SD part at Figure 5 (i.e. *productivity rate*, *works released to the station*, and *fabrication finish rate*). These are the points in which SD models update DES model (for *productivity rate* contact point) and receive updates from DES model (for *works released to the station* and *fabrication finish rate* contact points). On the one hand the contact points which send updates from DES model to the SD model form disconnections in SD modeling parts and might cut off the previously recognized feedback loops in the model. For example, as shown in Figure 5, the SD model receives the updates of the *fabrication finish rate* from the DES model. This means that regardless of previously recognized relationship between *productivity rate*, *station busy status*, and *number of operators*, as the causes, and *fabrication finish rate*, as the effect of them, in the SD model (see section 3.1) *fabrication finish rate* will not get calculated in the SD model and feedback loops B1, R1 and R2 will look uncompleted. All faded variables and relations in Figure 5 refer to this disconnection.

On the other hand, there are also other types of contact points which send updates from the SD model to the DES model, e.g. *productivity rate*. These points are the points which complete the feedback loops and form the hybrid feedbacks between operation and context level of the system. For example, as shown in Figure 5, *productivity rate* is calculated in the SD model and its values are sent to the DES model and the DES model will use these values to come up with the *fabrication finish rate*. But, what really has caused us to not calculate the *fabrication finish rate* directly in the SD model? The answer is: besides the recognized and captured causes in the SD model there are more causes mainly originated from the operational issues, such as station breakdown, crane unavailability and limited working capacities of the next stations, which affect the *fabrication finish rate* of the station. Compared to the SD

modeling approach, these effective factors usually are captured more properly in DES models.

4.2. Model Analysis

The main purpose of developing this hybrid model of fabrication shop is due to investigate the most appropriate combination of the set working hours and time break schedules at the fabrication shop. The key point is that according to the explained dynamics of the fabrication shop, the fatigue level and its consequent productivity rate at each station can dynamically get changed based on the assigned workloads to the stations and the working hours schedule.

Suppose a situation in which shop managers are using a constant working schedule all around the year. Suddenly the fabrication shop becomes committed to a big project. So, fabrication shop will face a tight fabrication finish schedule, the schedule pressure will go up and shop managers are going to set additional overtime for the shop (see the feedback loop R1 in Figure 5). This additional overtime will exert its fatigue effect on the productivity rate and will cause a reduction in fabrication finish rate which will add the schedule pressure. On the other hand, further committed works will result in more work released to the stations (Figure 5). This will increase the busy portion of the time in the stations, the result of which is increased effect of continuous work fatigue on productivity and additional decrease in the productivity rate. In such situations the reinforcing mechanism at both feedback loops R1 and R2 (Figure 5) gets active and can have significant effects on the fabrication shop process. One of corrective actions, which can moderate the mal-effects of this situation, is to shorten the duration between two consequent time breaks, especially when it reaches to the end of the shift. However, it should be taken into account that a real steel fabrication shop is usually a complex combination of different types of stations. Depended on different stations' capacities and volume and types of contracted structural steel projects, the concentration of the workloads at the stations dynamically gets changed within the fabrication shop. In this perspective, without using a robust modeling approach, tracking the effects of any made changes to the work schedule on the productivity will be impossible in a real steel fabrication shops.

The developed model of fabrication shop will enable the fabrication shop managers to test resulting effects of alternative arrangements for the working hour schedule. The model automatically will consider the expected changes to different stations' workloads and will directly reflect the effects of the made changes to the final throughput of the fabrication shop. The schedule arrangement with the best achieved result can be set as the based schedule for the shop. This schedule adjustment process can be done several times during the year, especially for the periods of the year in which there are considerable amount of changes to the types of the committed works for the shop.

5. Conclusion

In this article we introduced a new approach to the way that structural steel fabrication shop manager can adjust the fabrication shop working hours for enhancing the total throughput of the fabrication shop. A hybrid SD-DES model has

been developed for this purpose which captures the mutual effects of the fatigue level, as a context level variable, on the productivity rate, as an operation level variable, at the fabrication shop operations and allows shop managers to examine alternative work schedules for choosing the most appropriate option. While the adjusted schedule, as the main output for our developed model, requires no special investment in the fabrication shop (i.e. no changes to the shop equipment or no additional facilities required), it is expected that the achieved result can be easily enforceable to the fabrication shop. As future research work, we are going to implement the model for a real fabrication shop. As well, we will attempt to explore and add new feedbacks between context level and operation level effective factors to our hybrid SD-DES model.

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Korean Real Estate Market and Mortgage Lending Policies: A Quantitative Approach

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Abstract

The Korean government has announced new policies to regulate mortgage lending, which aim to decrease both the Loan to Value ratio (LTV) and the Debt to Income ratio (DTI); this is due to the recent upturn in house prices and the increase in the number of mortgage loans that have been the result of deregulation policies such as increasing both the LTV and DTI, adopted in the second half of 2008. The government expects mortgage lending policies related in both the LTV and DTI to control housing demand and to stabilize house prices in the influence of market status. However, it is difficult to analyze how effective is these kind of policies on price and demand through an empirical approach. Also, because mortgage loan is a key element of real estate financial market, impact on secondary market in charge of mortgage securitization should be conducted. Consequently, a comprehensive and systematical method is necessary to analyze the effects of new government policies. This paper, therefore, utilizes an integrated perspective and applies a system dynamics methodology to develop Korean real estate market dynamics models. Using these system dynamics analysis, this research understands changes in housing market and mortgage lending agencies, as well as secondary financial market. In addition, the authors use system dynamics simulations to examine the interplay between mortgage loan variations, housing prices, and demand. This research found the missing links of empirical policy analysis and connected these links in order to expose the hidden side effects of these policies, as well as proposed comprehensive solutions and systematic approaches of dynamic systems.

Introduction

The Korean real estate market currently is experiencing an upturn in housing demand and an increase in house price. This is due to policies adopted by the Korean

government in the second half of 2008, which boosted mortgage lending in an effort to increase housing demand. In response to present conditions, however, the government has announced a comprehensive real estate program which will regulate mortgage lending by commercial banks; the program mandates a decrease in both the Loan to Value ratio (LTV: the amount of a first mortgage lien as a percentage of the total appraised value of a real property) and the Debt to Income ratio (DTI: the percentage of a consumer's monthly gross income that goes toward paying debt) in an attempt to control housing demand and to stabilize house prices. However, neither house prices nor consumer demand are expected to exhibit much change due to the existence of secondary lending agencies (e.g., mutual savings banks and credit unions), which can issue mortgage loans and that are unaffected by the new government policies. Consequently, the Korean housing market could fall into deep confusion; an empirical approach to the analysis of the housing market for forecasting is difficult but necessary.

Several analytical studies of real estate policy exist. Shiller and Weiss (1999) proposed a framework for comparing real estate valuation systems through the simulation of mortgage lenders' profits and density estimation. Park et al. (2008) demonstrated the effectiveness of bank lending restrictions and analyzed the relationship between bank lending and apartment prices using real data. However, these studies utilized empirical approaches encompassing only a few factors and did not consider diverse perspectives. Instead, a comprehensive and systematic method is required to analyze the real estate financial market and the causal relationships between market influence factors. Kim (2007) has been the only study that has understood and analyzed the basic mechanisms of the real estate market and market policies in a macro perspective; to do so, Kim used system thinking.

The current paper uses Korean real estate and mortgage market dynamics models developed with an integrated perspective and system dynamics methodology; these models are based on the fundamental principles of and the causal loops found in housing markets and emerge out of the economic activities both of consumers and financial agencies. Dynamics models provide information to decision makers through a comprehensive approach elucidated by diagrams representing feedback loops. This study estimates the effects of current policies upon LTV and DTI ratios using these simulation models.

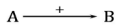
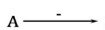
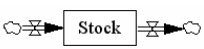
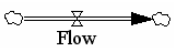
The policy models employed were constructed by concentrating on the law of supply and demand and the price expectations of consumers.

Previous Research

System Dynamics

System Dynamics (SD) is a modeling tool that provides an understanding of strategic problems in complex dynamic systems. An SD model provides system users with insight into the feedback processes and dynamic behavior of a system. Table 1 shows the legends in SD models.

Table 1. Legends in the Causal Loop Diagrams (Sterman 2000)

Legends	Explanation	
	When other conditions are the same	When Factor A increases (decreases), Factor B increases (decreases)
		When Factor A increases (decreases), Factor B decreases (increases)
	Including weighted delayed time between two factors	
	Positive feedback or self-reinforcing loop	
	Negative feedback or self-balancing loop	
	Stocks : Define the state of a system and represent stored quantities, also called 'Levels'	
	Flows : Define the rate of change in system states and control quantities flowing into and out of stocks	

Influence Factors in Models and their Relations

Evidence of a relationship between factors within the real estate market is shown in Table 2. The dynamics models used in this research are based on fundamental economic theories and expert views of market states.

Table 2. Influence Factors in Models and Correlations

Factor A	Factor B	+/-	Sources
credit rating for lending	mortgage loan borrowers ratio	+	Fischer 2005
default probability	borrowers' repayment	+	Fischer 2005
demand	perceived price change	+	Baumol & Blinder 2003
demand response to expected profit	potential demand	+	DiPasquale & Wheaton 2004
expected profit from trading	potential demand	+	Fischer 2005
expected profit of primary agencies	credit rating for lending	-	The Bank of Korea, Lander 2008
expected profit of primary agencies	mortgage loan ratio	+	Lander 2008
Fund of primary agencies	mortgage loan	+	Saunders & Cornett 2005
House Price	default probability	-	The Bank of Korea
House price	demand	-	Baumol & Blinder 2003

House price	expected profit from trading	-	Kim & Kim 1999
Perceived house price	expected profit from trading	+	Kim & Kim 1999
price elasticity of demand	potential demand	+	E. Jung 2005

Policy Models

Price Model

In the housing market, house prices are determined through the acknowledged market principle of supply and demand. However, this study assumes that housing demand generally plays the leading role; supply has been static, with the exception of new town developments which have had only a temporary ripple effect on the market. Since the policy models used are constructed to analyze the policies' effect on areas of over-demand, such as capital regions, the authors ignore supply in this study. Housing price models thus focus on the relationship between house prices and demand in the following manner.

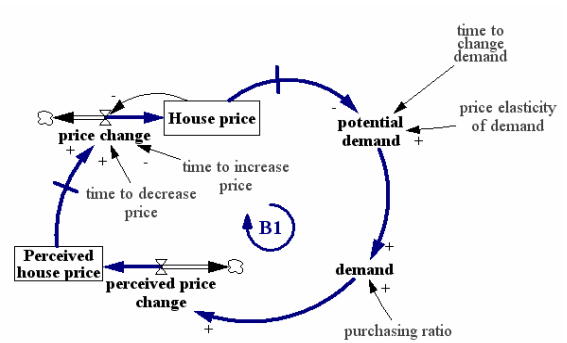


Figure 1. Demand and Price Self-control

Figure 1 shows how house price self-control through demand changes in accord with general market principles. In this model, *perceived house price*—which is defined as the consumer's perception of the possibility of price volatility before the house price is determined—is influenced by *demand* change. When *perceived house price* is transformed into *house price* as a result of housing transactions, housing *demand* is controlled as a balancing feedback process of demand and price in Loop B1.

However, in the housing market, a reinforcing feedback relation of expected demand, price, and profit contrary to general market principles is in play. As illustrated in Figure 2, the *expected profit from trading* is an essential factor in this relationship. The *expected profit from trading* is defined as the householder's expectation that a profit will be produced through a future trade in houses. Further, the *expected profit from*

trading is affected by time variables between the perceived house price and the actual house price.

In the housing market, when housing *demand* is high, consumers expect future house prices to increase (i.e., perceived house price increases). This reinforcing loop shows that *house price* and housing *demand* are caused by mutual rising tendencies.

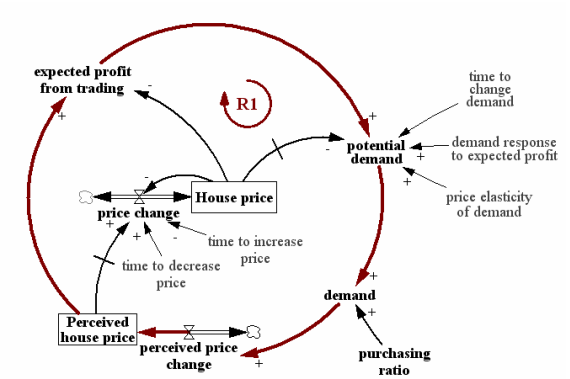


Figure 2. Consumers' Expectancy of Marginal Profits.

Figure 3 shows the result of the price model simulation of consumer marginal profit expectation. House prices are simulated in accord with changing demand and in response to expected profit. The *demand response to expected profit* is defined as a coefficient of demand variation by expected profit change, which has a unit of Won per person. When consumers do not expect a profit, house prices will be stationary and the *demand response to expected profit* will be zero. When consumers do expect a marginal profit, house prices will either fluctuate widely or tend toward a long term upward swing. Previous research, which examined the Boston real estate market from 1961 to 1992 (DiPasquale and Wheaton 2004), revealed a *demand response to expected profit* of 0.00038 [$/Person]. However, this coefficient cannot be applied to the current Korean housing market. Instead, this study assumes a *demand response to expected profit* of 0.000012 (Won/Person), obtained through an analysis of house price tendency in relation to the changing effect of consumer expectations. Applying this value results in a house price tendency in accord with current Korean house prices.

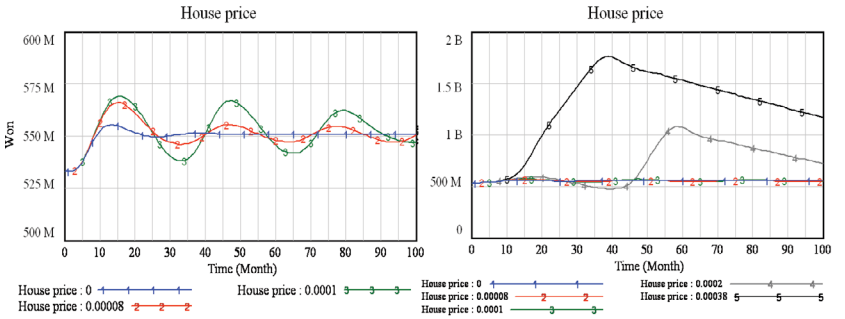


Figure 3. Simulation: House Price Tendencies by Consumers' Expected Marginal Profit

Mortgage Market model

This study describes the general real estate financial market structure, with a focus on mortgage lending, using System Dynamics (SD) modeling (illustrated in Figure 4). The *fund of primary agencies* refers to the cash liquidity of primary mortgage agencies; *mortgage loaned money* refers to the cash liquidity that has been lent to mortgage borrowers and has not yet been repaid. The financial market lends to the borrower at the *mortgage rate*. The more financial agencies lend, the higher their profits; primary agencies expect to maximize their earnings and thus either increase the amount of loans or lower the credit rating (*expected profit of primary agencies* → *mortgage loan ratio; credit rating for lending*). Financial agencies therefore continue to lend *mortgage loans* until their fund liquidity disappears (Loop B2). However, if financial agencies issue *mortgage bonds* to ensure fund liquidity and investors buy these bonds, they will lend *mortgage loans* and issue *mortgage bonds* much more frequently.

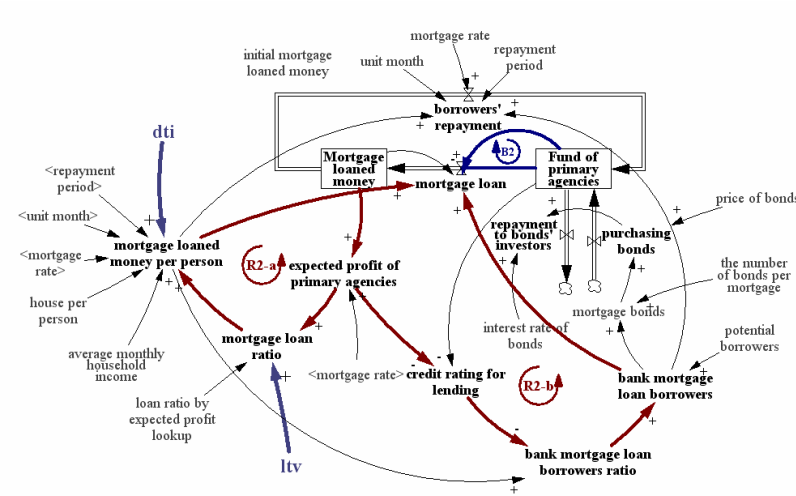


Figure 4. Mortgage Lending in Real Estate Financial Market

Based on the these causal loop diagrams, this study has attempted to construct a simulation model using correlations between influence factors as shown in Table 2 and national data, as shown in Table 3.

Table 3. Data in Simulation Models

Independent Factors	Sources	Value	Unit
initial house price	The bank of Korea 2008, KB Bank 2008	533,000,000	Won
initial demand	http://www.cisr.co.kr/	76,000	Person
price elasticity of demand	Korean Housing Institute	-0.37	dmnl
purchasing ratio using loan	KB Bank 2008	65.4%	%
loan ratio of primary agencies	The bank of Korea 2008	28.76%	%
base rate	The bank of Korea 2008	4.93%	%
mortgage rate	The bank of Korea 2008	6.92%	%

In these models, the ratio of mortgage loan to mortgage worth (*mortgage loan ratio*) of primary agencies is decided as the minimum value between the maximum LTV ratio permitted by government policy and the loan ratio of lending agencies. Also, the mortgage loan amount (*mortgage loaned money per person*) is decided as the minimum value obtained between the maximum DTI ratio permitted by government policy and monthly repayments calculated by lending agencies.

Policy Analysis

This study simulates future house price tendencies and demand effects by changing LTV and DTI ratios. Figure 5 shows the changes in house price and demand when diverse LTV and DTI values are applied, following the assumption that 50% of potential borrowers will transfer their mortgage loans from banks to secondary agencies. Simulation results reveal that the regulation of LTV and DTI ratios will stabilize both house prices and demand in the short term. Further, the more that government lowers DTI and LTV ratios, the greater the tendencies for house prices and demand either to stabilize or fall in the long term.

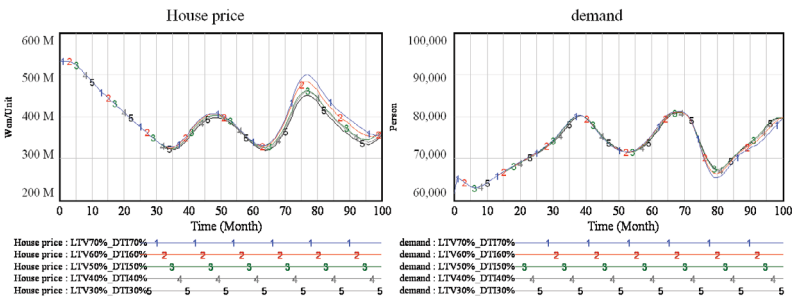


Figure 5. House Price and Demand Changes by LTV, DTI Regulations

On the other hand, the regulation of LTV and DTI ratios can result in the transfer of potential borrowers from primary banks to secondary agencies, such as mutual saving banks or credit unions, which have lower fund liquidity. When potential borrowers choose secondary mortgage loans in response to regulations, house prices will be unaffected (as shown in Figure 6). Assuming that 75% of borrowers shift to the secondary market, a short term fall in house prices can be expected. However, if 90% of borrowers move to the secondary market, house prices will remain consistent with prices in an unregulated market. That is, if potential mortgage borrowers transfer to the secondary market after the implementation of mortgage lending regulation, the effectiveness of government policies on house prices could be offset by an increase in demand caused by an increase in secondary mortgage loans.

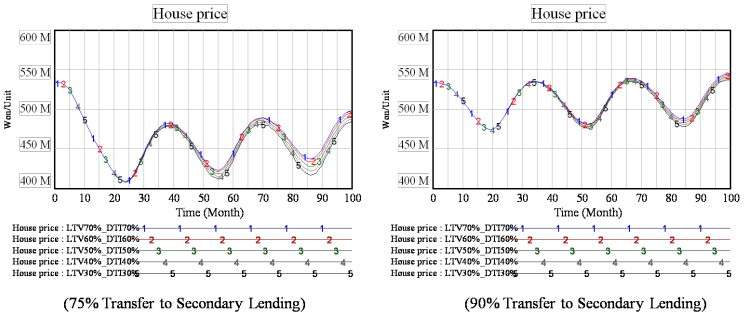


Figure 6. House Price Changes by Transfer Rates to Secondary Lending Agencies

Conclusions

Utilizing system dynamics simulations, this study attempted to analyze the Korean government's regulation policies regarding LTV and DTI ratios. In these policy models, house price and demand are placed in balancing loops, such as demand controlling loops. Further, a reinforcing loop that incorporates the expectation of future marginal profit is shown to have a great effect on house prices by increasing price volatility and upward tendencies. The regulation of excessive demand through mortgage lending policies can help to control these upward tendencies on a pertinent level. However, the same regulations may cause potential mortgage borrowers to shift to the secondary market and thus offset the intended effect of regulations on house prices. Consequently, secondary lending agencies need to be regulated equally with primary agencies to maximize the effectiveness of government policies.

Through considering various perspectives using system dynamics simulation, this research can provide decision-makers with more evidence to support both their policy regulation and deregulation.

Future research needs to expand simulation models to include the behavior of primary agencies. Also, the financial behavior of a construction company related to housing supply should be examined; this will more effectively examine the impact of mortgage lending policies.

Acknowledgements

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Lessons Learned From Utilizing Building Information Modeling For Construction Management Tasks

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Abstract

The research presented in this paper focuses on understanding areas in which BIM is being utilized in general contracting companies and what these companies have as lessons learned from utilizing BIM. The authors conducted extended interviews with professionals (such as BIM managers, project managers, planners) from two different general contracting companies over various projects. The discussions were held such that each participant provided his/her experience over a project, where BIM was used for at least one phase of a construction project. The results of the discussions and interviews provided a wide range of case studies (in overall eight cases) on BIM utilization and lessons learned by project members related to BIM usage on these case projects. This paper provides an overview of each case project, introduces the phases of projects where BIM was helpful, and provides findings on lessons learned by project members with BIM usage. Practically, the lessons learned from these contracting companies can be helpful for construction professionals to improve their practices of BIM usage.

Keywords: case studies, building information models, construction scheduling, estimating and coordination

1. Introduction

Generation and sharing of construction project information based on building information modeling (BIM) have been a widely accepted practice within the architectural, engineering, construction and facilities management domain (AEC/FM). Companies operating within the AEC/FM industry have been

benefiting from using BIM in order to improve the efficiency of information sharing among various actors of construction projects. Among these companies, general contracting companies utilize BIM for streamlining efficiency in construction management tasks, such as estimating, scheduling and coordination. Still in the AEC/FM industry, the impact of utilizing BIM on the construction companies' projects performance and business processes is not understood in details. In order to measure the impact and benefits of utilization of BIM in construction management tasks, there is a need to understand how BIM is currently utilized in different companies. Before measuring the impact of BIM usage, the phases of construction projects in which BIM is incorporated and the business process changes due to BIM usage need to be understood.

The authors focused on the need stated above and started to conduct a research with the participation of general contracting companies in USA to understand first the changes in the business processes related to construction management tasks in the AEC/FM industry with BIM usage. In this paper, the authors provide findings of this research that was conducted with an initial set of general contracting companies. Findings include changes observed in the business processes that are executed at different phases of a construction project with BIM usage, and lessons learned from the perspective of professionals working in these processes.

Various studies in literature mentioned the importance of measuring tangible benefits of BIM in construction projects (e.g., Boryslawski 2006, Leicht and Messner 2007, Heller and Bebee 2007, Smilow 2007, Hartmann et al. 2008). These efforts not only led by research institutions but also by industry participants, such as BIM tool providers (e.g., Solibri 2005, Graphisoft 2004). Among these studies, some even measured the benefits of BIM corresponding to a phase of a project and for a given task (such as during cost estimating, planning and coordination). For example, Alder (2006) identified that with BIM, cost estimating can be 44% faster as compared to traditional quantity take offs. CIFE (2007) showed also that cost estimating accuracy improves 3% and estimating can be even faster (80%) as compared to traditional methods. Savings project plans are measured to be around 19% (Matta and Kam 2005). During coordination of subcontractors work, around 25% faster and 20-30% cost savings are measured (Khanzode et al. 2008). Software providers mainly looked at BIM benefits in terms of savings from BIM usage from total project costs. However, these studies are limited in number, focus only to a specific construction management task (i.e., cost estimating, coordination, planning). In addition, measured benefits change in wide ranges (e.g., estimating 40 % to 80% faster), and business process changes are not detailed. In the research presented in this paper, the aim is to understand the changes in the business processes that would lead to such variations in benefits and help general contracting companies to understand these processes for executing various construction management tasks.

2. Research method

In order to understand changes in processes related to construction management tasks and lessons learned from these changes, the authors conducted extended face to face interviews with professionals (such as BIM managers, project managers, designers, estimators and schedulers) so far from two different general contracting companies. The discussions were held such that each participant provided his/her

experience over the projects, where BIM was used for at least one phase of a construction project.

During the face to face interviews, a questionnaire, designed by the authors, was used to guide the interviews. This questionnaire incorporated five sections, incorporating demographics, too. Each section was specific to a group of participants and incorporated questions specific to that group. The groups included subcontractors, software vendors, owners, and general contractors. Questions directed to each group were mainly related to BIM usage on specific past projects completed/handled by the participating companies. In addition, for each project that was provided as an example by the participant, the authors asked about further questions to learn the project characteristics and the benefits of using BIM as compared to using traditional business processes.

3. An overview of the participants of the research study

So far, the authors had access to seven participants from two general contracting companies and six subcontractors, each from a different discipline (plumbing, fire protection, mechanical, piping, electrical, sheet metal). An overview of these participants is provided in Table 1. Table 1 introduces the number of participants from each company, participants' role in the company, and their experience in the construction industry in years. Average experience of participants in the AEC/FM industry was around fourteen years, where the minimum experience level was five years and the maximum experience level was twenty-five years. Company I was a general contracting company that operated locally in Pennsylvania and was experienced in commercial projects. The other participating company (Company II) was a global contractor and was experienced in housing and commercial projects.

Table 1. Participants of the research study.

	Company I		Company II	
Role	Number of participants	Years of experience	Number of participants	Years of experience
Project manager	1	25	1	20
BIM manager	1	17	2	6-7
Project planner	0	NA	2	5-14
Subcontractors	0	NA	6	10-25

4. Utilization of building information modeling (BIM) over case projects and lessons learned

Based on the detailed interviews with the participants, the authors combined the results and summarized them in this section. The results are overviewed in Table 2, which shows business process changes with BIM use and lessons learned from the cases. Participants provided eight case projects where BIM was used for construction management tasks. These case projects included a variety of facility constructions, such as a museum, hospital renovations and expansions,

construction of a resort, office towers, government buildings and research centers with costs ranging between $ 95 and $ 500 million.

Table 2. An overview of the case projects where BIM was utilized during and before the construction phase.

Project characteristics	**Construction management task that BIM was used**	**Traditional business process**	**Lesson learned**
Case Project 1 *Type:* Museum *Cost:* $ 450 million *Completion:* 2008	Coordination of MEP*, plumbing, fire protection subs	2D shop drawings over light tables	• Reduction in the number of iterations per floor • Clear visualization of clashes
Case Project 2 *Type:* Hospital *Cost:* $ 320 million *Completion:* 2011	Scheduling and phasing of construction works	2D documents and hand sketches	• Expedition in planning • Reduction in construction time • Trust of owner to the reliability of plans
Case Project 3 *Type:* Hospital renovation *Cost:* $ 150 million *Completion:* 2009	Constructability analysis and design check Vision to use for cost estimating	2D drawings On screen quantity take off	• Reduction in cost & rework during construction • Accurate and faster cost estimates
Case Project 4 *Type:* Office tower construction *Cost:* $ 500 million *Completion:* 2006	Phasing of demolition work	2D documents and hand sketches	• Reduction in planning time • Trust of owner to the reliability of plans • Less waiting/idle time between trades
Case Project 5 *Type:* Hospital renovation *Cost:* $ 222 million *Completion:* 2009	Scheduling and phasing of construction works	2D documents and hand sketches	• Expedition in planning • Reduction in construction time • Trust of owner to the reliability of plans
Case Project 6 *Type:* Resort construction *Cost:* $ 135 million *Completion:* 2011	Scheduling and phasing of construction works	2D documents and hand sketches	• Expedition in planning • Reduction in construction time • Trust of owner to the reliability of plans
Case Project 7 *Type:* Research center for health services *Cost:* $ 400 million *Completion:* 2008	Coordination of MEP*, plumbing, fire protection subs	2D shop drawings over light tables	• Reduction in number of iterations per floor • Clear visualization of clashes
Case Project 8 *Type:* Government building *Cost:* $ 95 million *Completion:* 2008	Coordination of MEP*, plumbing, fire protection subs	2D shop drawings over light tables	• Reduction in number of iterations per floor • Clear visualization of clashes

*MEP: mechanical, electrical and piping. The new business process in each of the projects incorporated BIM and/or 4D.

As detailed in Table 2, in the case projects BIM was mainly used during the construction phase for (a) the coordination of works to be executed by the subcontractors, (b) the phasing/scheduling of construction works (c) the constructability analyses and design checks before construction. Construction companies had also a vision of using BIM for cost estimating before construction, and for tracking and maintaining operation and maintenance items during facilities management phase of construction projects. As the last two uses were vision at the time the research was conducted, these uses are not detailed in this paper.

The following subsections provide details of each case project, the construction management task that BIM was used, a summary of the traditional business process, and potential benefits obtained by the companies with BIM use in these construction management tasks.

4.1 Using BIM for coordination of work and lessons learned from museum, research center and government building projects

Project 1 was a museum project that was composed of 250, 000 square-foot, twelve residence floors and 14 exhibition spaces. It was mainly a steel structure worth of around 450 million USD, and was completed in 2008. Projects 7 and 8 were a research center and a government building, having costs of 400 and 95 million USD. In these projects, the company that participated in this research study was the general contractor.

BIM was mainly used in coordination of mechanical, electrical, plumbing (MEP) works in these projects for extended periods. For example, in Project 1 BIM was used during construction between February 2006 and December 2006 for 10 months for every week. The traditional process included 2D drawings and light tables to coordinate spaces and installation of components for MEP and iterate this process many times to eliminate clashes. In this traditional process, there were around 10-12 iterations to coordinate the works in one floor.

In the new process, with utilization of BIM, the parties develop detailed models for the components that they were responsible to install from 2D shop drawings approved by the architects and engineers. The entire work is divided into coordination zones and for each zone, the responsible subcontractor adds its components to the base model provided by the general contractor. While modeling of the components to be installed, each subcontractor models both hard and soft/access dimensions for better coordination. Hard dimensions are those that are required by manufacturer or codes (e.g., handicap clearances, door widths, wall heights). Soft (access) dimensions are those required to access a piece of equipment or install a piece of equipment. For example, there may be 92 cm clear space between the ceiling and deck above and there may be a lateral access required to service an equipment of height 61 cm. If the access door or equipment is located at 46 cm, then there is a potential issue, and soft dimensions are modeled to see these potential problems beforehand. While modeling hard dimensions, subcontractors can put a simple solid that represents a group of objects (e.g., a wall with a thickness that incorporates metal studs and insulation layers), or can put multiple layers of objects composed of different object types (e.g., a wall, an insulation layer and a metal stud layer objects). While modeling soft dimensions, subcontractor can put a separate element to show the required

access space or embed the dimensions of the required space within the main element (i.e., increase the size of the main elements by the required space dimensions).

After the models are ready, these models are then submitted to the general contractor before coordination meetings. The person, who is responsible for detecting clashes on BIM, overlays these models on each other using specific tools for identifying clashes on the zone that will be discussed in an upcoming coordination meeting. These clashes are analyzed and if they are really clashes they are listed to be discussed in the coordination meeting. During the meeting, each clash is shown in BIM to the clashing parties (i.e., the parties who are responsible for the installation of clashed components) using smart boards and a solution is generated. If the project has a work station at that job site, BIM is updated to reflect the final solution by the general contractor on the fly; if not, the responsible party updates the model and uploads to the server to be used by the other parties.

With BIM based coordination, the number of iterations for coordination is generally reduced and the coordination is faster. Specifically, it was down to 5-6 iterations per floor in the museum project (Project 1). In addition to having faster coordination of work, users have cost savings and reduced rework at the job site. For instance, in Project 1 with BIM usage, users discovered that there were major conflicts with the duct work, some structural members and the electric works. The slabs were at fixed elevations and the duct work was a tight work with no flexibility of change in the design. They realized the problem before the installation started at the job site, and changed the electrical works with a redesign, which was according to the fixed conditions of slabs and duct works.

Another example that was large in scale was related to ductwork. In 2D, the ductwork looked like a step wise duct both from top and bottom of the ducts. While developing the building information model, the ductwork subcontractor realized that the continuous duct did not have a step like shape from its bottom. If this problem was missed until the job started at the job site, there would be rework, liquidate damages to be paid to owner due to late completion, time of request for information resolving, and trade waiting times for the affected trades (such as lighting, ceiling work).

In addition, the participants stated that they identified more clashes as compared to 2D drawings, which eliminates false positives (i.e., not identifying a real clash). As shown in these projects, general contractors benefited from BIM use during coordination of works with reduced surprises at the site.

4.2 Using BIM in scheduling and phasing and lessons learned from new hospital, hospital renovation and resort construction projects

Project 2 was a hospital project with a total of around 700, 000 square-foot facility including eight story inpatient pavilion, and a five-story support services building. The project was worth 320 million USD, and would be completed in 2011. Projects 5 and 6 were 222 million USD hospital renovation and 135 million USD resort construction projects. In these projects, the company that participated in this research study was the construction management company.

BIM was mainly used in planning, scheduling and phasing of construction works. The traditional process included 2D documents to sequence work and

simulate coordination of equipment and cranes used in construction operations. The problem in the traditional processes was that the project planners had difficulty in visualizing overlapping activities and operations at the job site.

The new business process for the construction phasing and scheduling processes included developing construction phases, generation of zones and sequencing of activities based on the BIM of the project. In these three projects, BIM was developed before the construction management company started using BIM in phasing. For example, in Project 2 BIM was first developed by the steel manufacturer including steel frames, detailed by the gypsum board manufacturer for the interior walls and augmented by the construction management company with exterior enclosure and construction equipment and cranes.

With BIM, it was easier to visualize the project execution over time and see possible time and space conflicts between the operations. For example, in Project 2, construction management company gained 2 months of time in construction period with the utilization of BIM during scheduling and phasing of construction works. In addition to these, the construction management company had reduction of cost in 'general conditions' due to less staff being employed.

4.3 Using BIM in constructability analyses and lessons learned from a hospital renovation and expansion project

Project 3 was a hospital renovation and expansion project including a new seven story acute care tower and new patient care space. It also included demolition of some of the existing buildings and renovation of some others. The project was worth 150 million USD and would be completed in 2009. In this project, the company that participated in this research was the general contractor.

At the time the professionals from the general contractor company participated in this research, Project 3 was just awarded to the general contractor and BIM was at that time being used for constructability analysis and keep track of design coordination and design changes as a requirement of the owner. The objective in the future phases of the project was to use BIM for clash detection and phasing of construction works. The traditional process of constructability analysis and design checks included the utilization of 2D drawings and documents and having meetings using the information changed on these drawings and documents. The problem in the traditional process was that the task was error prone in terms of identification of problems/errors before construction, or design conflicts before it was too late at the job site.

In this project, a BIM tool was used by the general contracting company and by the architect to develop BIM of the facilities that will be newly constructed and renovated. The purpose was to identify design problems and conflicts while developing the building information model and to fix them before the construction process began. General contractor was expecting to select construction methods while BIM was being developed and identify constructability problems with the given design, contact to the owner and the architect if problems were observed. For the renovation parts, the 3D model would be generated using a laser scanner and then would be mapped to the final (i.e., required) to-be version of the project BIM and clashes would be identified before installation of new components started. Related to constructability analysis, the general contractor expected to have 1200- 5000$/day of gained revenue from BIM use in this process. Due to

unexpected problems, lost revenues could be expected up to 10, 000 $/day depending on the problem.

In addition to constructability analysis and design consistency check, the general contractor wanted to use this project as a pilot project to start benefiting from model based estimating process. Their vision was to obtain quantities from the building information model of project automatically to reduce human errors experienced during traditional methods of estimating (currently, on screen take off was utilized in the company). With the model based estimating, they expect to obtain faster and more accurate cost estimates.

4.4 Using BIM in managing demolition work and lessons learned from an office tower construction project

Project 4 was a 42 story steel tower construction project to be used as office space with around 860, 000 square foot of construction over functioning railroad tracks. The project was worth 500 million USD and completed in 2006. The participants of the research study were from the construction management company of this project.

BIM was mainly used in planning and phasing of construction works. The traditional process included 2D documents to sequence work and simulate coordination of construction operations. The problem in the traditional processes was that the project planners had difficulty in visualizing and sequencing operations at the job site. For this particular project, phasing of the project also included moving and demolition of existing railroad tracks and moving the tracks to another location. So, in addition to construction phasing, the construction management company had to incorporate demolition of old subs and stations and building of new subs and stations, putting sheet metal protective shielding around the existing retaining wall, taking down that retaining wall and building structural steel. With 2D documents and sketches, it would be hard to track the sequence of demolition and reconstruction tasks.

The new business process for construction phasing and scheduling included generation of zones and sequencing of activities based on the BIM and visualizing the construction simulation over its 4D model. The steel structure members were modeled by the architect and provided to the construction management company. Then, the schedulers added additional components of wires for trains, existing tracks and stations, retaining wall and protective sheet metal shielding, scaffolding for the retaining wall, a platform for steel structure and new tracks and stations to the model. They created a 4D model by working with the schedulers. For example, demolition of the retaining wall was originally 50 days and in the 4D simulation they visualized it at 5 steps.

Via utilizing BIM and 4D model, the construction management company could sequence the work with realistic durations and sequences, and could convey that information to owner and subcontractors in an effective and visual way. The 4D simulation helped them to create zones and sequence demolition of existing structures and moving of tracks to their final location without a problem. It resulted in time savings and gain of owner's trust to the work-plan generated by the construction management company. With the 4D simulation, faster construction was observed with also 15-20 percent cost savings from BIM.

5. Conclusions

This paper detailed a set of initial findings related to an ongoing research. Initial findings revealed that general contractors in USA have benefited from BIM usage with their own lessons learned. Lessons learned from BIM usage in these companies can be grouped in three categories, as (a) lessons learned from BIM use before construction starts, (b) lessons learned from BIM use during construction, and (c) lessons learned from BIM use after construction phases.

Before a construction project starts, the companies mainly used BIM as an effective and visual communication tool between the owner and subcontractors. In addition, during preconstruction, general contractors used BIM mainly for constructability analysis and design consistency check to eliminate unexpected problems and reworks during construction phase. With less reworks, they had reductions in total project costs, from 1200- 5000$/day from BIM use in this process.

During construction, BIM was mainly used in the companies that participated in this study for coordination of subcontractors' works (e.g., plumbing, fire protection, MEP) and eliminate clashes of components way before installation of those components starts. With BIM implementation in coordination phase, companies had reduction in number of iterations per floor. For instance, the number of iterations was reduced to 5-6 iterations per floor in a particular project from 10-12 iterations per floor. They also identified clashes that could be missed in traditional way of coordination (i.e., 2D shop drawings overlaid on light tables). In addition, during construction, companies used BIM for construction phasing and planning with faster planning phases, and reduced construction times (e.g., around 2 months of time gain in a particular project).

After a construction project is complete, the general contracting companies have a vision to use BIM for facilities management. Among various tasks to be performed after a construction is complete, companies would like to use it for punch-list administration, keeping up to date manufacturing and installation information about maintenance items, which are needed during repair and replacements.

To summarize, general contractors benefited from BIM use and would like to benefit from BIM use by developing visions to deploy BIM use over various construction project phases. With more deployment of BIM use in traditional way of executing construction management tasks, challenges such as defining levels of details in BIM, privacy rights and defining responsible parties in developing a building information model of projects are expected to be resolved in a shorter time.

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Multi-Objective Dynamic Simulation-Optimization for Equipment Allocation of Earthmoving Operations

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Abstract

The management of equipment allocation for earthmoving operations is a complex dynamic series of discrete events. This paper presents a common and flexible Petri net model for the optimization of equipment allocation for a given construction period, cost and labor. A case study was conducted on a real construction project involving earthmoving operations. The data required by the research was collected on-site. A Petri net model was used to represent the dynamic constraint relationships among various types of equipment and their assigned tasks. The model describes the process workflow and equipment utilization for an earthmoving operation. The model was tested and sensitivity analysis carried out. Based on simulation results, and the given conditions, a minimum cost solution to the equipment allocation problem is obtained. This paper provides both practitioners and decision makers with a real study, a simulation model, and a useful approach to the equipment allocation problem in construction.

Keywords: earthmoving operations; simulation; equipment allocation; multi-objectives optimization; Petri net

Introduction

Earth moving operations can be represented as Discrete Events Systems. It refers to all the operations involving the cut, loading, haulage, unloading, grading, humidifying and compaction of materials in a civil engineering building, aiming to adequately shape the natural field to the specifications of the project (Prata 2008). The management for equipment scheduling is a dynamic discrete event which is affected by a large number of uncertainties and random factors.

The main goals of simulation-optimization for earthmoving operations are to improve productivity, equipment efficiency and construction safety. According to the specific construction project, the suitable equipment is selected to maximize productivity and consequently maximize profit of contractors, and projects are completed with the

least cost and within the given targeted project duration (Reda, 1990). In an earth moving process, contractors tend to use the equipment available instead of allocating the ideal number of machines. In these situations, given the available equipment, equipment characteristics and parameters, main factors and cost information, a simulation model can predict the construction situation of earthwork operation, estimated time of completion and cost to provide a reliable basis for earthmoving organization and management.

Considerable work has been carried out to develop models for planning earthmoving operations so as to achieve the previous stated goals. Halpin and Woodhead (1976) used queuing theory. Halpin and Riggs (1992) evaluated different fleet scenarios by MicroCYCLONE. Marzouk and Moselhi (2000, 2004) optimized the earth moving operations using an object-oriented simulation approach and Genetic Algorithm (GA). Hegazy and Kassab (2003), Cheng and Feng (2003) and Cheng et al. (2005) proposed simulation–optimization by combining GA with CYCLONE or other simulation techniques. Bargstädt and Blickling (2005) proposed an IT system which realizes earth moving teams, permitting the user to establish scenarios in real time. The system has a graphical user interface which provides for visualization of the established scenarios. Moselhi and Alshibani (2007) presented a robust system for planning, tracking and control of earth moving operations combining a module of spatial technologies. Zhang (2008) presented a particle swarm optimization algorithm to search for the potential equipment-configurations. Prata et al. (2005, 2007) suggested the Petri nets as a method for loader and truck teams dimensioning via simulation. Prata et al. (2008) proposed a model using Stochastic Colored Petri Nets to represent the operational dynamics of earth moving work.

Most of these simulation optimization algorithms focused on optimization of simulation results rather than dynamic processes of earthmoving work. Prata et al. (2008) considered the operational dynamics of earthmoving work for taking local operations as objects of simulation-optimization, including loading earth and truck hauling in order to determine the quantity of haulage units to be used conjointly with a loader. But the proposed Petri net model could not simulate the whole operation process. Moreover, the model did not respond to the dynamic random events during the construction.

In the field of scheduling research, one of the important problems is to show the scheduling process dynamically and visually. Color Petri net combines the advantages of Petri net and high level programming languages. The concurrency of Petri net makes it suitable to describe the system characteristics of concurrency, resource competition and synchronism. Compared to other modeling methodologies, Petri net is based on strict mathematical theory. It supports the designer to validate the rationality of the system from the view of formalization and graphically simulate the distributed system (Liu 2007). Modeling earthmoving operations with Petri net can not only express the static characteristics of the earthmoving operations but simulate the dynamic behavior in the construction process. The information collected is used for both qualitative and quantitative analysis of earthmoving processes.

In this study a general extensible Petri net for optimizing earthmoving equipment configurations is proposed by integrating colored Petri net and ML high level

programming language, which is capable of expressing dynamic constraint relationships among various equipment. The Petri net model considers multiple criteria and the preference of decision-makers. The reasonable plans for different optimization goals can be generated on the analysis of the model.

Colored Timed Petri nets

The Petri Nets theory was born from the thesis defended by Carl Adam Petri in the Faculty of Mathematics and Physics of the Technical University of Darmstadt (Germany) in 1962, entitled "Communication with autonomata". Petri net has the characteristics of strict mathematical foundations and understandable graphical representation. At the end of the 60s and beginning of the 70s, researchers from MIT in the USA developed the foundations of the concept of the Petri nets.

An ordinary Petri net is a 4-tuple *PN = (P, T , Pre post)*, formed by a finite set of places *P* of dimension *n*, a finite set of transitions *T* of dimension *m*, an input condition *Pre: P x T → N,* and an output condition *Post: P x T → N*. To each place an integer non-negative number denominated token is associated.

According to Jensen (1992), a more compact representation of a Petri net is obtained via the association of a data set (denominated token colors) to each token. A colored Petri net is a 9-tuple: $CPN = (\Gamma, P, T, A, N, C, G, E, I)$. The concept of color is analogous to the concept of type, common among the programming languages. In the colored Petri nets, the quantity of places, transitions and arcs is, generally, sensibly reduced via the addition of data to the structure of the net.

CPN Model of Earthmoving Operation

CPN Model

The simulation model of an earthmoving operation based on Petri net is defined on the basis of a colored timed Petri net. The correctness of structure and operation for the model can be validated by liveness and safety of a Petri net. The formulism for the modes is expressed as follows:

Definition 1 CPN Simulation model of an earthmoving operation

CPN Simulation model of an earthmoving operation (CPNSMEO) is a 9-tuple:

$$CPNSMEO = (R, P, T, F, M_0, C, G, I, S) \quad (1)$$

Where:

(1) R is a finite, non empty multi-set of types, denominated colors set, see definition 2;

(2) P is a finite set of places of dimension n;

(3) T is a finite set of transitions of dimension m;

(4) F is a finite set of arcs so that $P \cap T = P \cap F = T \cap F = \varnothing$;

(5) M_0 is an initiation status marking.

(6) C is a color function, defined from P on R;

(7) G is a guard function,

$\forall t \in T : [Type(G(t)) = Boolean \wedge Type(Var(G(t))) \subseteq R]$, defined from T;

(8) I is an initiation function, $\forall p \in P : [Type(I(p)) = C(p(a))_{MS}]$, defined from P.

(9) $S(S \in [0, 1])$ is the firing possibility of transition T when it conflicts with other transitions. S=1 when there is no conflict.

Definition 2 Token color multi-set

R is a multi-set based on an object oriented, denominated colors set. $R = \{ID, OR, B, i, e, A\}$,

Where:
ID is the only identification of token in the system
OR is the activity type of token. The value is *ON* or *OFF* decided by a predecessor activity for expressing the synchronousness or asynchronousness of the activity;
B is the Boolean value of tokens, $B \in BOOL$;
i is the number of an iteration;
e is the Timestamp;
A is the subset of the resource characteristics.

Definition 3 Status Marking

M is the status marking. M_0 is the initial marking. In the case of natural numbers ($i \in N$), $M_i(p)$ is the number of colored token of place p. Transition t is binded and enabled if and only if
(1) $G(t) < b > = \text{True}$;
(2) $E(p, t) < b > : M_i(p) \mid \forall p \in \bullet t$;
(3) The timestamp of any binding token exceeds the time limit

If transition t fires, the marking is changed from M_i to M_{i+1} in a legitimate firing time. The firing result is as follows:

$$M_{i+1}(p) = M_i(p) - E(p, t) < b > + E(t, p) < b >, \forall p \in P \quad (2)$$

$$M_{i+1}(p) = (M_i(p) - E(p, t)\langle b \rangle + E(t, p)\langle b \rangle, \forall p \in P \quad (3)$$

CPNSMEO is different from the general colored Petri net. The token colors in CPNSMEO are determined by execution environment and influenced by other token colors.

Model Analysis

Application Example

The example, Zijin City high-rise residential project located in Harbin of China, is chosen as the subject of this research. The total building area is 320000m^2. The project involves excavating construction foundation with 300m long, 200m width and 6m deep, and moving 360,000m^3 (bank volume) of moraine (loose density = 1.2t/m^3, loose density = 1.53t/m^3) from construction site to an soil placement pit located at a distance of approximately 15km from the project site. The teams include excavator, dozer, loader and truck.

A maximum of eight excavation sites can be set on construction surface within the construction site. Each excavation site can include a maximum of two excavators working simultaneously. Loading area contain up to five loading sites. Each site permits a maximum of two loaders to load one truck at the same time. In the dumping

area, there is a maximum capacity of 3600m^3 for temporary earth storage. In addition, because the construction site is located in the city, the transportation is restricted to traffic situation. The traffic has a great impact on truck transportation between 6a.m. to 10p.m. The impact is relatively small during other times. Table 1 shows the detailed data.

The available equipment includes 14 excavators, six dozers, seven loaders and 35 trucks. The equipment is rented daily. Each type of equipment runs 24 hours with an eight-hour shift. The rental price (including driver cost and other cost) is shown in Table 2. The rental price for an excavator is 1,200RMB per 8 hours, for an excavator is 1,200RMB per 8 hours, for a dozer is 600RMB per 8 hours, for a loader is 800RMB per 8 hours and for a truck is 300RMB per day.

Table 1 Earthmoving operation time and parameters

	Excavators	**Dozers**	**Loaders**	**Trucks**
Type	WY160	T3-100	ZL20	EXQ153
Volume of soil	1.6m^3/time	100m/min	1.0 m^3/time	13 m^3
Triangle function of volume of soil	(1.5, 1.6, 1.7)	(1.7, 2.0, 2.2)	(0.9, 1.0, 1.1)	See Table 2
Triangle function of time (min)	Excavation (1.4, 1.6, 1.7) Load (0.6, 0.8, 1.0)	(0.9, 1.0, 1.2)	(0.5, 0.6, 0.7)	See Table 2

Table 2 Triangle function of truck operation time (min)

	Haul	**Dump**	**Return**
10 p.m.-6 a.m.	(13.0, 14.5, 15.0)	(1.1, 1.2, 1.4)	(10.5, 11.5, 12.0)
6 a.m. – 10 p.m.	(18.0, 20.5, 21)	(1.1, 1.2, 1.4)	(17.0, 18.0, 20.0)

Simulation Model of Earthmoving Operation

Based on the above theoretical foundations of the colored Petri nets, a simulation model CPNSMEO of earthmoving operation was constructed according to the practical characteristics of workflow (see Figure 1). Figure 2 shows the T5 sub layer of soil transportation. Figure 3 shows the T3_6 sub layer of soil load.

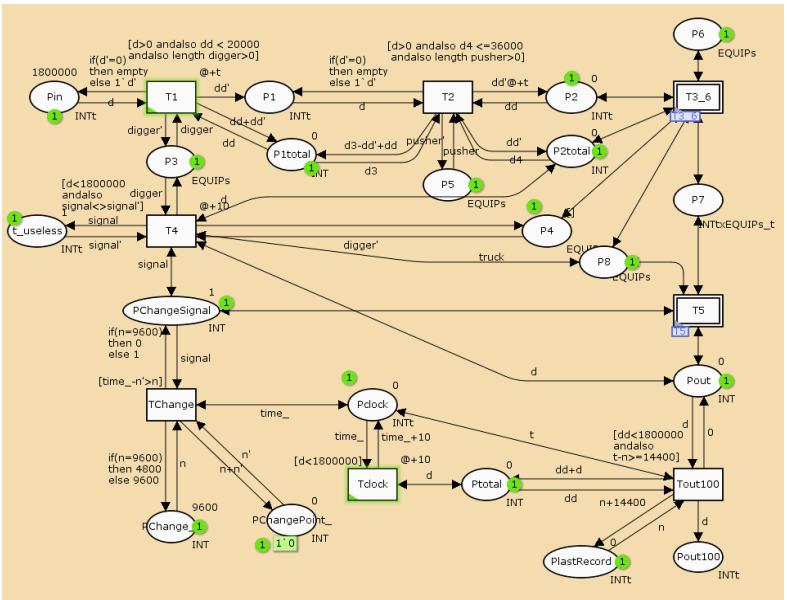


Figure 1 Colored timed Petri net model of earthmoving operation (top layer)

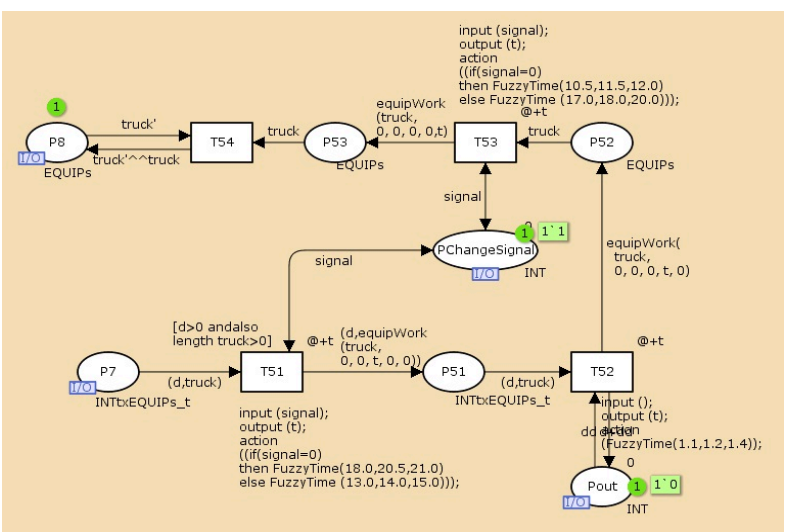


Figure 2 T5 sub layer of soil transportation of CPNSMEO

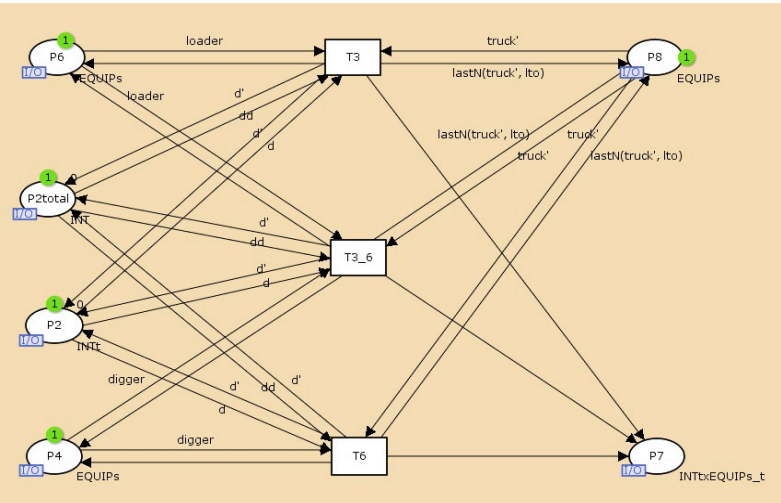


Figure 3 T3_6 sub layer of soil load of CPNSMEO

Table 3 introduces the captions of the places and the transitions of the proposed model. In this model, CPNSMEO uses *timed integer* variable to represent the volume of soil. *Timed integer list* variable is used to represent equipment. The equipment working hours are represented by triangle functions. The average value of 100 observations on site is used as parameters value.

Other transitions and places that cannot be noted in Table1 and 2 are auxiliary parts for model control and establishment.

Table 3 Definitions of the main transitions and places of the model

Transitions	Places
T1: soil excavation	Pin: soil to be excavated
T2: soil moving on construction site	P1: soil for temporary storage
T3: loader's loading	P2: soil to be loaded
T4: excavator's maneuver	P3: excavator ready to maneuver
T5: soil hauling by the truck (sub layer)	P4: excavator for loading
T3_6: excavator and loader's loading soil	P5: dozer ready to maneuver
T6: excavator's loading	P6: loader ready to maneuver
T51: truck's soil hauling	P7:truck with load ready for departure
T52: truck's unloading	P8: truck ready to load
T53: truck's return	P51: truck hauling
T54: truck's positioning	P52: truck returning
	P53: truck in loading site
	Pout: soil in dumping area

The soil in place Pin is excavated at transition T1 and stored temporarily in place P1.

The soil is moved at T2 to place P2 and ready for loading. The soil in place P2 is loaded to place P8 through the subnet T3_6 of soil loading. After the operation in transition subnet T5 of haul, the soil is moved to dumpling area. The empty truck returns. The transition structures like T4 realize the automatic allocation to the equipment on site: (1) Model can automatically regulate transportation capacity of trucks at different times; (2) If the soil volume in place P1 arrives at 2000m^3, which is the temporary storage upper limit, the excavator will stop work. If the soil volume in place P2 arrives at 3600m^3 which is the temporary storage lower limit, the excavator will stop work; (3) when the truck capacity enhances between 10p.m. and 6a.m. and the soil volume of temporary storage in place P2 is more than 3000 m^3, the model automatically transfers some of the excavators to loading area. When the truck capacity declines between 6a.m. and 10p.m., and the soil volume of temporary storage in place P1 is less than 3000 m^3, the model automatically transfers some of the excavators to excavation area. Therefore, the model can effectively reallocate the equipment according to the construction site situation.

Multi-objective Simulation Optimization

The model was implemented and simulated utilizing the software CPNTools, a public domain program developed by Aarhus University, dedicated to modeling, simulation and analysis of Colored Petri Nets. This software possesses an interface which allows easy handling by the user, facilitating the specification of scenarios. Table 4 shows the 28 equipment configuration plans which are the simulation results made by traditional equipment configuration management methods.

In this case, the cost of truck depends on the total volume of soil. Therefore, the number of truck does not affect the whole construction equipment rental costs. In order not to make too many trucks idle, the threshold value of truck number is needed for maximum volume of soil. Using the equipment configuration in scenario 28, the threshold value of truck number is 20 through model simulation only to adjust the number of trucks. More than 20 trucks will not be able to continue to improve the transportation capacity of soil. Meanwhile, less than 20 trucks will probably lead to deficiencies in soil transportation.

Table 4 Summary of the scenarios of earth moving

Scenario	Number of excavators	Number of dozers	Number of loaders	Number of trucks	Working time (d)	Scenario cost (RMB)
1	8	4	5	25	21	1165500
2	10	4	5	25	19	1191300
3	12	4	5	25	20	1398000
4	14	4	5	25	18	1387800
5	8	4	6	25	21	1215900
6	10	4	6	25	21	1367100
7	12	4	6	25	20	1446000
8	14	4	6	25	18	1431000
9	8	5	5	25	18	1031400
10	10	5	5	25	16	1032000
11	12	5	5	25	15	1075500

12	14	5	5	25	15	1183500
13	8	5	6	25	16	955200
14	10	5	6	25	16	1070400
15	12	5	6	25	16	1185600
16	14	5	6	25	16	1300800
17	8	5	7	25	17	1055700
18	10	5	7	25	17	1178100
19	12	5	7	25	16	1224000
20	14	5	7	25	16	1339200
21	8	6	6	25	15	922500
22	10	6	6	25	15	1030500
23	12	6	6	25	15	1138500
24	14	6	6	25	13	1080300
25	8	6	7	25	16	1022400
26	10	6	7	25	14	995400
27	12	6	7	25	14	1096200
28	14	6	7	25	13	1111500

The model has been tested in selecting equipment configuration to minimize project time, project cost, and project time and cost, as presented in Table 5 and Figure 4.

Table 5 Equipments for different optimization goals

Optimization	Excavator	Dozer	Loader	Truck	Time(d)	Cost(RMB)
	WY160	T3-100	ZL20	EXQ153		
Minimized Time	14	6	7	25	13	1111500
Minimized Cost	7	6	6	25	15	868500
Minimized Time & Cost	10	6	7	25	14	995400

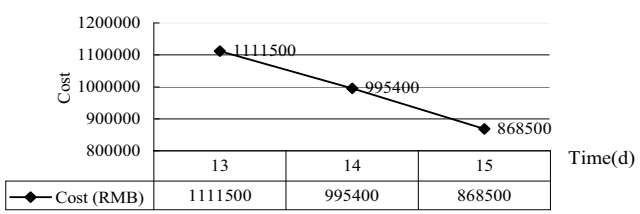


Figure 4 Optimization prototype for the application example

Conclusion

This study proposed a general and extensible Petri net for optimizing earthmoving equipment configurations. The developed model can express the dynamic constraint relationships among various equipment during the construction process. The model supports for: 1) dynamic and quantitative description of workflow and equipment resources in earthmoving operation, 2) visualization of dynamic management and optimization of equipment assignment, 3) an effective means for equipment configuration for planners and managers. The use and the capabilities of the developed model were analyzed through a construction project example.

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Real-time Data Collection and Visualization Technology in Construction

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Abstract
Data on construction resources (personnel, equipment, materials) is vast and the effort to collect and analyze it automatically is a priority in the construction industry. Once remote sensing and intelligent data processing technology are applied to supplement manual data recording, however, very few data visualization tools in construction exist that allow visualizing dynamic resource data in a field realistic virtual reality environment and are at the same time able to perform this task in or near real-time. Moreover, technology to assist in real-time data visualization and situational awareness can have a significant impact on stakeholders' successful and safe completion of construction projects. This research addresses the need for real-time data collection and visualization technology in construction applications. It reviews state-of-the-art technology in this field and presents a new framework that implements real-time remote sensing and data visualization technology in two significant construction applications: (1) Real-time pro-active construction safety assessment and training, and (2) Real-time construction productivity and performance monitoring. Preliminary results to each of these scenarios are presented and discussed.

Keywords: 3D, Decision Making, Modeling, Productivity, Real-time, Safety, Simulation, Tracking, Ultra Wideband, Virtual Reality, Visualization.

1. Introduction

The distributed nature of construction project information and the presence of multiple teams performing on site are well known characteristics of a typical construction project. Communication of essential information among project stakeholders is considered a key for successful construction engineering and management. Traditionally, an enormous amount of site information is available to

project team members. It is mostly communicated by means of paper documents including 2D drawings or verbal language. A significant deficiency in the traditional information delivery process has been that the project team is not always able to make rapid and correct decisions because of unavailable or insufficient data, or data that is hardly or badly presented.

This research focuses on developing a deeper understanding of construction information that should be provided in real-time and visually. A more effective use of the real-time information lies in its visualization; providing a visual understanding would allow project stakeholders to make fast decision and facilitate real-time remote control both on construction project level and operation level.

Thus, tracking and visualizing dynamic resource data in a field realistic virtual environment in real time offers several benefits to a project management team. For instance, workers' safety and health learning and education practices can be enhanced through real-time data collection and visualization approaches. Previous research efforts indicated that workers in the execution of their work often do not have good perception of the surrounding risks that are related directly or indirectly to their work task. According to Rasmussen's model, their motivation to achieve a high productivity pushes them to work 'near the edge' in terms of their exposure to risk (i.e. beyond the zone of control or recovery) (Mitropoulos et al. 2005). One such alternative to prevent similar work situations is training construction workers for safety through frontal teaching and instruction of hazards. Virtual reality learning and training offers an active learning experience where the user is in control and is required to deliberate proper actions.

This research integrated sensing and visualization technology of project critical resources (personnel, equipment, and material) in real-time. Realistic and rapid work status performance monitoring and worker training scenarios were built to investigate the procedure of enhancing decision making in construction project safety and task control management.

2. Background and Literature Review

In the past decades sensor technology has been widely applied to civil engineering and construction research problems and also for automated progress monitoring. Some location tracking technologies providing unique spatial-temporal information to resources are Radio Frequency Identification (RFID), Robotic Total Station (RTS), Global Positioning Systems (GPS), and Ultra Wideband (UWB). Each of these are candidate technologies to collect viable project related information on static and dynamic resources. However, some of the above technologies are constrained in their use by the complexity and layout of some construction sites. For instance, GPS can only be applied outdoor. Ultra Wideband, a more recent commercially available radio frequency technology, has been previously tested successfully in semi-open areas on construction sites (Teizer 2008). It suggests that multiple (other) technologies would be suitable for collecting data. As far as the information is extracted from the sensor data set, it must be visualized to the decision maker to provide relevant knowledge in an accessible manner.

There have been many efforts trying to implement virtual environments for visualization of architectural design and facilitating the building construction on

project level. Maldovan and Messner (2006) investigated the potential use of a virtual mockup to replace the existing physical mockups. Messner and Horman (2003) used an immersive Virtual Reality (VR) system consisting of a large scale immersive projection for students in the architectural engineering program at the Penn State Univ. in order to experience and experiment with three-dimensional (3D), full scale virtual models of construction projects.

Visualization technology has already been widely applied to the construction management and practice. Virtual construction allows all the stakeholders to indentify construction problems early in the design phase and enables contractors to manage the projects more efficiently. Most of the existing VR applications in construction management are aimed to visualize construction scheduling and quality control. Chau and Anson (2003) conducted a research on 4D graphics for construction planning and site utilization aiming to assist a planner who deals with daily activities and site management. Retik and Varszawski (1990) explored the potential application of computer graphics to construction scheduling and outlined the possible features of the tool. McKinney and Fischer (1998) presented and evaluated a 4D application integrating AutoCAD, Primavera, Jacobus Simulation Toolkit and Walkthru. Their work illustrated how feature extraction of 4D-CAD models can help identify construction problems. Koo and Fischer (2000) suggested that a 4D VR model increases the comprehensibility of project schedules and allows users to detect potential problems such as scheduling conflicts prior to the construction phase. More effective allocation of resources would results. At the same time easier evaluating of selecting alternative construction methods would allow to shrink construction schedules. Wand and Dunston (2009) also contributed in the area of the determining the benefits of mixed reality collaborative environments for design perception.

Despite much research in adoption of VR technologies on building design and construction project level, their application is not very common on everyday construction task level. One reason is that they can not represent and reproduce the immersive environment in real time. In addition, these tools are somewhat difficult to use and the visualization provided by them is not easy to customize with respect of intensive and dynamical characteristics of construction operations (Issa et al. 2003). On the construction operation level, Kamat and Martinez (2003) formalized a specific description to facilitate the automated communication between simulated dynamic construction scenarios and computer graphics facilities that depict the operations in 3D virtual worlds. Kamat and Martinez (2005) had also conducted a research on dynamic 3D visualization and simulation of articulated construction equipment, such as crane and excavator, by using principles of forward and inverse kinematics. Lai and Kang focused on collision detection strategies for virtual construction simulation (2009).

Apart from the implementation in engineering practice, many efforts have been invested in the application of information technology especially of advanced virtual reality (VR) and virtual environment (VE) technologies in building science education such as school teaching and learning (Bouchlaghem and Wilson 2002, Issa 1999).

However, these adoptions of VR in education used mostly simulated data in a made up environment. Very little effort has been made on implementing real-time immersive environment in construction training and education, even though a real-time training can enhance the memory retention and increase the learning gains of the trainees.

Apart from construction industry and construction education, VR has already been widely used in other fields. Santamaria and Op den Bosch (2002) introduced an application of tools that integrated near-real-time visualization with publish and subscribe mechanism to achieve remote monitoring and control of dynamic objects in an underwater scene for underwater operations. Fernandes and Raja (2003) modeled a virtual training system as an integrated system consisting of a training visualization suite, an interface model and instruction module. Its applicability in the manufacturing industry has been studied (Fernandes and Raja 2003).

3. Research Methodology

A major objective of implementing real-time data collection and visualization technology in construction is to increase the awareness of the project team so that it can make more informed decisions in less time and at lower cost. In order to accomplish this objective, the solution is consisted of four central phases: (1) data collection, (2) data processing and visualization, (3) decision making, and (4) learning and improving. Figure 1 illustrates a detailed workflow for implementing sensor data in construction safety engineering and management. Visualization is one key component to make information available in (3) and (4).

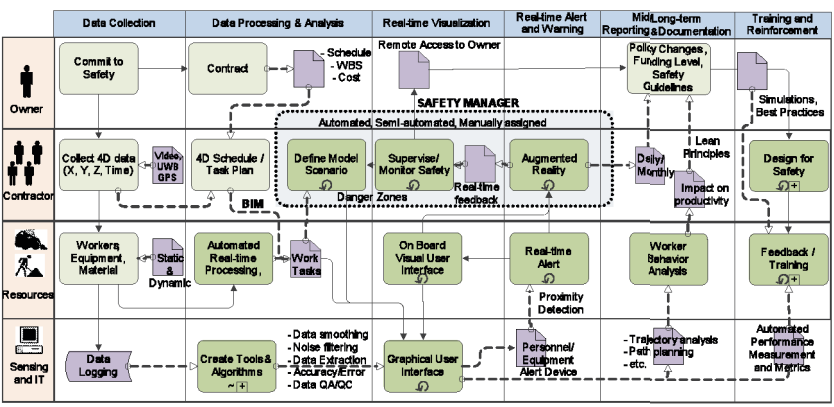


Figure 1: Framework for real-time data collection and visualization for safety

Different stakeholders require different information. A variety of sensing technology exists to collect relevant data for each stakeholder. Raw spatial and temporal data is collected by the sensor and must be processed to form relevant information before it is delivered to decision maker. Some construction applications including safety and health practices may require real-time feedback, which requires real-time data acquisition and processing. Data that is not used for real-time decision making can be

used for training and education purposes in near real-time or post real-time data processing data analysis. With the help of robust data distribution within this framework, stakeholders are able to make their decision with the help of interactive three-dimensional (3D) scenes.

3.1 Real-time Data Collection and Processing

In most construction tasks multiple objects exist that generate data. Such objects relate to construction resources (workforce, equipment, material). Data is generated from several of these objects and several systems on the job site, many of which are isolated from each other. Data transfer and consolidation becomes a challenge. One alternative is to apply a protocol for all data streams in order to uniform data reporting. For simplification, this approach focuses on a single data source from a specific tracking technology, providing location (X,Y,Z) and timestamp information.

3.2 Real-time Data Distribution and Visualization

To send relevant information to all project stakeholders that must have access to relevant data at the same time, a local data server was chosen that collects raw data. In addition a 3D online viewer was installed to visualize information to any project stakeholder regardless of the current location. The data server of the visualization system had the mechanism of data subscribing and publishing. It utilized existing internet and intranet infrastructure. Figure 2 shows the developed data collection, data distribution, data processing and information visualization architecture.

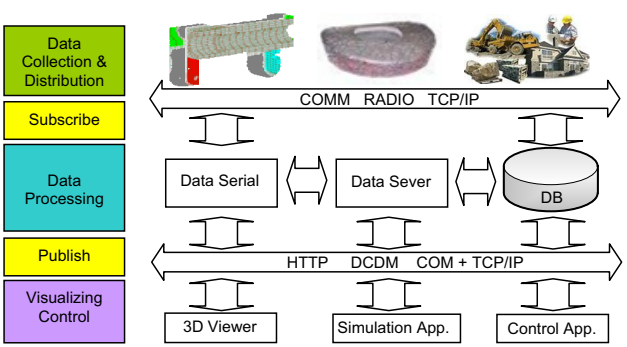


Figure 2: Architecture of data collection, data processing and visualization

4. Experiments and Results

Several experiments have been conducted to test the applicability of implementing real-time data collection and visualization technology in construction operations. The experiments are in particular concentrated on dynamic resources, as defined in the research scope. The first experiment illustrates a simulated scenario in which a worker is approaching heavy equipment and elevated loads. The second scenario presents an ironworker training procedure and includes real-time data collection and visualization

4.1 Simulation Scenarios of Close-calls (a.k.a. Near-misses)

Safety statistics indicate that workers may not communicate the majority of near-misses to existing site safety management. Lack of awareness of the incident type and fear of punishment of the workers are a few reasons why they are often not reported. An interactive 3D virtual environment can facilitate a more detailed inspection of construction operations. In particular, dynamic scenes can be viewed from multiple perspectives so that potential near misses can be studied. Combining this technology may even allow equipment operators to get a better spatial understanding of their location to other resources. Figure 3 (A-E) shows several scenarios of close calls (a.k.a. near misses) where limited perspectives of worker-on-foot or equipment operators (crane or dozer) cause recordable incidents.

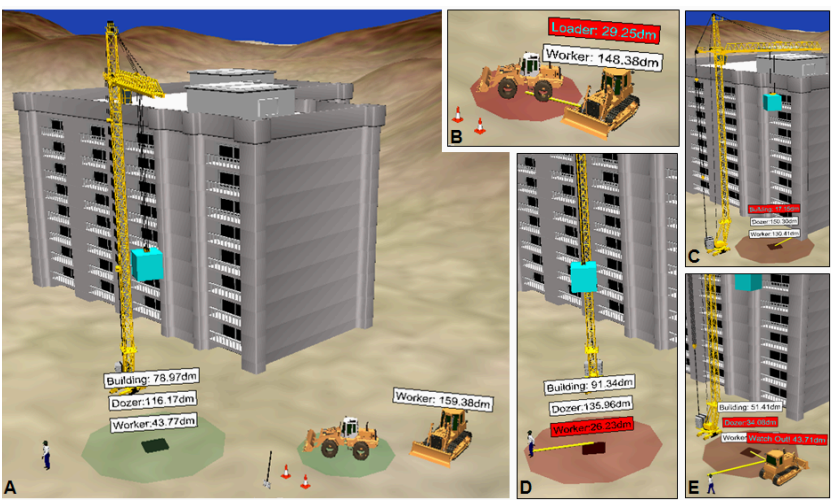


Figure 3: Visualization of close calls (a.k.a. near misses) using simulated data

The scene consists of five major objects (entities), a dozer, a loader, a worker, a crane with load and a building. Spatial data is subscribed to the server and the processed information is published to a 3D online viewer. Two preliminary defined dangerous zones are denoted by green circles to indicate the proximity to a static loader and the area projected from the load onto the ground. The distance between each pair of entities is computed automatically and in real-time from time-stamped trajectory data of the sensors. Both circular regions maintain in green when the center of its distance to all the other resources (worker, equipments, and material) is larger than minimum safety distance (proximity threshold). Regions switch to red (equivalent to the alert status) when the proximity threshold is smaller than the minimum recommended safety distance. In this virtual reality scenario, real-time calculation and visualization of the distance between several objects (see Figure 3) is indicated above each object. Real-time monitoring and recording of safety distances and thus automated near-miss data collection becomes feasible.

A particular strength of the developed virtual reality model is scene realistic field-of-views. For example, the activity of the crane involves the rotation of the crane arm along the base axis and translation of the elevated load. Since the sensor data can only provide absolute spatial information, same as the derivative of heading, multiple sensor data sources are necessary. The crane structure was broken down into three major subcomponents, crane base, crane boom and the pulley attached to the boom with a connection to the hook. In this experiment it is assumed that the crane cable that has the load attached does not swing the crane boom is rotating. Three sensors were attached on each subcomponent of the crane to collect absolute spatial information and the activity of the crane.

This experiment shows potential benefits. Risks can be easily detected by the decision maker (e.g., equipment operator) in advance and in real-time. A screen on board of the equipment knowing the color will change from green to red should another object violate the safety perimeter of the equipment. Workers on ground can be alerted of the situation of being too close to equipment or other objects (e.g., suspended loads during lifts). As the distance between machine and human is quantified automatically it also provides a visual update in real-time. The user can access the situation from any perspective in the virtual model and in an immersive manner, putting the viewer even inside the equipment cabin of crane or dozer. Realistic views of the field-of-view of worker-on-ground also become feasible. Detailed information of working activities can be performed form any preferred viewpoint in an interactive manner, for instance the view from the cabinets of crane and moving dozer can be displayed spontaneously and simultaneously. In addition, the user has the option to prioritize the visualization of relevant information over other less relevant information.

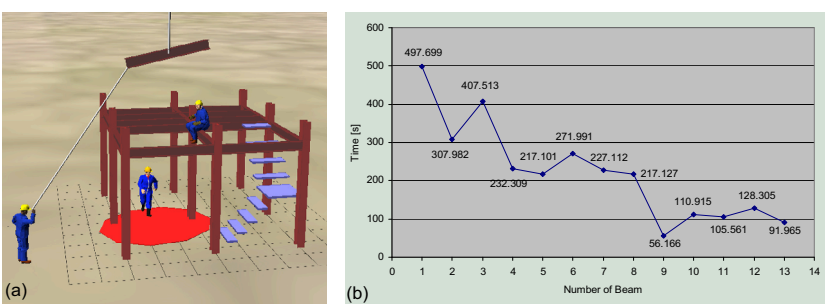


Figure 4: (a) Visualization of iron worker training facilities, and (b) time needed to connect steel members

4.2 Visualization of Trajectory Data from Union Iron Worker Training Facility

A second preliminary experiment focused on improving the safety performance and working efficiency of union ironworkers. Experiments were conducted at the Southeast Regional Ironworker Training Facility to test the applicability of the developed real-time data collection and visualization system. Spatial trajectory information of ironworkers and steel beams were collected by tagging the helmet of the ironworker and the steel members with UWB tags. Figure 4a presents a scenario

during the rigging and connecting of steel members. A suspended load above a worker on ground triggers an alert (red circle). The times to connect steel members in these particular training sessions were recorded.

Figure 4b indicates the learning curve of the same union ironworker connecting the steel members. Overall, five union ironworkers and one trainer were equipped with UWB tags. Their spatial movements in the training environments were recorded. The ironworkers were rigging, hoisting, and connecting on a two story mock-up structure that is located at the training facility. The beam was first rigged to the crane hook in the material deposit area. Then the steel beam was moved with the crane to the assembly zone where two connectors connected the steel beam to the vertical columns. The two connectors stayed on the steel structure all the time while two riggers and a crane operator walked on the ground level.

In the data processing phase, the velocity of the monitored tag was derived. A high speed is considered as a violation of preliminary defined safety rule since running is always prohibited on real construction site. Moving velocities of workers and materials are considered as an indicator of working efficiency. The speed range implies whether the worker is performing a work task or sits idle. This depends on the type of work task. Developed algorithms checked whether the location of any worker was within a pre-defined work zone or a hazardous zone. Productivity and safety performance data was computed and recorded.

Data recorded and visualized in the virtual reality tool in Figure 4a shows the only safety violation throughout the entire training period. A dangerous zone (3.5 meters radius) below the swinging load was defined prior to the experiment. This zone is represented by the red circle on the ground. Entering this area (cylinder or cone; from a spatial perspective) was defined to be a safety violation according to current best safety practices in erecting steel.

The automated data recording was later visualized and presented to the participating training crew. Within the visualization that was replayed, it can be recognized that the rigger stepped into the pre-defined dangerous zone from the left, and walked across the dangerous area (underneath the suspended load). Eventually, the rigger left this area towards the front of the virtual image. According to the recorded safety data, the rigger stayed within this dangerous area for about 8 second.

The productivity of a worker is represented by the time that is spent on a specific individual task. This experiment measured the time connecting 13 different steel beams to a column. For each connection, the time was recorded. Figure 4b visualizes the connecting time. Although it is eventually difficult to record the exact start and end time of the work task, measuring the time the worker spent in one particular connection location is feasible. The presented data shows a learning curve of the connecter. It took 497 to connect the first beam. The trainees then received an instructor lesson on how hoisting and connecting could be improved. After about 8 connections, the connection time leveled to roughly 100 seconds per bolted connection. Waiting times of the connector for the crane are included. As a whole, such data represents the crew effort rather than individualized information. However, information on crew productivity should be given priority unless objective individual measurements are possible.

5. Conclusions and Recommendations

A preliminary mechanism of implementing real-time data collection and visualization technology in construction industry was presented in this paper. Although virtual reality technology has already been widely used in construction research and development, and even in applications for and on high profile construction job sites, little research has been done on the problem of real-time data collection and visualization of construction operations. The presented research approach contains significant steps towards solving this problem. The concept of acquiring site relevant data to critical project resources (workforce, equipment, material) was presented. Real-time data collection of these resources, broadcasting its relevant information in real-time to the decision maker for real-time data processing, and embedding the resulting information in visual virtual 3D models has been demonstrated.

Future work is necessary to validate important research questions whether relevant information can be provided to decision makers and whether they are able to profit from the selected research approach. Initial experiments are few and limited. The entire framework for safety and productivity entails long term research projects and validation, including several experiments for site data collection and visualization. Studies need to be performed to measure tools that are required for advancing and whether construction information such as productivity and safety practice can be quantified and visualized in real-time. Ways need to be found to allow stakeholders to make fast decision on both operation and project level while the construction project is ongoing. By subscribing the data to multiple locations via internet and intranet infrastructure, distributed project teams can visualize the entire operation in 3D view as it takes place on a local site. Proving that such tools can be made available successfully will ultimately benefit in rapid decision making. The envisioned outcomes of this research can then enhance existing project and task based learning techniques by increasing job site safety and health planning and evaluation, improving task based performance measurements, and lower overall construction cost and schedule.

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SIMULATION-BASED MULTIPLE HEAVY LIFT PLANNING IN INDUSTRIAL CONSTRUCTION

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Abstract

Heavy lifting in industrial construction involves the installation of prefabricated modules and equipment weighing up to 1000 tons. Placing a prefabricated module requires a specific crane with a minimum capacity and specific configurations and riggings. Site construction process should follow a certain sequence. If the required cranes are not available or the predecessor modules or structures are not built yet, the module has to be stored in a storage area. Prior to lifting a module, several supporting tasks must take place including adjusting the location, configuration, and rigging of the crane and preparing the ground beneath the crane. Therefore, planning multiple heavy lifts is a complex process. However, it has a significant impact on the cost, schedule and safety of the project. This study employs a simulation-based approach to produce a heavy lifting planning system for mobile cranes. This system assists the project manager and lift engineer in decisions regarding the selection of mobile cranes and their locations and configurations for different lifts. It also produces a schedule that reduces the total cost and enhances the schedule of the project. This system is under implementation on an industrial plant in the province of Alberta, Canada.

Keywords: Heavy lift planning; Modular construction; Mobile crane; Simulation; Schedule

1. Introduction

Modular construction is a popular and cost-effective method for building remote industrial facilities (e.g. refineries, oil-processing plants), particularly in areas with harsh weather conditions. A module refers to a construction unit that is built off-site and transported to the work site for construction of the facility (Taghaddos et al. 2009). Prefabricated modules in industrial construction may weigh up to 1000 tons and are usually lifted with mobile cranes in North America (Hornaday et al. 1993; Lin and Haas 1996).

Planning multiple heavy lifts in congested industrial plants, particularly if the plant is built by modular construction (Figure 1), is a complicated and time consuming process. It includes determining the appropriate type, configuration, and rigging of the crane for each lift, preparing the prelift location of the module and the crane, verifying the lift capacity rating of the crane, and ensuring sufficient clearance during the lifting process (Lin and Haas 1996). Several activities may take place to prepare a crane to lift a module. These activities include mobilizing the crane to the site, changing the location, configuration and rigging of the crane, preparing the ground and putting mats underneath the crane's foundation. Each of these activities requires a different amount of time depending on the type of the crane (e.g. 1 day, 10 days).



Figure 1. A typical congested industrial plant

Developing reliable multiple heavy lift plans with minimum risk involved has a major impact on the cost, schedule and safety of the project. A good plan has to consider various aspects of the project to lift the modules on time, with the right sequence, with suitable cranes. An optimized plan minimizes the extra supporting activities such as storing the modules, mobilizing the cranes, relocating or reconfiguring the cranes. In a project that involves mobile cranes with several hundred dollars per hour (e.g. $1,500/hr) rental cost, some small modification in the

heavy lift plan may reduce or raise the project cost significantly. Moreover, any flaws in the lift plan or any accident during a lift may delay the schedule or result in injuries, equipment damages, and sometimes loss of life (Varghese et al. 1997).

This paper introduces a simulation-based approach to produce a multiple heavy lift planning system. This system is developed in collaboration with PCL Industrial Management Ltd. and is under implementation on a real industrial plant in Alberta. The produced model selects the mobile cranes, determines their locations and configurations for different lifts, and produces a lifting schedule for the entire duration of the project. It also reduces the total cost and enhances the schedule of the project by employing an optimization algorithm inside the simulation model.

2. Problem Statement

This study addresses the problem of multiple heavy lift planning in modular construction of the industrial plant. Field construction is the last ring of the supply chain of large-scale industrial construction, which also includes drafting, spool fabrication shop, and module assembly. Modules are made of pre-assembled components such as structural steel frames, racks of pipes, cables, equipment, or a combination of miscellaneous components (Taghaddos et al. 2008; Borrego 2004). Once all the required components of a module are built in the fabrication shop, the module is assembled in the assembly yard beside the spool fabrication facility and then transported to the field. Previous research in industrial construction at the University of Alberta studied the spool fabrication shop and module assembly yard in detail (Taghaddos et al. 2009; Sadeghi and Fayek 2008; Wang et al. 2009; Mohamed et al. 2007; Song et al. 2006).

Once a module arrives at the field from the assembly yard, if it can be lifted by the next day, it sits in the pick-point area. Otherwise, if the crane or the pick-point is not available or the predecessor modules and structures are not constructed yet, it goes to a storage area. This adds the daily rental cost of storage, transport cost, loading and offloading cost, and mobilizing cost of transport equipment to the project's budget.

A limited number of cranes (e.g. maximum three cranes) can mobilized to the site to carry all the modules in the project. These cranes have to be selected among the heavy cranes that are potentially available in a limited period for the rent. The first objective of this study is determining the cranes that are cost efficient and safe to be mobilized during the construction process of the plant.

Each mobile crane can be mobilized to predefined locations (Figure 2) by various configurations and rigging (e.g. 1 point, 2 points, 10 points). A crane can pick a module from different locations and with different configurations and riggings. Therefore, the below questions have to be addressed for each single lift:

a. Which crane should lift the module?
b. Which support activities (e.g. relocation) does the crane require?
c. Where should the crane pick up the module from?
d. Where should the crane sit to lift the module?
e. What configuration and rigging should the crane have to lift the module?
f. When should the required support activities of the crane start?
g. When should the crane lift the module?

This study aims to answer the above questions for all the lifts during the construction process (e.g. 2 years period) such that the total project cost is minimized and the modules are placed on time and in sequence. Minimizing the total cost implies minimizing relocation and reconfiguration of the crane, which enhances the safety of the project. Of course, the global optimum cannot be found for a scheduling problem, which is Non-deterministic Polynomial-time (NP) hard (Demeulemeester and Herroelen 2002). However, any improvement to the current traditional heavy lift planning methods is appreciated by the industry.

A lift schedule has to satisfy several logical constraints on the site. For example, modules should be assembled in sequence and a module cannot be placed between two adjacent modules. The bottom module must be assembled prior to its top module. Some of the predefined locations for the cranes are available for a limited period of time because of other construction activates on the site, and some locations may be available while a module is not yet installed.

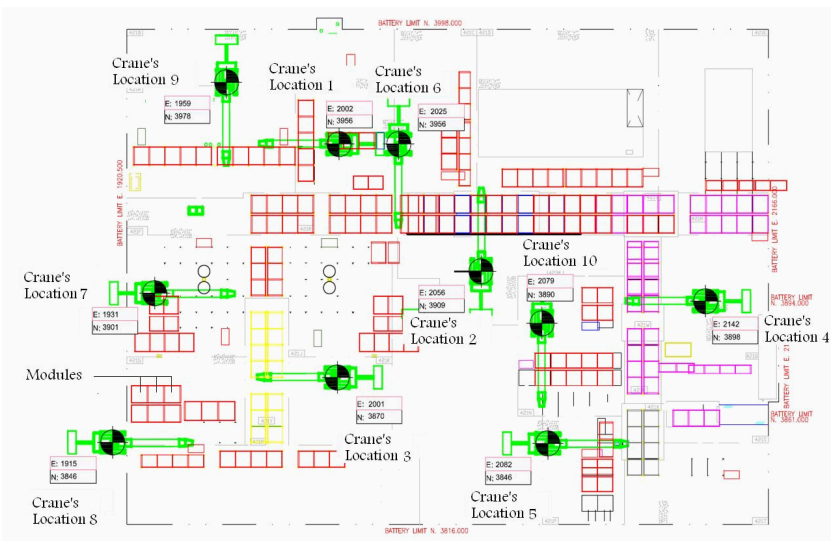


Figure 2. Plot plan with cranes' predefined locations

3. Related research studies

Heavy lift planning of mobile crane operations in the construction industry is mostly done intuitively by reliance on highly specialized planners and lift engineers. But the manual process of lift planning is very time-consuming and does not necessarily result in an optimum scenario. The fact that the pre-construction period of heavy planning is very constrained and cannot be performed without knowing the exact delivery dates of the modules, makes the problem more challenging. As a result, the need for a computer-aided heavy lift planning system has been identified by a number

of researchers and industrial practitioners since the early 1990s as a safe and cost-efficient tool (Hornaday et al. 1993; Varghese et al. 1997; Tantisevi and Akinci 2008; Shapira and Glascock 1996).

Research in computer-aided heavy lift planning began at the University of Texas about 20 years ago. Wolfhope (1991) recognized seven critical criteria to evaluate the feasibility of a lift, including availability of the crane, access to the site and lift area, location of the crane to execute lift, lift path clearances, safety, ground support during lift, and crane removal from the lift area. Hornaday et al. (1993) justified and developed architecture for computer-based heavy lift systems. Varghese et al. (1997) presented a computerized Heavy Lift Planning System (HELPS) to automate three of the above-identified tasks. In the last decade, some other commercial and industrial software have been developed to assist lift planners in selecting and scheduling the cranes (Bennett and Ditlinger 1994; William and Bennet 1996), and some researchers (Lin and Haas 1996; Tantisevi and Akinci 2008; Al-Hussein et al. 2005; Deen Ali et al. 2005; Moselhi et al. 2004; Mahalingam et al. 2000) have attempted to automate some other aspects of the heavy lift planning. However, no integrated planning system yet exists to consider different aspects of heavy lift planning for the multiple lifts throughout the project.

4. Research Approach

This paper introduces a system considering various aspects of heavy lift planning in industrial construction. Figure 3 shows the architecture of this system which is built upon previous research (Hornaday et al. 1993). This system reads the data from a database, runs a discrete event simulation model, and populates the results into the database. Therefore, the database includes some input information and some output tables filled by the simulation model. The input tables contain the information regarding the objects, cranes, site layout, and storage. The output tables contain the required data regarding the selected cranes, the status of the crane (location, configuration, and rigging) for each lift, the lifting schedule, the total cost and duration of the project, and the information to present a 4D animation of the entire construction process. The main feature of this system is that it considers different feasibility criteria recognized by Wolfhope (1991) as well as some extra factors:

a. It considers the arrival time of the modules to the site and early start data of the modules, which depends on the availability of structures on the site. It schedules a module to be lifted once the module is available at the site, the required structures or foundations in the site are built, the predecessor modules (e.g. module at the bottom) are installed, the required crane with enough capacity and boom length is available, the pick-point area to lift the module is available, and finally the lifting path of the module is not obstructed by any other module or structure.

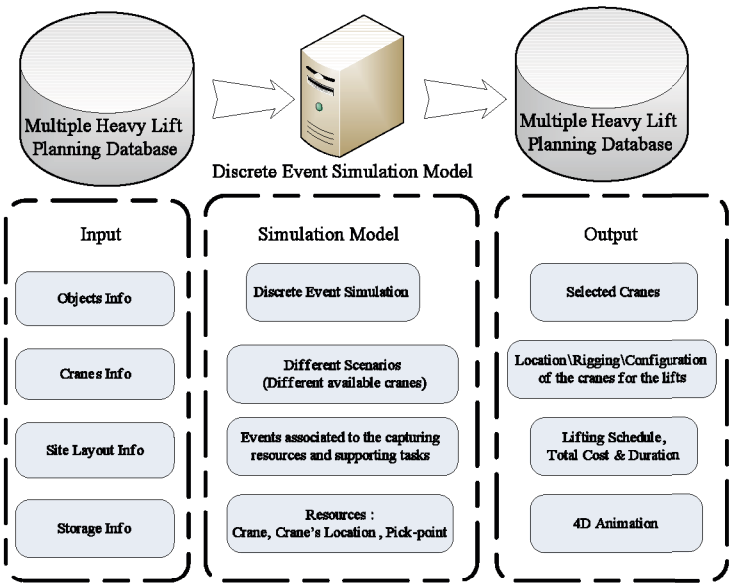


Figure 3. Architecture of multiple heavy lift planning system

b. This system proceeds by another preliminary study that associates a number of potential lifting options for placing the modules. This study takes into account a number of lift feasibility factors such as the capacity of the crane, boom length and configuration of the crane, crane's location and module's pick-point, and clearances. Each option introduces a crane with a particular configuration and location to lift a module from a pick-point.
c. This system can consider weekends and weekdays in the calendar as well as different shifts. These shifts include 4 day and 2-10 hr, 5 day and 2-10 hr, 6 day and 2-10 hr, 7 day and 2-10 hr, 4 day and 1-10 hr, 5 day and 1-10 hr, 6 day and 1-10 hr, 7 day and 1-10 hr, 5 day and 1-8 hr. Therefore, the planner can see the impact of different shifts on the cost and schedule.
d. One of the main outputs of this system is selecting suitable mobile cranes for all the lifts during the entire project. These cranes are selected among the potential cranes for the rent in certain periods of time. All the costs and durations associated with the supporting activities of each crane are also available.
e. The other output of this system is producing the lifting schedule, while considering availability of the cranes and accessibility to the site and lift areas. This schedule determines the lifting date and pick-points of the modules, the moving date and locations of cranes for different lifts, the date that a crane has to change its configuration or rigging and its new status. It also determines the cranes' mobilization and demobilization time, as well as their initial locations,

configurations and riggings. It also arranges to prepare or remove the ground and mats underneath the crane.

The multiple heavy lift planning system is developed based on a discrete event simulation model, which employs the core services of Simphony 3.5 simulation engine within Visual Studio 2008 programming environment. Simphony 3.5 is the new generation of Simphony.Net (Hajjar and AbouRizk 1999) targeted at the version 3.5 of the .NET.

In this project, different scenarios were generated to consider different combinations of the cranes to carry the lifts. If the combination of cranes cannot carry all the lifts in a scenario, the simulation engine stops and jumps to the next. The developed simulation model can run all possible scenarios or work with a developed Genetic Algorithm (GA) to run only a few. In practice, the total number of cranes is limited to a small number (e.g. maximum three cranes). So running all scenarios usually does not take more than a few minutes or a few hours (depending on the project). However, if the maximum number of cranes is not limited, running all the scenarios is not feasible and GA is the alternative solution. For each possible scenario, the following steps are performed:

1. Define resources (cranes, cranes' locations, modules' pick-points) based on the database information.
2. Define a waiting-file to capture resources and associate it with the defined resources.
3. Synchronize time of simulation engine with working hours based on the selected shift and weekdays.
4. Generate modules based on modules information and schedule their arrival at the site.
5. At every period of time (e.g. every day):
   - 5.1. Loop over all the arrived entities. For each entity:
     - 5.1.1. Check various constraints (e.g. if the required structures are built, the predecessor modules are installed, and the modules are built in a logical sequence).
     - 5.1.2. If the constraints are satisfied, loop over potential lifting options of the module. For each option (a combination of resources):
       - 5.1.2.1. Check the constraints regarding availability of required resources or maximum number of cranes.
       - 5.1.2.2. Check the other constraints (e.g. obstruction).
       - 5.1.2.3. If all constraints are satisfied, determine the bidding cost and required date to start crane's supporting activities and let the module bid for the resources in the option.
   - 5.2. Assign available resources (cranes, locations) among the bidding modules based on minimizing the total cost and on time delivery by employing a greedy optimization algorithm.
6. Run the simulation model based on the resource assignment results as follows:

6.1. Module waits in the waiting-file to capture the assigned crane and location.
6.2. Mobilize the crane, if it is not yet mobilized,.
6.3. Prepare the ground and put the mats underneath crane, if there is not any.
6.4. Reconfigure the crane, if the module needs a different crane's configuration.
6.5. Move the crane into new lift position, if the module needs a different crane's location.
6.6. Disassemble the precious rigging and assemble the new one, if the module needs a different crane's riggings.
6.7. Module waits in the waiting-file to capture the pick-point.
6.8. Lift and place the module, if the lifting process finishes at the same date. Otherwise, lift the module at the beginning of the next business day.
6.9. Release all the module's resources.
6.10. Populate the data into the database.

7. Finalize the scenario by the below steps:
7.1. Walk the cranes off the pads
7.2. Demobilize all the used cranes
7.3. Remove the ground preparations and the mats
7.4. Calculate the total cost and duration for the scenario

In the above-explained simulation model, the mobile cranes, locations of the cranes, and pick-points of the modules are modeled as the resources. In each scenario, an optimization algorithm (e.g. greedy algorithm) is employed to assign a specific set of resources (crane, location, and pick-point) to each module. The crane and location are captured at the start of supporting activities and the pick-point is captured at the start of lifting activity. All these resources are released at the end of lifting activity.

In each scenario, the total cost and the produced schedule have to be evaluated. At the end, the scenario with minimum total cost and the best schedule is proposed to the planner. Balancing between cost minimization and on time assembly of the modules is a time-cost trade-off and requires further research.

Another feature of this model is providing the required scheduling data to feed to a CAD application and illustrating the 4D animation of lifting and supporting activities during the entire construction process.

5. Limitations

The developed simulation-based system for multiple heavy lift planning has some limitations and should be advanced in the near future. Currently the optimization algorithm inside the simulation model is a greedy algorithm and the other optimization algorithms (e.g. dynamic programming) have to be experimented. Moreover, the mobile cranes, locations of cranes, and pick-points of the modules are the only resources inside the model, while several other resources can be incorporated in the simulation model including the mats, transport equipment, and storage area. Optimizing the best sequence to assemble the modules is another area for further research. The time-cost trade off is also an appealing research area, which has a key impact on the decision making process. Finally the construction process in the site

has to be connected with the other supply chains in the industrial constructions. For example, the modules arrive at the site from the module assembly yard. Linking the simulation model of the module assembly yard or fabrication shop to the simulation model of site construction is an important step to model the entire industrial constriction process. This large-scale simulation model assists the planner to decide about the best time to transport a module or spool from module assembly yard or fabrication shop to the site. It also results in a more realistic estimate of the arrival dates and the capacity of the entire system.

6. Conclusion

Multiple heavy lift planning of industrial projects is a critical and challenging issue, particularly if the plant is built by modular construction. Several cranes are involved in a congested site. Modules arrive on different dates and have to be lifted by a certain due date. The lifting process of the modules should follow certain sequences and should be synchronized by the construction of other structures. Moreover, limited resources (e.g. cranes, space) are available in the field.

There is some research toward automating some aspects of heavy lift planning. However, no research considers various lifting feasibility criteria for all the lifts. In this study, a simulation-based heavy lift planning system that automates different aspects of lift planning for all the lifts is introduced in industrial construction application. This system reads required data from a database, selects the suitable types of mobile cranes, and produces a lifting schedule. This schedule includes the lifting date and start time of cranes' support activities, as well as location, configuration, rigging of the crane, and associated cost for different lifts. This system reduces the total cost and enhances the project's schedule and safety significantly. This system is under implementation on a real case study.

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Spatial Trajectory Analysis for Cranes Operations on Construction Sites

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Abstract

Managing the behaviour and trajectory of an object lifted by a crane is critical to a successful lift. This paper presents advancements in the development of mathematical algorithms for lifted object trajectory paths and analyses. The proposed methodology is divided into smaller manageable phases to control the process and at the same time to create independent modules. Each step of the lifted object movement was geometrically tracked, starting at the lifted object pick-point, through an optimum path development and completing at the object final position (set-point). Parameters such as the minimum distance between the lifted object and passing obstructions and minimum allowable clearance between the lifted object and the crane boom are some of the many predefined rules which were taken into account. The lifted object's spatial trajectory analysis and optimization is a part of the complex assignment relating to the crane selection process. A numerical example is presented to demonstrate the effectiveness of the proposed methodology and illustrate its essential value.

Keywords: mobile crane lifts, object trajectory, site layout, mathematical algorithm

Introduction

Computer advancement for the design of construction equipment has brought major changes to equipment functionality, productivity and construction practices. Mobile cranes, among other heavy industrial machinery, have increased in size, capacity, manoeuvrability and versatility inducing an increase in capacity.

The consequences of the misuse or improper planning of a crane lift can be severe. The preparation and planning of heavy lifts can be complex and involve challenging issues during lift analysis. Fast-tracked construction projects involve frequent changes to the construction plan thereby requiring many what-if scenarios and changes to the lift plan. The lift engineer extensively relies on computer technology to deliver solutions faster and safer than before.

Virtual reality combined with an interactive planning environment that explores human potential and computer advancement is an efficient alternative for spatial integration. A lead article introducing spatial integration in construction [Bernold 2002] presented the historical advancement and objectives of such technology. In other studies, authors found mathematical computations that helped identify configuration space and concepts to develop tools for creating lift paths [Raghunatha et al. 2002]. In addition, two levels of heuristic searches have been implemented for three-dimensional bin-packing problems [Raj and Srivastava 2007].

Trajectory and shortest-path developments are also of concern in this field. Ishigami et al (2005) encountered issues in the proper design of an all-wheel dynamic model during a steering trajectory analysis for planetary exploration rovers: the model's contact between the rigid wheel and loose soil was based on a terramechanical approach. A Makov-decision process with two algorithms addressed the problem of planning the shortest path for reliable landmark-based robot navigation strategies in the presence of significant sensor uncertainties [Briggs at al 2004].

Trajectory path analysis is also needed in applications such as tooling equipment, military rocket tracing, satellite space travel and even environmental disasters where oil spills must be traced. In the machine industry [Makhanov 2007], three algorithms for the tool path optimization of a numerically controlled five-axis milling machine were introduced. The focus of these algorithms is the development of a flexible geometric structure which adapts itself to a certain cost function as defined on the required part's surface. Algorithm 1 is based on the variation grid generation. Algorithm 2 is based on a modification of the space-filling curves technique. Algorithm 3 is based on the construction of vector fields composed of optimal cutting directions.

For military applications [Azimov 2005], the development of analytical, approximate analytical and numerical methods are used for solving variation when determining optimal rocket trajectories in gravitational fields and are also applied to study flight dynamics.

Yet the industry that stands most to benefit from this technology is the construction industry. A user customized database [Al-Hussein et al. 2005, Moselhi et al. 2004] integrated with mathematical algorithms for choosing a proper crane with respect to lift capacity while utilizing 3D animation for visualization techniques has been developed and is available on the market. Following this development, more complicated 3D analyses were evaluated. One analysis used a 3D optimization approach for construction using a tilt-up panel method [Manrique et al. 2007]. Another analysis used a combination of advanced visualization, the above-mentioned

crane selection process and detailed schedule optimization and interactive communication techniques [Olearczyk et al. 2009].

Proposed Methodology

The proposed methodology will be used for multiple crane configurations and positions and multiple lifted objects; thus, the use of commonly used CAD software for lift analysis is not practical. It will also be used in a more elaborate crane lift analysis program. Crane data, object data and obstruction data were entered into a database for mathematical analysis to determine the trajectory path. The process shown in Figure 1 is for one single lift with a given crane position, object pick-point location, and object set-point location.

The methodology consists of tasks and decisions. The input includes the information necessary for the system to run such as crane configuration data, the lifted object parameters, site configuration (slope or natural limitation areas) and obstruction data information for objects that could limit or impair the lift operation. During obstruction data input preparation special emphasis must be placed toward detailed and accurate obstruction positions since these items are critical to safe and smooth trajectory development.

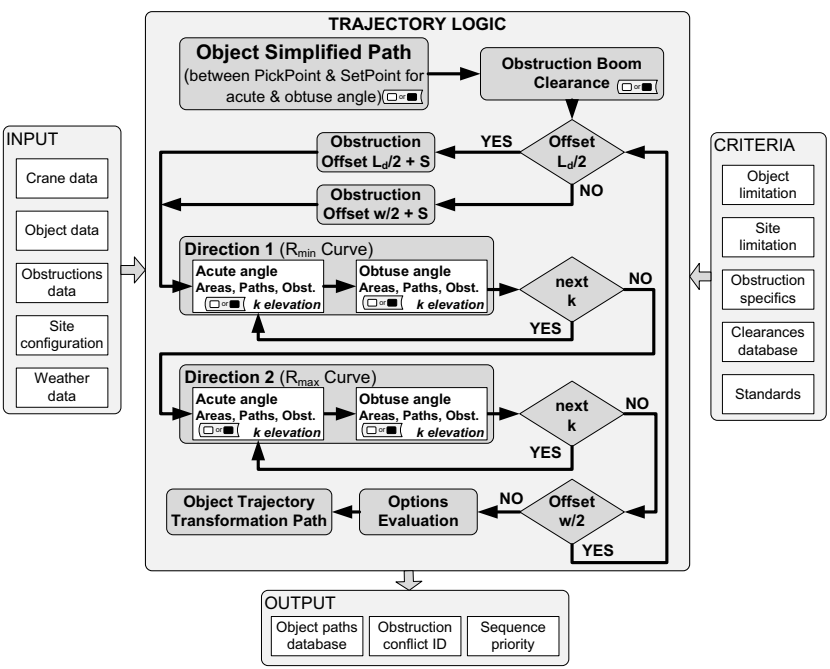


Figure 1. Methodology flowchart

The trajectory logic module is the center of the methodology with the most important components being the object shortest-path development and obstruction boom

clearance. The traffic light symbols represent a checkpoint where the task is completed either successfully or unsuccessfully. For example, after successful obstruction boom clearance, the algorithm then assigns the proper offset to the particular obstructions in the interested area. The trajectory path represents the hook position of the crane, and to clear the lifted object away from an obstruction, an offset to the obstruction dimension is required. This offset is the lifted object's geometric centre to either the diagonal half length (L_d) or half width (w) with an added minimum clearance distance (S) value (usually three feet).

In a simple trajectory following an arc from the object pick-point to its set-point, two radial directions are checked to modify the simplified path in acute and obtuse angles. Critical to this particular layout configuration is the k value (the distance from the top of an obstruction to the ground, see Figure 5). The expected amount of k elevation levels on a project is five. At the end of each system operation task, the resulting data is sequentially coded and stored for future trajectory optimization processes. Figure 2 shows an example of the number of analyzed path configurations for three different elevations.

3 elevations k_1,k_2,k_3 - all passed boom clearance

L_d/2+S - obstruction offset				w/2+S - obstruction offset			
Angle	**Elev**	**Direction**	**Status**	**Angle**	**Elev**	**Direction**	**Status**
acute	k_1	1	(failure) F	acute	k_1	1	P
"	k_1	2	P (passed)	"	k_1	2	P
"	k_2	1	F	"	k_2	1	P
"	k_2	2	P	"	k_2	2	P
"	k_3	1	F	"	k_3	1	P
"	k_3	2	P	"	k_3	2	P
obtuse	k_1	1	F	obtuse	k_1	1	F
"	k_1	2	P	"	k_1	2	P
"	k_2	1	F	"	k_2	1	F
"	k_2	2	P	"	k_2	2	P
"	k_3	1	F	"	k_3	1	F
"	k_3	2	P	"	k_3	2	P

Figure 2. Configuration example

Each elevation must pass an obstruction boom clearance check to be considered for object trajectory path development. The maximum and minimum offsets equations

$$\frac{L_d}{2} + S = Max\ Offset \qquad \frac{w}{2} + S = Min\ Offset$$

where:

L_d – lifted object's diagonal dimension (see Figure 3)
w – lifted object's width dimension
S – minimum clearance distance value (usually three feet)

are used to enlarge each obstruction area. When obstruction offset areas overlap, a union operation

$$\sum_{j=1}^{n} P_{kj} = M_{kj} \qquad \sum_{i=1}^{n} Q_{ki} = N_{kj}$$

where:

P_{kj} – intersected obstructions – crossing the CST (crane simplified object trajectory) line

Q_{ki} – intersected obstruction – non crossing CST line

M_{kj} – union region or P_{kj} crossing the CST line obstruction offset

N_{kj} – union region or Q_{ki} "floating" obstruction offset

is used to create one larger obstruction area, and this new area is given a new identifier (ex. M_{kj}). However, when the P_{kj} offset overlaps with the Q_{kj} offset, an M_{kj} region union is also created (see Figure 6 and 7). One or several obstruction areas may be analyzed at each k level in both radial directions (see Figure 4), and valid paths can be stored for further path optimization.

An optimization algorithm, used during the Option Evaluation task, will select valid solutions based on user-defined criteria. Limitation variables independent of the object and crane configuration are then put into the system.

Trajectory Path Logic Development

Object shortest path

To define the object shortest path from the pick-point (PP) to the final set-point (SP), an arc between the two points is created based on the radius distance from the closest point to the crane set-point (CS). Figure 3 shows a crane object simplified trajectory (CST) line developed in an acute angle section. There is a similar developed CST line between the pick-point and set-point covered in an obtuse angle section as well.

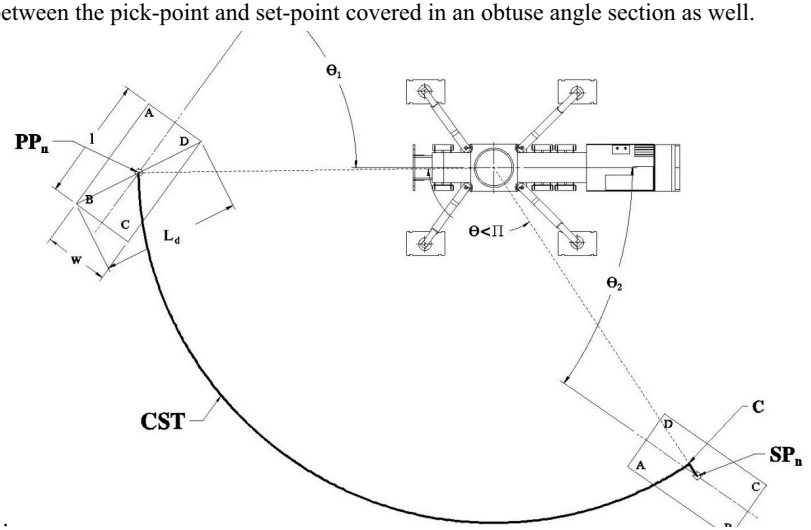


Figure 3. CST acute angle trajectory

At this point, the main objective for the crane object simplified trajectory evaluation is to ensure that the path is between the minimum and maximum crane radii values (R_{min} and R_{max}). This trajectory is the simplest and fastest for a crane operator to follow.

Obstruction boom clearance (Figure 4)

After the crane object simplified trajectory is calculated, the obstructions within the boundary established by the crane's maximum radius (R_{max}) are identified as well as the pick-point and set-point lines. The crane R_{max} is based on the crane's capacity to lift the object weight. Obstruction height and position information is available in the project database and is used to calculate and confirm clearances for the given crane configuration (P_{k1} and Q_{k1}).

Figure 4 shows an area based on the acute angle obstruction offset equation

$$\frac{B}{2} + S$$

where:

B – boom envelope width
S – minimum clearance distance value

There are two temporary obstructions (P_{k1} and Q_{k1}) in the area covered by the crane boom movement. These obstructions must be checked for crane boom clearance. If there is insufficient boom clearance, the trajectory path will be marked as a failure. If the radius has to be adjusted to obtain the required boom clearance, the maximum radius is modified to RQ_{k1} for the area behind the obstruction. Figure 5 shows a sectional view of Plane A and the adjusted radius RQ_{k1}.

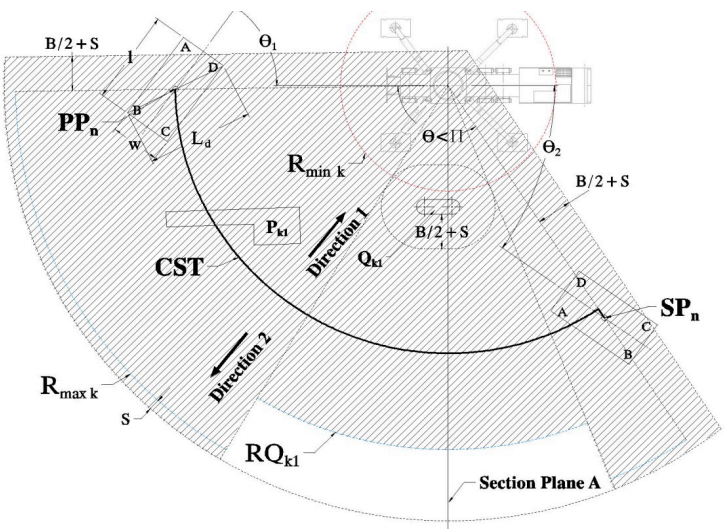


Figure 4. Acute lift angle obstruction offset on k_1 elevation

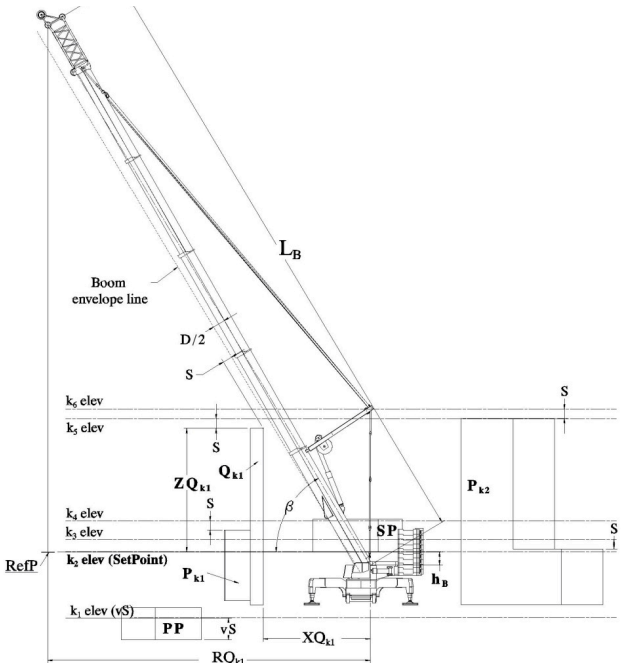


Figure 5. Section plane A elevation view

Figure 5 also shows the elevation set (k_n) for this particular setup. The acute-lift angle consists of only two obstructions; yet on the elevation view, a third obstruction (P_{k2}) exists in the obtuse section of the lift angle trajectory. Obstruction P_{k2} creates an elevation (k_6) which is analyzed only when the obtuse angle lift trajectory is analyzed. Elevations created from obstructions are vertically offset by the S value. The elevation created at the pick-point location is offset by vS (delivering equipment height), and the elevation at the set-point k_2 is the object's lowest resting point. For clarity and consistency, k_1 always refers to the pick-point position and k_2 to the set-point position. The next k value (i.e. k_3) starts from the lowest obstruction (or evaluation area height) and to the tallest obstruction.

Obstruction offsets

To identify a trajectory path and to maintain adequate clearance between the lifted object and the obstruction, the obstruction envelope must be increased accordingly. Distance

$$\frac{L_d}{2} + S$$

is analyzed first. This allows the object to rotate freely along the entire developed trajectory path at its optimum position (where the objects' long edge is perpendicular to the boom). If the distance between obstructions is too close and there is difficulty

finding an appropriate solution, the trajectory may be analyzed based on the minimum obstruction offset (w/2+S) value. A special envelope must be created to accommodate the smooth transfer of the object between obstructions (see Figure 6 shaded area). When the w/2 offset is introduced, the offset change applies only to the obstructions, and the perimeter of the object working area offset remains intact.

CST trajectory modification (R_{min} and R_{max} curve directions)

On each elevation plane, there may be different obstruction offset regions that must be considered. Union and subtraction operations on the obstruction polygons are the simplest options to consider in such configurations. Mathematically subtracting the unionized obstructions' offset areas from the entire object working area will define a suitable region for a particular lift. It will also determine whether the pick-point and set-point are in the same region, indicating a possible trajectory path solution. The concept of mathematical operations on region algorithms was previously developed and adopted for this application [Leonov and Nikitin 1997; Vatti 1992].

Figure 6 shows a united obstruction area (M_{k1}) in the acute-angle lift region that intersects the CST line at points Z_{11} and Z_{12}. All obstruction areas that do not intersect the CST line are called floating-area obstructions and are identified as N_{kj} (in this sample, N_{kj} does not exist). The main goal in the development of the object lift trajectory is to simplify the path even if obstructions are in its way. The intersection points between the obstruction offset area and CST line can support path development at either side of the CST curve (Z_{11} toward the R_{min} or Z_{12} toward R_{max}). To recognize the opposite side of the CST line, the obstruction offset maximum deviation is a tangent line to the obstruction offset area that crosses the CST line at point Z'_{11} and Z'12 (on corresponding sides of the main intersecting points).

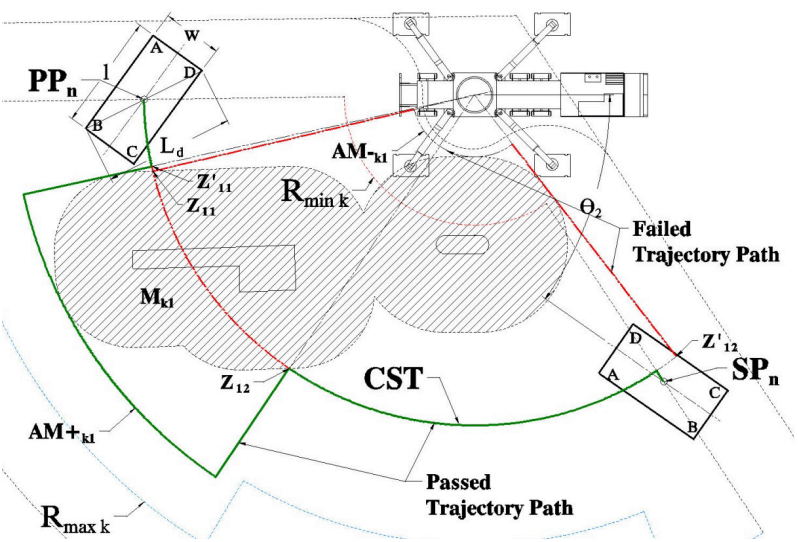


Figure 6. K elevation trajectory path development

Next, tangent arcs (AM_{-k1} and AM_{+k1}) to the M_{k1} obstruction area are constructed to bind the M_{k1} area to its minimum and maximum dimensions, respectively. These arcs must be located between $R_{min\ k}$ and $R_{max\ k}$ for the elevation being analyzed. In Figure 7, AM_{-k1} fails (Failed Trajectory Path) since its radius is less than $R_{min\ k}$; therefore, the entire object trajectory in the direction of R_{min} on k_1 elevation is marked in the database as a failure. When proceeding into the opposite side of the CST line, AM_{+k1} is perfectly positioned in the interested area, and the option for this side will follow this path: start at PP_n, Z'_{11}, radii transformation to AM_{+k1} arc, rotation as per AM_{+k1} arc, radii transformation to the CST line and end at SP_n.

The trajectory path developed with the w/2+S obstruction offset is optional and may depend on user criteria should the $L_d/2$+S offset path fail.

Option Evaluation

The path development algorithm will analyze all possible trajectories on each identified elevation for acute and obtuse angle lift options in both direction (toward R_{min} and R_{max}). Any full or partial path will be identified and stored for further analysis and then optimized for a final trajectory path movement. An option evaluation algorithm is customized by the user and will consider many options (such as staying as close as possible to the ground for heavy loads), the shortest path (for bulky but not heavy load), etc.) The developed final object lifted trajectory path is flexible insomuch that the algorithm can run indefinitely through code to permit the analyses of many obstructions, crane configurations and object scenarios. Furthermore, all of this can be done independent of CAD. This provides the user with a great tool to experiment with many possible scenarios that current graphical software cannot handle effectively.

Conclusion

This paper presents an algorithm that simplifies the complex process involving the selection of spatial trajectory path for lifted objects using mobile cranes. The proposed method calculates and optimizes the object lifted path for critical/heavy lift objects, and focuses on modular construction. Due to initial data preparation and complexity of the process a scenario base methodology was adopted in this study.

The recommended methodology analyzes all potential trajectory paths first for evaluation if the lift can be performed, and secondly determining the optimum trajectory path that the crane operator can use to lift the object from pick-point to its final location. The success of the presented technique provides a safe and cost effective solution for mobile crane lift of an object, and is expected to be used by planners, lift engineers and construction superintendents to run several user defined scenarios. A case study presented in this paper highlighted essential features of proposed methodology to illustrate its capability. The presented spatial object trajectory development path is one part of much larger crane application software being developed to assist in the crane selection process.

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State-Based Simulation Mechanism for Facilitating Project Schedule Updating

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Abstract

Discrete-event simulation (DES) has long been used as a management tool to analyze and study construction processes. Project scheduling is one of its useful applications in construction domain. By simulating the behavior of a production system over time, the DES is able to reproduce the process of how jobs and resources interact with each other. A schedule can then be viewed a record of this artificial history. However, simulation-based scheduling is, more often than not, limited to create the initial schedules. The problem of how to update project schedule based on the current progress is rarely addressed in construction simulation research. This paper presents a state-based simulation approach that can facilitate project schedule updating by (1) reading the starting time (i.e. the point of time to update the schedule); (2) resuming the work load of production system at this time and running from there; and (3) updating the new schedule (from simulation) based on the As-Built project progress. An illustration example is used to illustrate how the new modeling approach is used to perform schedule updating and its benefits are discussed as well.

Introduction

Project planning and scheduling is one of the most important but also most challenging task in project management. Limitations of conventional scheduling tools (e.g. Critical Path Method (CPM))motivate researchers to adopt Discrete-Event Simulation (DES) as an alternative to solve scheduling problems in construction (Zhang et al 2002; Song and AbouRizk 2006; Hu and Mohamed 2009). This is due to its apparent advantages, such as explicitly accounting for resource interactions and handling dynamic and stochastic nature of construction operations.

Many research attempts have been made to develop simulation-based scheduling tools. This includes SimCon (Chehayeb and AbouRizk, 1998); Activity-based simulation model for project scheduling (Zhang et al 2002); simplified discrete-event simulation approach (SDESA) (Lu 2003); Virtual shop model (Song and AbouRizk 2006); Simulation-based scheduling for module yard assembly (Mohamed et al. 2007). However, a review of these tools indicates they are always limited at some point. These limitations can be summarized as following: 1) many of these tool requires users to have significant knowledge about the specific simulation tool before they can apply it to real construction processes ; 2) simulation models (developed by these tools) are usually tied up with one type of network logic (i.e. a set of distinct activities plus their sequences) or just able to allow few variations (e.g. variation in activity duration and etc.); and, more importantly, 3) most of them are not capable of performing schedule updating.

This paper introduces a new state-based simulation mechanism for structuring simulation models. It addresses the limitations described above and provides improvements in each. Particularly, it facilitates project schedule updating by (1) reading the starting time (i.e. the point of time to update the schedule); (2) resuming the work load of production system at this time and running from there; and (3) updating the new schedule (from simulation) based on the As-Built project progress. Scheduling requirements and the current simulation practice are described in the first section, followed by the introduction of the state-based simulation mechanism. The concept "state-based mechanism" and how it supports schedule updating is also explained afterwards. A prototype system is developed based on the proposed mechanism and a simplified case is used to illustrate how the schedule updating is achieved. At the end, both benefits and limitations about this tool are listed and its future improvements are pointed out.

Scheduling requirements

Contractors are often faced with scheduling projects that involves several similar work packages. These work packages usually refer to a construction product or an element that constitutes a part of a larger project. For example, a house unit in a residence project or a pipe spool in an industrial construction project. Each work package is defined with a number of physical features (e.g. identification, type, length, weight and etc.) as well as specific network logic. In a repetitive project or a job shop situation, work packages usually involve very similar or even identical operations. However, perfect repetition is a rare case in the real world. Instead, variations can often be found in work packages. For example, operations might vary in work quantity, production rate and duration. Some operations might not even be involved at some work packages. Moreover, the sequence or precedence relationship between operations might vary significantly as well. In a spool fabrication shop, for example, each spool tends to have a unique routing pattern (i.e. operation sequence) among machines, even though they all involve the same operations—cutting, fitting and welding. In a residential project, some houses might require that windows and roof installation should come before drywall erection; while, for others, the sequence could be reversed. These variations in similar work packages, coupled with

scheduling constraints (e.g. technological constraints, resource constraints and optimality constraints), need to be fully addressed during the scheduling process, which entails that an adequate scheduling tool has to be capable of both enforcing the constraints and, at the same time, having a high level of flexibility to account for variations.

Schedule updating is another major functionality that schedulers expect from a scheduling tool. This is because uncertainty is an inherent feature of construction projects. Bad weather, broken machines or missing materials all have the possibility of delaying the whole project and obsoleting the original schedule. Therefore, it is always necessary to update project schedules on regular basis.

Current simulation practice

The current simulation practice for modeling construction operations seems not fully support these two scheduling requirements. For network logic, it depends on mapping the logic into a flow of operations with duration associated with each and explicitly enumerating all the possible logics (required by different simulation entities) in the simulation model. These logics are usually represented by using a set of connectors and branching elements (as shown in Figure 1). Therefore, as the diversity of network logic increases, the simulation model will get exponentially complicated. As for schedule updating, most of current simulation-based scheduling tools do not support such function. This is because they often contain an implicit rule that scheduling has to start from the very beginning (i.e. no spools are being processed in the fabrication shop or no work packages have been performed by any working crew). Even for the few scheduling tools which do support schedule updating, they still follow this rule. To generate a sound schedule update, they have to manipulate the simulation and force it to 1) run in a way that exactly imitates the As-Built progress and then 2) start scheduling from that point. Although feasible, it is quite an unnatural way of updating schedules.

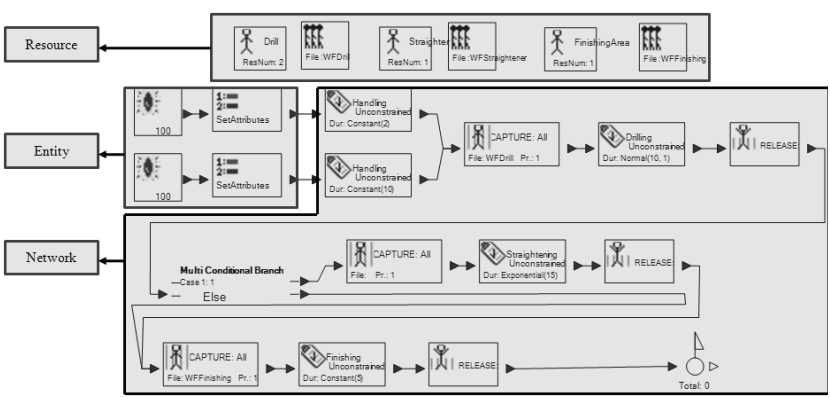


Figure 1 Three fundamental elements for a typical simulation model

State-based simulation mechanism

Declarative modeling approach suggests that a modeller looks at the world through a sequence of changes in state. Declarative models contain two primary components: states and events. They can be embedded within an object and are suitable for representing the dynamics within the object (Fishwick 1995). In the case of state-based simulation mechanism, objects specifically refer to simulation entities (i.e. work packages represented by entities). The state of an object focuses primarily on the completion status of a simulation entity (i.e. how much progress has been made in a work package). As previously stated, each entity is composed of distinct operations. The state of each operation can be simply described by its percent completion (completed portion divided by total work quantity). These states of individual operations, together with their sequence logic, at any point in time constitute the entity state (Figure 2). The state information is updated whenever a state-altering event occurs (e.g. an operation is just finished). These events trigger the transition of the entity state from one to another (until the final state is reached) and therefore drive the entire simulation forward.

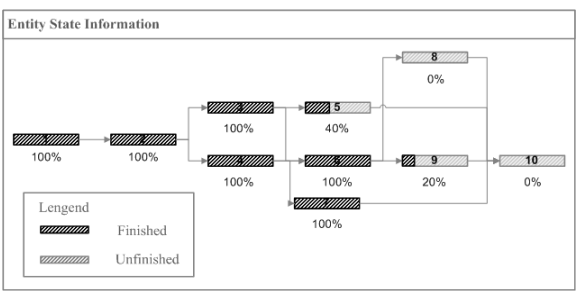


Figure 2 An example of entity state information

A state transition can be accomplished using different mechanisms. The basic types of state-based declarative models are: deterministic, nondeterministic, and production rule/logic (Fishwick 1995). The use of production rule/logic provides more general power, and it is the one chosen for implementation in the proposed framework. The inference rules or logic, which controls the transition of an entity from one state to another, can be expressed by operation constraints (e.g. the completion of all predecessors or the availability of required resources). The rules should have access to state information of its owner entity, so that it can 1) determine which operations can be started right away; 2) notify the entity to update this information when operations are performed. In the prototype system (will be described in later sections) a simulation element called "Dispatching Element" is developed to help entities to access their state information. This element also controls the dispatching of an entity according to the changes in the states of the entity.

Figure 3 shows the general algorithm for state transition in this framework, which is modified from state-based simulation algorithm (Fishwich 1995). Consider a

simulation entity which starts with the same state as in Figure 2. It will first take a look at its current state through the "Dispatching Element" and figure out which operations can be started immediately. In this example, they are operations 5 and 9 (instead of operation 1 again). The "Dispatching Element" will then send the entity to the corresponding operation elements for finishing these operations. After they are done, the state of the entity will be updated. Based on the new state, the entity will analyze which operation can be performed next again (i.e. it should be operation 8 in this case), and the loop will continue until the entity is completely finished.

```
Start simulation
    Set current time to zero
    Set Start state to any state in the automaton
    while not (final state) do
        Scanning current state information
        Identifying activities that can be started (based on activity constraints)
        dispatching entity to corresponding activities
        performing activities and updating current time by ΔT
        updating current state
    End while
End Simulation
```

Figure 3 Entity state transition algorithms

In order to implement the state-based simulation mechanism, simulation model needs to be structured in a different way. More specifically, the network logic will be extracted from the simulation model and carried directly by simulation entities themselves (as shown in Figure 4). This is because the network logic specifies operation constraints, which, in turn, define the state transition of an entity. A product-process integrated entity information model (Figure 5) is developed to help entities contain such information. It consists of four different types of information: 1) product information; 2) process information (i.e. network logic); 3) state information; and 4) schedule information. Equipped with such integrated information model, entities are enabled to route themselves through various operation elements without need of any connectors or branching elements. Therefore, the simulation model is reduced to resource modeling, which is simply a snapshot of the current production system (various workstations in Figure 4). Since each resource is associated with a specific type of operation, behaving as a workstation or a construction crew, it can be modeled by a 'Composite' element (AbouRizk and Mohamed 2000), which has a detailed child model that defines how many resources are available for this particular operation and how it will take place (in Figure 4).

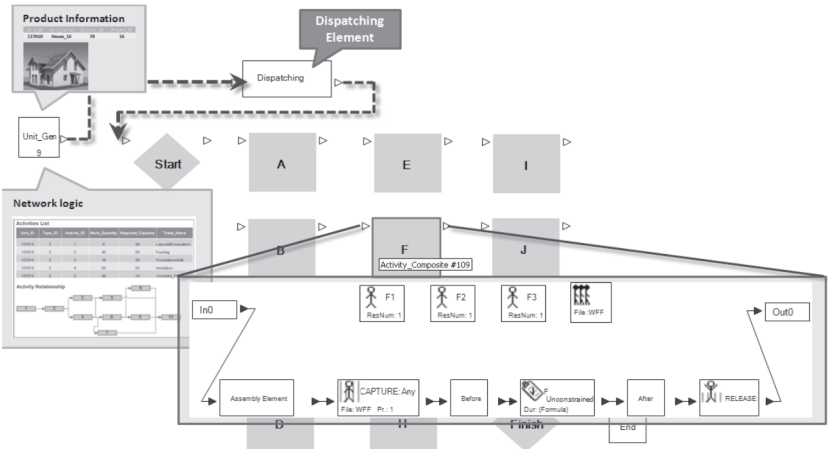


Figure 4 An example state-based simulation model

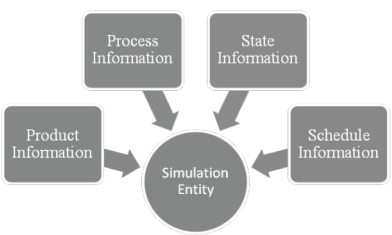


Figure 5 Product-process integrated entity information model

The state-based simulation mechanism allows entities to start simulation based on their current states. This means that if an entity enters the simulation model with a partially completed state, it will be processed precisely as what its state allows it to do, instead of having to start from the beginning again. This also means that the simulation is now able to schedule an entity (or a work package) from any point in its life span (i.e. from 0% to 100% completed). Therefore, if simulation users feed the simulation model with an as-built progress report (i.e. a group of entities with their completion status respectively) of any point of time during the project execution, the simulation can run directly from that point and produce a schedule update based on the report. In addition, the simulation is also endowed with the ability to reconstruct the current work load of a construction system (e.g. either a construction project or a job shop). It is particularly useful to model a situation where the construction system is already loaded with certain work, when work packages enter the system.

Another advantage of using the state-based simulation is that the simulation model becomes independent of entity network logics. No matter what specific sequence an entity choose to go through operations, it can always be simulated as long as all the

relevant operations are included in the model. This flexibility enables the simulation model to handle any type of variations in work packages.

The Prototype System

A prototype system was developed for scheduling construction projects (i.e. mainly refers to repetitive projects or job shops), which integrates with Microsoft Access® and Microsoft Project®. In this system, the simulation model extracts both product and process information (i.e. equal to job information and network logic) from a Microsoft Access® database and loads it onto entities. After running, it produces a schedule or schedule update and sends it back to the database. Meanwhile, a user-defined function was developed in the Microsoft Access® database which translates simulation times into real calendar dates. Finally, this table-format schedule is converted to Gantt chart style by integration between the Microsoft Access® and the Microsoft Project®.

The core component of the prototype system is a simulation model. This system adopts Simphony.Net (AbouRizk and Mohamed 2000) as its simulation platform and develops a special-purposed simulation template (Hu and Mohamed 2009) for simulation modeling. In order to reduce code-writing, the Hybrid Special Purpose Simulation (HSPS) development approach (Mohamed and AbouRizk 2006) is also used to build models.

Sample Application

To illustrate the schedule generating and updating of the prototype system, an example project is created. Assume there are three different types of product units to be constructed. The network logic to build each of them is shown in Figure 6. Variations in these networks should be noted. For example, type 2 differ from type 1 in that Activity E does not occur in it and durations vary in Activity D, G, I and J; while type 3, though involve all the same activities as in type 1, has a very distinct network from the first two types, with significant different sequences and durations in activities. For simplification purpose, all the activities have a deterministic duration. Assume 9 product units are to be processed, each with one of the types mentioned above. The start date of the project is 14/12/2009.

A simulation model is created for this project (Figure 4). After feeding both the product and process information of these product units to the model, it generates an initial schedule for the entire project (solid black bars in Figure 7). Assume that at the end of fifth day (18/12/2009) some progress deviations are found in the project. Table 1 listed all the activities that have progress deviations (i.e. for the activities or units that are not listed here, it means they are not started yet). When inputting this actual progress information (again from the database), the simulation automatically generates a schedule update. A comparison between the initial schedule and updated one is provided in Figure 7 (i.e. the black bars represent initial schedule; while the grey bars represent the updated schedule).

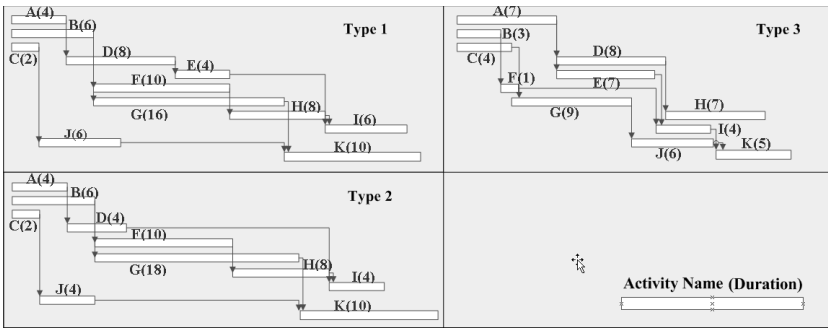


Figure 6 example networks logic for three product types

Table 1 Progress deviations at 28/07/2008

	Activity ID	Activity Name	Original Schedule	Actual Progress	Schedule deviations
Unit 1	1	A	100.0%	100.0%	on time
	2	B	83.3%	50.0%	2 days behind
	3	C	100.0%	100.0%	3 days behind
	4	D	12.5%	12.5%	on time
Unit2	1	A	100.0%	100.0%	on time
	2	B	83.3%	50.0%	2 days behind
	3	C	100.0%	100.0%	3 days behind
	4	D	25.0%	25.0%	on time
Unit 3	1	A	14.3%	14.3%	on time
	2	B	100.0%	100.0%	2 days behind
	3	C	75.0%	0.0%	3 days behind
Unit4	1	A	14.3%	14.3%	on time
	2	B	66.7%	0.0%	2 days behind
	3	C	75.0%	0.0%	3 days behind

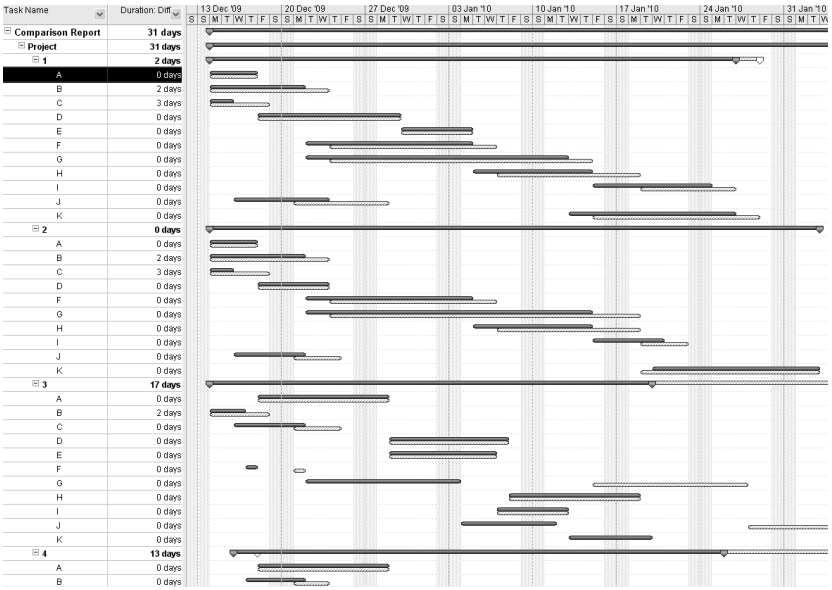


Figure 7 Initial schedule VS. Updated schedule

Conclusion

This paper presents a new way of structuring a simulation model. By providing simulation entities with an integrated product and process information model and a state-based simulation mechanism, the simulation model lends itself to an ideal scheduling and schedule updating tool. Meanwhile, it also obtains high level of flexibility in handling network logic variations, which is a limitation in most of current scheduling tools. The simplification of the simulation model, plus the opportunity of defining network logic outside simulation, makes this simulation-based scheduling approach user-friendly. Future development of this approach includes integration with other information systems and the optimality of schedules under work continuity or cost minimization.

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Studying Dynamic Decision-Making in Construction Management using Adaptive Interactive Simulations

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Abstract:

Construction projects consist of multiple components such as on-site equipment resources, site layout, labor productivity, unexpected external events, and human decisions regarding resource allocation and activity rescheduling. Stochastic spatial and temporal interactions between those components result in dynamic complexity of construction projects. Decisions made in such dynamic task environments must consider both immediate impacts and long-term dynamic feedback. The objective of this research is to use the adaptive interactive simulation framework as an experimental test bed to study dynamics of decisions in construction scenarios. A simulation of a four story structural steel framed office building project was implemented within Interactive Construction Decision Making Aid (ICDMA) under five different decision strategies. Simulated construction performance data at each decision control point was collected and analyzed to compare the project dynamics resulting from five strategies, and those strategies were assessed as well. This research provides a perspective to study dynamics of decision making through interactive simulation while furthering the knowledge of effective decision making and the development of dynamic decision support systems in construction management.

Introduction

Decision-making in construction projects involves the management of multiple inter-related components such as site layout, critical equipment resources, labor productivity, unexpected events, resource allocation and rescheduling of activities. Uncertainty associated with each of these quantities, and the evolving relationships between them within the constraints of time and space are at the root of complexity in project management. Accounting for this complexity is critical to effectively plan for

contingencies and test the usefulness of alternative decision-making strategies. However, predicting the consequences resulting from such complex behavior is difficult as they are often emergent within dynamic contexts. We argue that interactive adaptive simulations provide experimental platforms to test and compare the sensitivity of the project plans and estimates to alternative decision strategies and dynamic project complexities (Watkins 2008, Mukherjee et al. 2009). In this paper we propose and illustrate a methodology for studying dynamic complexity in construction management using interactive simulations as an experimental testbed.

This research uses relevant research in construction decision-making using System Dynamics, interactive simulation, and Markov decision process as a point of departure. The Dynamic Planning Methodology (DPM) uses concepts and methods in System Dynamics (SD) to account for dynamic feedbacks in the planning and control of fast-track construction projects. (Park and Pena-Mora 2009, Pena-Mora and Park 2001, Lee et al. 2006). Interactive simulations such as RiverWare (Biddle 1999) have also been used to aid real-time optimization of water resource system operations, for developing training programs for system managers and technicians, and in demonstrating system management alternatives (Cunningham and Amend 1984; Cunningham and Amend 1986). Among other methods, Ioannou (1989) uses Markov decision process for the solution of the risk-sensitive dynamic decision problems.

Each of these methods studies decision-making as a choice between de-contextualized management strategies – accounting for uncertainties in long-term behavior, and models of cause-effect relationships. In this research we take the next step by developing a method that can be used to analyze and compare the evolution of outcomes associated with different decision-making strategies. A project specific implementation of a general-purpose interactive simulation environment the Interactive Construction Decision Making Aid (ICDMA) is used as an experimental platform to illustrate the method, specifically emphasizing the data collection and analysis process. The method is the contribution of this research – it can be used to gain insight into the behavior of specific simulated projects. The results of the analysis can be used to enhance the planning of contingencies during the pre-construction process – especially in the management of complex construction projects with limited historical precedence.

ICDMA Simulation and Methodology

ICDMA is a specific implementation of a general-purpose interactive simulation framework (Rojas and Mukherjee 2006, Watkins 2008). It simulates a construction project based on the as-planned schedule and costs as defined in a web-based database. The user of the simulation takes on the role of construction manager/ primary decision-maker whose goal is to complete the project on schedule and under budget. During the simulation run, the user is presented with random external events that force the simulated project to deviate from its original plan. The user has to respond to those events by making decisions on resource allocation. The consequences from the decisions result in new scenarios for the user to respond. This process continues until the completion of the simulated construction project.

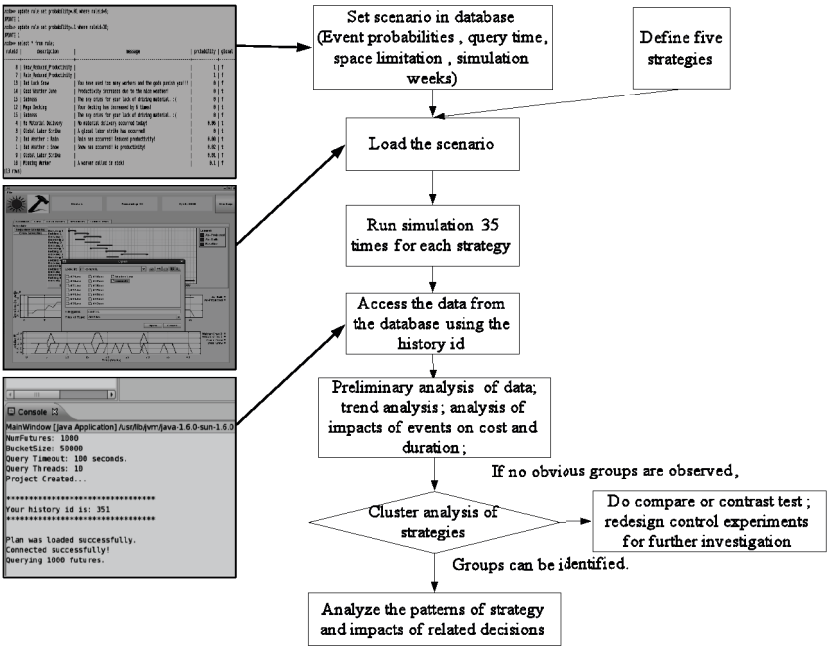


Figure 1 Flowchart of Methodology

ICDMA implements the construction of a four-storey structural steel framed office building that was built in real life. The simulation was based on the schedule and construction information documented by Daccarett and Mrozowski (1999). In previous work we have shown that the underlying construction models in ICDMA is capable of simulating the as-built performance of the actual project as described in Anderson et al. (2009). The research also illustrated the use of the querying algorithm, in ICDMA, to forecast likely project outcomes from any point in the project using current project information. A space of *possible* project outcomes consisting of future traces under varying conditions, constraints and decisions were generated and analyzed using a Monte Carlo sampling method. Each candidate in the future space is a complete simulation trace of the project. The *actual* project outcome was the most likely scenario in the space of possible outcomes.

In effect, the querying algorithm forecasts the likelihood of future scenarios and outcomes by *querying* a space of simulated project futures. In this paper, we take the next step in investigating the application of ICDMA and the querying algorithm to compare alternative decisions by statistically analyzing and clustering the simulated future outcome space. Specifically, a *potentially problematic* scenario is established and different control strategies to deal with its resolution are explored in an interactive simulation mode. The application of this research is during the pre-planning and planning phases of complex construction projects.

The scenario was set-up by simulating the office-building project to 14 days in the future. At this point, the project was behind schedule. External events expected in the project's future were rain (major weather), snow (extreme weather), labor strike, no material delivery, and worker sick. Their respective probabilities were set at 0.08, 0.02, 0.01, 0.06, and 0.10. Hence, the probability it will rain is 0.08 each time the simulator is advanced by one time unit. In addition, the space capacity was set to 3,000 units. If the space occupied by the material exceeds this limitation, a space conflict event occurs. These probabilities are specific to the project at hand and the investigators using the simulation can choose appropriate values to reflect the circumstances of their projects.

Once the scenario is set up, decision strategies are established and the simulation is run in the interactive mode using each of the strategies for a period of concern. During the simulation run, the decision-maker is required to manage the project by making decisions that specifically adhere to the strategy under investigation. In this research the window of concern was considered to be 6 days from day 15 to day 21. Hence, the decision-maker was allowed to implement control measures adhering to each strategy 6 times, once at the end of each day (details on strategies and data collection follow). Thirty-five such simulations were carried out for each of the decision strategies. During the simulation construction performance data at each decision control point was collected and stored in a database, organized by the history ID of each simulation run. The data is analyzed to compare the project dynamics resulting from five strategies. Figure 1 presents a flow chart of the methodology discussed.

A decision strategy is defined as the guideline and direction that provide the basis for a family of decisions towards achieving a project outcome. Five strategies are defined and implemented in ICDMA in this paper. Future studies using this method could choose a different set of strategies to reflect the reality of the project being simulated. A *control strategy* is used to reflect baseline conditions and the other four strategies are chosen as alternative approaches to managing the project at hand. In this case, the control strategy aims at completing the project by adhering closely to a baseline decision sequence. The *crash strategy* tries to crash the schedule to save time. The *reassign strategy* aims to optimize the project by prioritizing activities on the critical path. The *safety strategy* aims at reducing the risks due to delayed material delivery by ordering materials ahead. The *catch up* strategy tries to catch up with the schedule when it falls behind. It is important to note that the strategies make no direct adjustments for bad weather, global strike, and material delivery failure. The strategies were coded to respond to the consequences of the events rather than to the occurrences of the events. Detailed descriptions of the guidelines provided by each of the decision strategies are shown in Table 1.

Data Collection

Data was collected at the end of each simulation time point. The categories of data collected include: (i) Outputs of the querying algorithm including a set of simulated future spaces (set size = 1000) and a frequency distribution of final cost and duration outcomes of the simulated projects, and (ii) Metrics (as described below) defining the project status and specific decisions that were taken at the end of each decision control point. These data sets were collected after each of the 6 decision control

points for 35 runs per decision strategy. Hence a total of (6 x 5 x 35=) 1050 data sets were collected.

	Labor& material allocation	**Policy on Space Conflict**	**Material policy**	**Labor policy**
Control Strategy	Do not crash.	Reduce material inflow uniformly on all activities.	Do not order materials ahead.	Do not recruit workers if they call in sick.
Crash Strategy	Crash critical activity.	Allocate the space from non critical activities to the most critical activity.	Do not order materials ahead; Order more material on the most critical activity.	Recruit workers if they call in sick; Recruit more labor on the most critical activity; One crane operator must be ensured.
Reassign Strategy	Crash critical activities.	Reduce material inflow uniformly on noncritical activities; Do not reduce that on critical activities.	Reassign resources from noncritical to critical activities; Never order materials ahead.	Recruit workers if they call in sick.
Safety Strategy	Do not crash.	Reduce material inflow to 150% of normal on critical activities and uniformly on noncritical activities; Reduce uniformly if all are critical.	Order materials ahead on critical activities as a buffer.	Recruit workers if they call in sick.
Catch Up Strategy	Crash critical activities.	Reduce materials on non-critical activities uniformly, and never reduce material on critical activities.	Do not order materials ahead; Order more material on the most critical activities.	Recruit workers if they call in sick; Recruit more labor on the most critical activities; One crane operator must be ensured.

Table 1 Strategy Description

Description of the metrics collected from the simulation to describe the status of the project and the decisions taken at the end of each day are:

Labor data: (1) Number of laborers assigned per plan for each activity (unit=person); (2) number of workers who actually worked for each activity (unit=person).

Material data: (1) Number of materials assigned per plan to be installed (unit varies); (2) number of materials actually installed (unit varies); (3) number of materials not used and stored due to reduced productivity (unit varies).

Space data: (1) Space that has been used on site (unit=square yards).

Cost data: (1) As-planned labor cost (unit=$); (2) as-built labor cost (unit=$); (3) as-planned material cost (unit=$); (4) as-built material cost (unit=$); (5) as-

planned indirect cost (unit=$); (6) as-built indirect cost (unit=$); (7) predicted cost for entire project (unit=$).

Duration data: (1) Predicted duration for entire project (unit=day).

Activity data: (1) Activities that are being current – and schedule status.

Decision data: (1) Number of extra laborers recruited (unit=person); (2) actual number of materials that has been ordered (unit varies); (3) Percentage of schedule duration reduced; (4) Material and labor production rate in percentage - work schedule and increased labor budget in hours and percentage; (5) Activity priorities; (6) Decision time to judge the project condition (unit=second); (7) Decision time to response to the events (unit=second).

Events data: (1) list of external events that occurred.

Dynamic Decision Making Analysis

This part describes how the data collected from interactive simulation can be used to study the dynamics of decisions specifically how the decisions for each of the five strategies influence long term behavior of the construction project.

Preliminary Data Analysis: For each strategy, 35 simulation runs are carried out. The average costs and durations of those 35 simulation runs from day 15 to day 21 reflect how the system responds to the strategies. Since the costs and durations are represented by the frequency distribution, their expectations are calculated by approximating the frequency distribution into a probability distribution. The expected value of predicted costs and duration from day 15 to day 21 under five strategies are shown in Figures 2 and 3.

The horizontal axis in Figure 2 and 3 is the simulation time (unit=day), and the expected values of predicted duration and costs are on the vertical axis (unit=$ for cost and unit=day for duration). Figure 2, shows that as the simulator advances, the predicted costs and durations for the entire project decrease except for decisions made using the reassign strategy. Two explanations are offered for this general declining trend in cost and duration. One is that the temporal constraints (including activity relationships in the simulated project) are more complicated towards the beginning than towards the end of the project. As all decisions have a cascading impact on the schedule, the project status near the completion is less affected as, more activities are temporally connected earlier in the schedule. The sooner the decisions are made and events occur, the greater the impacts on the temporal constraints, resulting in a higher costs and longer durations. The second reason is that the occurrence of external events decreases as the project evolves. As the remaining duration is reduced, the probability of external events in future reduces, thus reducing the cost to mitigate the impacts.

Comparing cost data between control strategy and safety strategy indicates that ordering the materials ahead could help reduce both project cost and duration. From Figure 2, it can be seen that the control strategy is less cost efficient than the safety strategy. The difference between the two strategies is that material is ordered ahead under safety strategy. Without materials in stock, the project would be delayed in case of material delivery failure. Figure 3 also illustrates that predicted remaining durations after each day under safety strategy are shorter than that under control strategy.

Increasing resource input into more than one critical activity at one time seems to be more efficient in minimizing cost and duration. The differences in those two strategies are that only one critical activity could be crashed under crash strategy while more than one activity could be crashed under the catch up strategy. In Figures 2 and 3, the predicted cost and duration under catch up strategy is lower and shorter than that under crash strategy. However, the following cluster analysis shows that this assumption depends on how the non-critical activities are implemented.

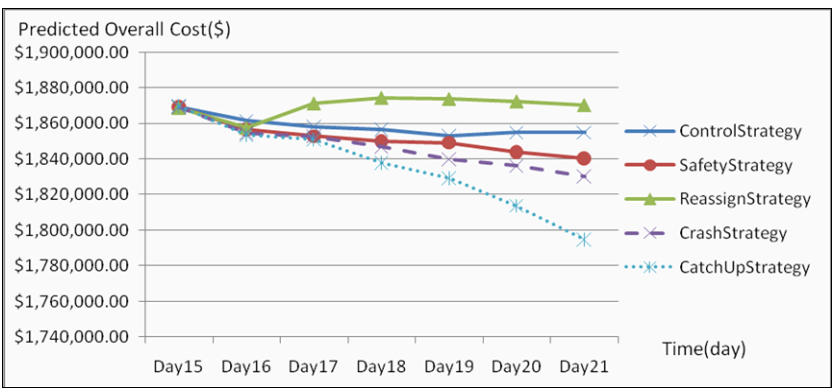


Figure 2 Predicted Project Cost from Day 15 to Day 21

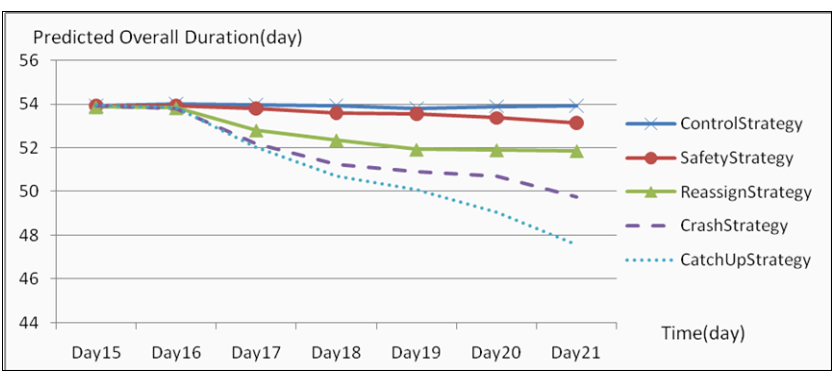


Figure 3 Predicted Project Duration from Day 15 to Day 21

Studying strategy groups might be meaningful because similar outcomes might have common behavior or mechanisms that drive them. From the project expenditures and durations under different strategies, we can see that control strategy, safety strategy, and crash strategy have similar outcomes and can be considered to be in the same group in Figure 2. Catch up strategy and reassign strategy offer distinctly different trends. In Figure 3, control strategy and safety strategy can be considered in

the same group. Catch up strategy and crash strategy offer different trends. It is difficult to classify the reassign strategy only based on Figure 3. Hence, the next step in the analysis is to conduct a cluster analysis to group strategies with similar outcomes.

Hierarchical Cluster Analysis: Cluster analysis is an exploratory data analysis tool aimed at sorting different objects into groups so that the degree of association between two objects is maximal if they belong to the same group (Aldenderfer and Blashfield, 1984). Cluster analysis is used to discover how outcomes from the simulation form associative groups. We used the Statistical Package for the Social Sciences (SPSS) to implement cluster analysis. The variables used on the cluster analysis were the expected values of the predicted cost and duration for the project from day 15 to day 21. The expected costs predicted in each day are chosen as variables and the cases are labeled by strategies.

A dendrogram was chosen to illustrate the forks between each of the simulation runs to indicate formation of coherent clusters. Ward's method was used to create clusters because it minimizes the sum of squares of any pair of clusters to be formed at a given step. (Aldenderfer and Blashfield, 1984). Z-score was chosen to standardize the data to eliminate the affects of the variance of variables.

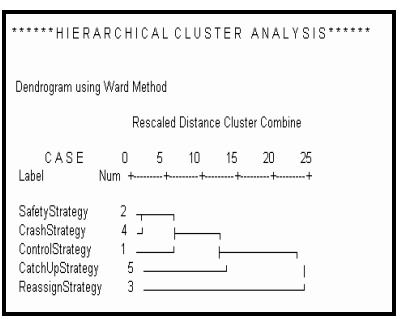


Figure 4: Cluster result with respect to cost

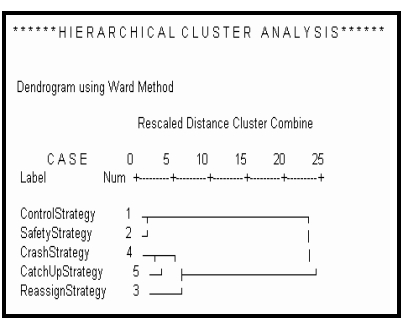


Figure 5: Cluster result with respect to duration

The dendrogram in Figure 4 was created using final project cost outcome. The safety and crash strategies are the most similar and are in one group. The control strategy is closer to that group than catch up strategy and the reassign strategy. Thus, the first group includes safety strategy, crash strategy, and control strategy while the catch up strategy and the reassign strategy are in the second and third group as what we have predicted from Figure 2. The dendrogram in Figure 5 was created using final project duration. The strategies can be grouped into two clusters. The first cluster includes control strategy and safety strategy, and the second cluster includes crash strategy, catch up strategy, and reassign strategy. Within the second cluster, two sub-clusters emerge. The first sub-cluster consists of the crash strategy and the catch up strategy, and the second sub-cluster consists of the reassign strategy. The sub-clusters provide a more nuanced perspective on the differences between the strategies.

Comparisons between those groups from duration data indicate that increasing labor and resource input on the critical activity reduces duration, even if its impacts on cost may vary. Critical variances between the first strategy group consisting of the control strategy and safety strategy, and the second strategy group consisting of the other three strategies, are that the later group has more labor and resource inputs on the critical activity. From Figure 2 and 3, the second group is more efficient in minimizing duration than group one.

However, whether a strategy is cost effective depends on how many non-critical activities are completed. The differences between the first strategy sub-cluster and the second strategy sub-cluster under the second strategy cluster in Figure 5 are that noncritical activities are impacted when resources are moved from noncritical to critical activities under the second strategy sub-cluster, while noncritical activities are hardly impacted under the first strategy sub-cluster. These differences show that increasing labor and resource inputs on critical activities is cost effective, as long as labor and material inputs into noncritical activities are not ignored. When the labor and material inputs are moved from noncritical activities to critical activities, critical activities are crashed while increasing the duration of noncritical activities. Beyond a threshold, the durations of the non-critical activities increase to the point where they become critical, incurring more indirect cost. This explains why the trend of cost under the reassign strategy is rising in Figure 2, and this is in the third strategy group in Figure 4.

Conclusions and Future Work

Preliminary data analysis together with cluster analysis indicates that it would be efficient to manage construction projects by (a) ordering the materials ahead; (b) increasing labor and material input on all the critical activities while ensuring the labor and material inputs into noncritical activities as well. While these results are specific to the project investigated, they reflect measures that contractors often use in practice, indicating the feasibility and usefulness of the proposed methods in studying the dynamics of decision-making. It is also indicated that it is important to study the overall project specific effects of fixed strategies and a good strategy will be a combination of the fixed strategies.

It is important to note that this paper provides only a preliminary investigation of the data. Further statistical analysis will need to be carried out to understand the time lags over which decisions have impacts. In addition, future research will provide enhancements to the simulation so that it can represent adaptive bottom-up influences resulting from labor and equipment interactions on site. These influences are critical to investigating and identifying dynamic feedbacks associated with alternative decision strategies. Future work also includes studying the similarities and differences between simulation results and the expectations according to general principles in construction management.

Finally, while this research is presented in the context of construction decision-making, the platform provided and the method proposed is extensible and can be applied to study decision-making in other temporally and spatially constrained dynamic task environments.

Acknowledgements

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System Dynamics Modeling of a Safety Culture

Based on Resilience Engineering

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Abstract

One of the keys to successful safety management is establishing a strong safety culture within a company. Because workers' behavior is influenced by the workers themselves, by their supervisors, and even by the top managers, understanding the dynamics among them is beneficial for establishing and sustaining a culture of safety on a project. To model safety dynamics, we review the literature for the relationship between a worker's personal care for safety and a strong safety culture. We also investigate, from the perspective of resilience engineering, how an organization can perceive a change in the safety culture and restore safety to an acceptable state. As a result, a conceptual system dynamics model is established for qualitative analysis, and the analysis reveals that the model can be applied to establish a resilience system for safety management and used to predict organization's future risk. Thus, a practical application of theories on a safety culture is presented, and with the model, managers can monitor the safety culture as arising from an interaction among workers,

managers, and the organization, and can improve safety based on an organizational perspective.

Introduction

Because of the relatively high fatality rate in the construction industry (Bureau of Labor Statistics 2007), safety is a top priority on construction sites. In an effort to improve site safety, research on accident causation has been actively conducted, and accidents have been found to be strongly correlated with management actions during a project (Hinze 1997); that is, accidents can be reduced by consistent safety management (Sawacha et al. 1999, Heinrich et al. 1980). Although safety management implicates various aspects, such as site layout, inspection, communication, human factors, safety training, and education, recently a safety culture has been emphasized as one of the crucial factors that contribute to an improvement in safety (Choudhry et al. 2007).

In that respect, modeling a safety culture would help workers understand the concept of a safety culture and its impact on the occurrence of accidents. Because workers' behavior and attitudes toward safety can be either self-motivated or motivated by supervisors, site managers, or even top managers, understanding the interaction among them plays a key role in establishing a strong and positive safety culture. Therefore, safety culture modeling would contribute to an understanding of the interactive relationship among them and lead an organization to create and maintain a safety culture. Moreover, to control an organization's state of safety in a safety culture, the concept of resilience engineering can be modeled and then adopted because the approach enables an organization to respond to changes and recover a state of safety (Schafer et al. 2009). To measure an organization's state of safety and its safety performance, leading indicators available for a safety culture are reviewed and are then integrated into this model.

To develop a model of a safety culture, the definitions of a safety culture and a safety climate first need to be mentioned to distinguish between the two concepts. The term *safety culture* has been defined by many researchers, but in this paper, the definition provided by the Health and Safety Commission (1993) is used; "the product of individual and group values, attitudes, perceptions, competencies and patterns of behavior that determine the commitment to, and the style and proficiency of, an organization's health and safety management." In addition, the term *safety climate* is defined as "a summary of molar perceptions that employees share about their work environments" (Guldenmund 2000, as cited in Zohar 1980). Thus, the term *safety culture* is used in this paper to represent psychological as well as managerial factors, whereas the term *safety climate* emphasizes workers' perceptions of safety.

Leading Indicators

Measuring safety performance is important but challenging in construction safety management. Methods to measure safety have been studied and applied on construction sites, but most of the traditional methods have been based on retroactive data, referred to as *lagging indicators*. Lagging indicators, such as incident rate or EMR (Experience Modification Rate), are not appropriate measures to evaluate current performance and prevent future accidents (Herrera and Hovden 2008). Statistical data illustrate an organization's historical performance or an industrial trend so that the information can be reviewed as a reference. However, the data have limitations when used as indicators for proactive management because statistical data do not accurately reflect site conditions and the progress of projects on each site. Thus, *leading indicators* have recently been adopted to identify and control the risk involved in certain construction activities.

A leading indicator is "an observable characteristic of an operational unit, presumed to bear a positive correlation with the safety of the system," and it has specific, measurable, achievable, relevant, and timed characteristics (Herrera and Hovden 2008, as cited in Holmberg et al. 1994 and Blackmore 1997). To apply the concept in practice, it is necessary to identify which factors can be leading indicators and how they are to be measured. Research has recently been conducted to identify leading indicators. For example, the Office of the Federal Safety Commissioner (OFSC) (2008) studied indicators that contained such characteristics and classified them into five categories: planning and design, management processes, risk management, psychosocial working environment, and monitoring, and Halama et al. (2004) recommended a "top 10" list of practical leading indicators among 300 available indicators. The leading indicators related to a safety culture are presented in Table 1 along with their methods of measurement.

Resilience Engineering

Resilience engineering is a proactive management approach that allows future risk to be anticipated and the safety level in an organization to be maintained, based on perceptions of current and changing safety levels and recognition of acceptable limits.

Table 1 Leading indicators for a safety culture (extracted from OFSC 2008 and Halama et al. 2004)

Leading indicator	Measurement
Worker's behavior	Behavior-based observation
Employee's perception	Corporate culture survey, productivity survey, and safety survey
Schedule delay	Number of days behind schedule
Management participation	Number of tours, walkabouts, or written communications
Safety committee meetings	Number of safety committee meetings held for a minimum duration within a specified time frame
Toolbox talks	Number of toolbox talks conducted during a time period
Safety education	Percentage of employees who have received site-specific safety education
Supervisor inspection	Number of supervisor inspections completed
Worker's involvement	Near miss and near hit reporting
Workplace inspection	Number of inspections by managers and OSHA representatives
Hazard	Percentage of reported hazards rectified within the defined time frame
Competence	Prehire screening of employees
Safety training	Number of employees or managers that have completed OSHA training

Beyond the conventional perspective that human errors and unsafe physical conditions cause accidents, it is necessary to control safety by predicting hazards and planning for the organization to recover safety to an acceptable state, just as the load in a stress-strain curve should be in the elastic zone to prevent the deformation of materials (Sheridan 2008). This approach provides a new direction in safety management, and the concept of resilience has recently been adopted in the construction industry (Schafer et al. 2009).

To establish a resilience system, therefore, the following three attributes are required: situation awareness, management of keystone vulnerabilities, and adaptive capacity (McManus et al. 2008). Because situation awareness is a starting point for a resilience system, leading indicators have potential application to measure an organization's current state in a resilience safety system, and it was also studied by Herrera and Hovden (2008) that monitoring the indicators facilitate the recognition of normal performance. Therefore, the leading indicators shown in Table 1 can be implemented as inputs to establish a resilience system for safety culture management.

The management process of a resilience system is presented in Figure 1. Similar to other key controls, such as cost, schedule, and quality, safety management involves initiating a project target that determines safety priorities and acceptable risk levels. Leading indicators and their methods of measurement are then identified to measure safety performance, and the measured indicators are scaled to apply to a safety culture model. Through analysis of the model, an organization's state of safety is identified and compared with the initial project goal. If the state is unacceptable, corrective management actions should be taken, and the project target for the safety level is replaced, based on the current state of safety.

System Dynamics Modeling for a Safety Culture

A system modeling approach takes advantage of an efficient understanding of critical factors and their interactions in complex systems over time; hence, this modeling methodology has been applied for various construction systems, such as schedules and productivity (Peña-Mora and Park 2001), quality and change management (Lee et al. 2005), and accident causation modeling (Mitropoulos et al. 2005). Because a worker's personal care for safety influences other coworkers' attitudes, and the aggregated climate in turn affects each individual worker, the factors affecting workers and their interactive relationship could cause a hazardous situation.

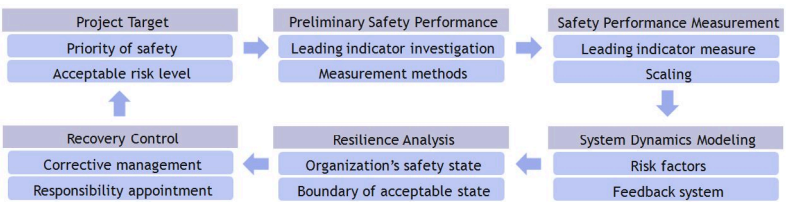


Figure 1 Resilience system management process

Moreover, the safety culture has an impact on a worker's behavior, and the attention top managers pay to safety may also increase when risk is perceived, or especially when an accident occurs. Therefore, it is hypothesized that a system model for a safety culture would contribute to understanding this complex correlation and be able to locate hazardous factors. The result is presented through a system dynamics model.

Cooper (2000) stated that a safety culture consists of three components—the person (safety climate), the behavior (safety behavior), and the situation (safety management system)—and that the three interact. Based on the model by Cooper (2000), the safety culture model proposed in this paper is divided into four components: (1) a person subsystem, which leads to participation in safety improvement; (2) a behavior subsystem, whereby the person subsystem affects the safety climate by participating in safety improvement; (3) a management subsystem, which represents factors affecting the efficiency of safety climate management; and (4) a measurement subsystem, which is used for performance evaluation (i.e., leading indicators).

First, the person model is based on the path model proposed by Goldberg et al. (1991), which illustrates the relationship between the safety climate and a worker's attitude. As shown in Figure 2, a positive safety climate increases a worker's motivation to engage in safe acts and promotes safety knowledge by disseminating instructions, which eventually lead the worker to participate in safety improvement. Furthermore, perceived risk increases anxiety and brings attention to safety issues, and this attention also increases the participation of the worker. This relationship was also adopted in the model by Choudhry et al. (2007). Second, the behavior model is based on the psychological courses of behaviors studied by Neal and Griffin (2009).

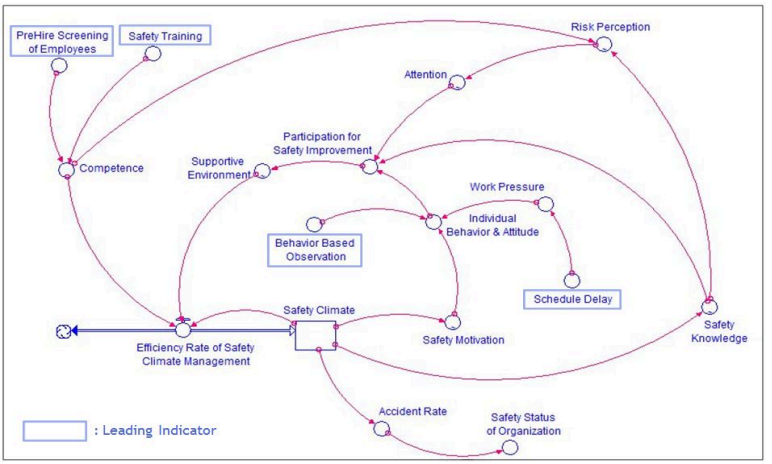


Figure 2 Simplified model of resilience system dynamics for a safety culture (based on the models of Cooper 2000, Choudhry et al. 2007, Goldberg et al. 1991, and Mohamed 2002).

An individual's motivation has a mutual relationship with safety participation, and increased motivation leads to an improvement in the individual's safety behavior and in the safety climate within a group. Third, the management model was extracted from a study by Mohamed (2002). In that study, factors affecting a safety culture were examined, and relationships among them were established. The last model shows how the leading indicators can be implemented for a system dynamics model. These indicators are used to measure the management factors and will be used as inputs for analysis.

Analysis

Through analysis of the system dynamics model, it was aimed to investigate (1) whether the leading indicators researched in the literature would work properly as leading indicators, (2) how the result from the simulation might provide insight into the relationships among components in the model, and (3) what impact the leading indicators would have on an organization's state. The first graph in Figure 3 shows the relationship among the variables *safety state of organization* (line 3), *safety climate* (line 2), and *individual behavior & attitude* (line 1), which were measured by the leading indicators *behavior based observation* and *schedule delay*. The result indicates that the variable *individual behavior & attitude* is strongly related to the variables, *safety culture* and *safety state of organization,* because the behavior of the variables has a similar shape in the graphs. Accordingly, although other factors, such as technical or environmental effects, were not considered in computing *accident rate* in this model, the result illustrates how these factors interact with each other.

Moreover, the variable *individual behavior & attitude* precedes the *safety state of organization* in terms of time; for example, line 1 (*individual behavior & attitude*) increases before line 3 (*safety state of organization*) begins to increase. Therefore, it may be presumed from this result that the leading indicators (i.e., *schedule delay* and *behavior based observation*), which were used to evaluate the variable *individual behavior & attitude*, can be used as leading indicators because the behavior in line 3 is predictable from the indicators. For example, if a leading indicator moves to follow an organization's safety state, this would mean that the leading indicator does not anticipate the state of the organization, so it is not a leading indicator.

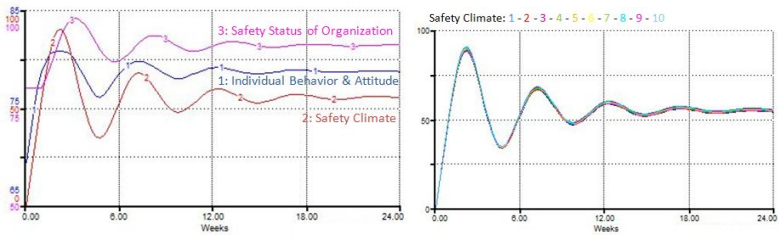


Figure 3 Simulation results: Relationships among leading indicator, safety culture, and organization's safety state (left) and Sensitivity analysis of behavior-based observation (0-100 with interval 10) to the safety climate (right).

Although the first diagram in Figure 3 shows the feasibility of using these leading indicators and their relationship, the second diagram illustrates the sensitivity of the *behavior based observation* indicator to the variable *safety climate*. The result is that *behavior based observation* does not have a significant influence on *safety climate*. This is because the model is based on the one proposed by Mohamed (2002), which consists of 10 factors affecting the safety climate, and the path coefficient of the behavior-related factor is not significant in the model. In this respect, a system dynamics model is a useful tool for a resilience system because it describes the correlation of factors and their effects on the organizational state as well as the feasibility of using the leading indicators identified previously.

Conclusion

This paper attempts to present that system dynamics modeling has the potential to be used to establish and maintain a resilience safety system. The concept of a leading indicator was introduced, and the leading indicators related to safety culture were presented through a literature review. Because the leading indicators can be used to evaluate the current safety performance, they would have synergy when combined with the concept of resilience engineering, which emphasizes proactive management. By integrating all the concepts into a system dynamics model, it was possible to analyze the feasibility of using the leading indicators identified previously, the factors related to a safety culture, and their impact on the safety state of an organization. In this paper, all the data were based on a literature review, so future work will focus on

validation to confirm that factors related to a safety culture work in the real world, as studied in this paper, and the time delay among factors will also be investigated thoroughly to identify the impact of the leading indicators on an organization's state of safety in terms of time. The model presented has such limitations, but this paper suggests that the system dynamics model has the potential to be applied for resilience engineering. With this model, it would be possible to identify the safety state of an organization and factors affecting that state. When an organization is not in an acceptable state, corrective management actions can be drawn from an analysis of those factors that expedite to increase the risk level of an organization. It is therefore expected that with this model, stakeholders would understand the concept of a safety culture in terms of the interaction among workers, managers, and the organization, and would make a decision for safety based on an organizational perspective.

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Virtual Organizational Imitation for Construction Enterprises (VOICE): Managing business complexity using Agent Based Modeling

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ABSTRACT

Increasing performance pressure has forced modern construction enterprises to seek growth while dealing with inherent complexity of the construction business. Business complexity (fragmented business mode, organizational complexity, etc.) has been considered a major source of performance issues in the construction industry. Unfortunately, there has been no efficient way to estimate its effects on organizational or project performance. This paper proposes a simulation-based organizational analysis platform called "Virtual Organizational Imitation for Construction Enterprises" (VOICE) to assess and manage business complexity of construction enterprises. A series of Agent-Based Models (ABM) were built using Repast Simphony to explore the relationship between social behaviors, organizational factors, and emergent organizational and project performance. The platform allows decision makers to simulate individual social behaviors, organizational structures, and environmental aspects of construction enterprises. Initial findings show that these factors affect the final performance of construction enterprises to an extent. As a socio-technical system, business complexity should be understood, assessed, and managed well. Results indicate that VOICE is a reliable platform to capture patterns of business complexity.

1. INTRODUCTION

Construction enterprises are currently suffering serious performance issues: productivity keeps dropping (Teicholz et al. 2001); time/cost overruns are common (Flyvbjerg et al. 2003; Bordat et al. 2004); and the business failure rate ranks 2nd highest among 10 major American industries (Knaup and Piazza 2007). New technologies and sophisticated project plan/control approaches (CPM/PERT, etc.)

have been applied to improve project accountability and efficiency. However, there is evidence that Critical Success Factors (CSFs) of projects have moved from "purely technical system and traditional cost-time-quality constraints" to "a combination of social and technical systems" (Mengesha 2004). The literature has pointed to organizational factors as main drivers causing performance issues, such as "internal administrative and procedures factors" (Arditi et al. 2000), "fragmented business mode of construction industry" (Teicholz 2004), "business practices and procedures" (Ellis and Thomas 2003), "inefficient communication" (Majid and McCaffer 1998), "business strategy related issues" (Flyvbjerg et al. 2003) and etc.

As discussed above, it is necessary to study construction enterprises in order to address serious performance issues. Studies have already revealed some common problems with the nature of the construction enterprise and its business mode, including fragmentation (Ruikar et al. 2007), organizational complexity (Koskela 2000; Moavenzadeh and Marchini-Blanco 2004), and information problems (Bouchlaghem et al. 2004; Holness 2008). In addition, a number of new performance improvement practices have been proposed to address these problems, like Building Information Modeling (BIM) and Integrated Project Delivery (IPD). However, few analysis tools exist for a thorough understanding of construction organizations, as well as the impacts of individual new practices. Although some project organizational analysis models have been developed (Jin and Levitt 1996), none of them is an integral analysis platform for analyzing construction enterprises. Therefore, this paper proposes the use of Agent-Based Modeling and Simulation (ABMS) to develop an organizational analysis platform for construction enterprises, which is called Virtual Organizational Imitation for Construction Enterprises (VOICE). The sections are organized as follows: in Section 2, ABM as the simulation method will be briefly introduced; Section 3 outlines the way to represent construction enterprises; Section 4 presents the results of an initial model; and Section 5 summarizes the findings.

2. AGENT-BASED MODELING (ABM)

Agent-Based Modeling (ABM) is a computational modeling approach for studying the emergent property of complex systems by simulating the simultaneous behaviors and interactions of autonomous individuals in the system (Macal and North 2007). Different from top-down modeling approaches (e.g., System Dynamics, Discrete Event Simulation etc.), ABM is a bottom-up approach: system behavior emerges from individual agents who act based on what they perceive as their own interests. It has been widely used in sociology, economics, cognitive science, anthropology, physical sciences and biology (Epstein and Axtell 1996; Macy and Willer 2002).

Models specially designed for construction enterprises have been built using ABM, one of which is Virtual Design Team (VDT). By marrying an organizational structure with a project's task precedence diagram, VDT analyzes how interdependencies between sequential and parallel activities raise coordination needs, and how organization and communication tools may change the coordination capacity of project teams (Jin and Levitt 1996). Along the same track, various ABM models have been built to investigate project network dynamics, integrated technologies

impacts, and organizational alignment (Ortiz de Orue et al. 2009; Unsal and Taylor 2009). Current models, however, only focus on particular problems; as such, they are insufficient for an integral analysis platform to analyze organizational behavior and emerging performance of construction enterprises. VOICE is proposed to fill this gap.

3. REPRESENTING A CONSTRUCTION ENTERPRISE

A comprehensive, concise and accurate representation of construction enterprises forms the basis for a well performed simulation model. A model's proper level of detail is the level where decision makers can plan, execute and assess, and key success aspects are included. In this paper, this is called simulating "controllable and critical factors." Studies of Critical Success Factors (CSFs) and Organizational Behaviors (OB) have been employed to build the simulation framework and determine the key factors entering into VOICE. Critical Success Factors (CSFs) are critical to the success of an organization or project, and without the presence of these factors, the organization or the project will probably catastrophically fail (Huotari and Wilson 2001). Based on the framework of CSFs (Chua et al. 1999; Chan et al. 2004; Fortune and White 2006), the following elements are crucial for the success of construction projects and organizations, and should be modeled: organizational structure, business process, information flow, and project characteristics. On the other hand, under the framework of Organizational Behavior (OB), work performance is human output dependent on individual behaviors, group behaviors and organizational system, and affected by both change and stress (Robbins 2005). Thus, this paper represents a construction enterprise having the following three components: individuals, organization (including authority structure, work process structure and information flow structure), and work input/output (work characteristics and work performance).

3.1 Representing Work

Studies have revealed that "project characteristics" is an important component of CSFs (Walker 1995; Chua et al. 1999; Chan et al. 2004), and the most significant characteristics are "type," "nature," "number of floors," "complexity," and "size" (Chua et al. 1999; Dissanayaka and Kumaraswamy 1999; Chan et al. 2004). Therefore, we assign the following attributes to a project and tasks generated by it (Figure 1).

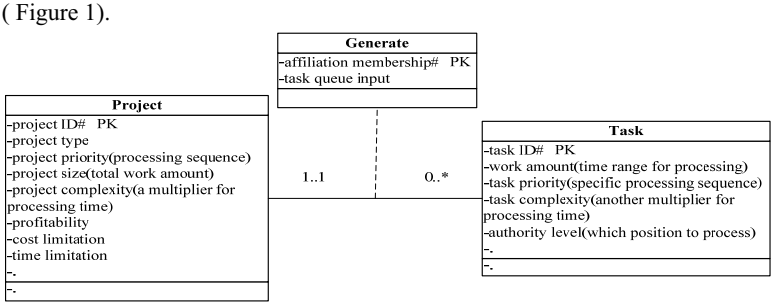


Fig. 1: UML diagram of agent project and agent task

3.2 Representing Individual Behaviors

Various individual behaviors are the basic determinants of work performance (Robbins 2005). Dependent on organizational behavior theory, this paper reproduces agents' behaviors with the following assumptions: (1) there are multiple roles inside one construction enterprise, and each role can be represented by one agent class that takes particular actions and makes decisions under particular rules; (2) each agent is imbued with bounded rationality, which means it does not follow the whole target of the organization. Instead, it moves toward more specific and particular work aims. For instance, one estimator aims to provide decision makers with a rational lump sum under given time without understanding other aspects of the project; (3) each agent occupies a particular position inside the organization which defines what task(s) the agent does, with whom the agent must communicate, to whom the agent reports, who reports to the agent, and so forth. As a result, the authority position, work arrangement and formal/informal network determine the agent's behaviors; and (4) each agent possesses specific knowledge, skills, and capabilities.

3.3 Representing Organizational Structures

It has been well documented that organizational chart, work process and information flows are all very crucial for the success of construction projects and organizations (Majid and McCaffer 1998; Arditi et al. 2000; Ellis and Thomas 2003; Elwakil et al. 2009). For example, Elwakil et al. found that organizational structure is an important CSF for construction organizations (Elwakil et al. 2009). This paper proposes that multiple structures should be incorporated in VOICE. They are: (1) authority structure (A): the formal organizational chart which determines the arbitrary delegation pattern within an organization and reflects the report directions; (2) work process (W): the work processing sequence among different agents. Because construction enterprises are project-centered, work process structure in this paper is in terms of project-oriented work; and (3) information flow (I): the formal/informal communication connection that determines the coordination, message and knowledge movement, considered the most informal and intangible structure within an organization.

3.4 Representing Performance Indicators

Single aspect measures of performance (e.g., project Key Performance Indicators [KPIs]) capture only a limited perspective of a construction enterprise (Rouse et al. 1997). This paper utilizes a comprehensive performance assessment framework which balances principals of Balanced Score Card (BSC) and Excellence Model (Neely 2002). BSC allows the performance assessment from four important perspectives: customer, financial, internal business and learning (Norton and Kaplan 1992). The Excellence Model focuses on a broad range of measures, among them processes, people, partnership, learning and innovation (Nabitz et al. 2000). A comprehensive assessment framework built on these aspects allows managers to

evaluate performance on a company-wide basis, and thus has been increasingly accepted by construction enterprises in practice (Neely 2002).

4. INITIAL MODEL AND FINDINGS

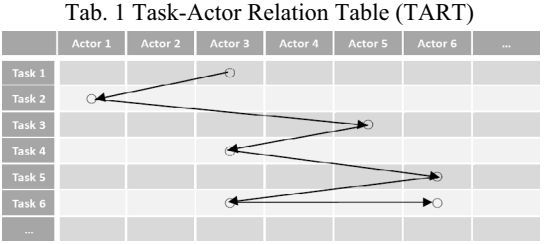
4.1 Model specification

A working model constructed using Repast S (an open source agent based modeling toolkit with pure java implementation) forms the starting point for VOICE. Initially, two assumptions are made to strengthen conditions: (1) the simulated construction enterprises can obtain as many projects as they can, and (2) performance indicators are simplified, including project time, workers' work stress, contribution of each worker, error rate on projects and effectiveness of the work. The initial model is comprised of five agent types (projects, tasks, managers, staff and president), with all of them being connected by three association classes (authority structure, work process and information flow structure). Their behavioral rules are as follows:

Projects: Multiple project agents can enter into the model simultaneously with predefined attributes (e.g., size, complexity, type, etc.). The major behavior of project agents is to generate tasks according to the fixed sequence (obtained from the task queue input). In default, only one task can be generated at one time; however, multiple tasks can be generated at the same time by one project if the "multi-successor" indicator is bigger than one. If one task is dependent on previous tasks, it will not be generated until all dependent tasks are finished. After generation, the task attributes will be assigned to each task. These tasks are then delivered to its first processor, which is a staff member, manager or a president, based on the work process structure. Then, they will be passed through all relevant processors. Once finished, they will be removed from the model and their work amount will be subtracted from the corresponding projects. If all the tasks of one project are finished, then this project instance will be removed from the model.

Task queue: Task queue is an important input which connects people and work, or in this paper, "Task" agents and their actors ("President", "Manager" or "Staff"). This reflects the pattern of task sequence and work arrangement that involves two steps: first, drawing a Task-Actor Relation Table (TART), which reflects the task assignment for every actor as shown in the following table. Second, task instances are assigned to actors based on the zigzag lines in TART, as shown in Table 1.

Tab. 1 Task-Actor Relation Table (TART)



Managers: Multiple instances of manager agent can enter into the model simultaneously with predefined attributes (e.g., competence, process quality,

preferences etc.). The responsibilities of a manager are assigning or processing tasks, approving work, resolving exceptions (e.g. high work pressure of the staff), and checking the quality of submitted/delivered tasks. To assign tasks, a manager first checks for any meetings occurring at that time. If there is, then all other activities will be paused until the meeting is over. If not, the manager agent checks the priority of all the tasks at hand and processes the most urgent one (if the task is to be done by the managers), or assigns it (if the task is to be completed by the staff), based on three preferences: preference 1, speed oriented (assigning tasks to the staff agent who can finish the task in the shortest time); preference 2, quality oriented (assigning tasks to the staff agent who can finish the task with the best quality); and preference 3, pressure oriented (assigning tasks to the staff agent with the smallest work pressure). A manager either approves tasks that are beyond its staff's authority level or submits such tasks to the president. Also, it reassigns the tasks if the submitted tasks' qualities are not satisfied, if the staff complains of work overload, or if tasks are returned by subsequent managers because of quality issues. Once tasks are finished within the manager's scope, they are delivered to subsequent managers (if there are any) or removed from the model (if there are no subsequent managers).

Staff: Based on the authority structure, there are a number of staff under one manager. To assess task needs, the staff agent first checks whether there is a meeting occurring. If there is, then all other activities are paused until the meeting is over. If not, it checks the priority of all tasks at hand and processes the most urgent one. As the first processing step, the staff agent will ask approval from its manager if the authority level of the task is beyond its level and if there is no approval with the processed task. Then the staff agent compares the total work time needed for all tasks at hand (work pressure) with available time (capacity) – if the work pressure is too great, then the staff will return the task to the manager for reassigning, whereby the manager will reassign the task to the staff with the smallest work pressure. After that, the staff agent will also check the task quality if it is a task delivered by other staff, and will return/report/correct the task based on its preferences (preferences 1, 2, and 3 stand for return, report and correct respectively), if the quality is not satisfactory. If information is needed for processing the task, the staff will ask for information from other staff, based on the information flow structure. It may also provide information to other staff based on the information flow structure. Once the staff agent starts to process the task, it will consume the amount of the processed task, and make mistakes. If the left amount of the task is equal to zero, then the staff will deliver the finished task to subsequent staff (if there are any) or submit the finished task to its manager (if there is no subsequent staff). After that, the competence and process quality of the staff agent will be improved according to the learning curve.

President: In the initial model, there is only one instance when the president agent enters into the model. Its responsibilities are selecting projects, approving the work, and setting up meetings. The president agent selects projects based on strategy and the president's preferences, while the selected projects will be triggered to generate tasks for the construction enterprise. The president agent also approves tasks

at the request of the manager; additionally, the president agent examines the exception indicator, which shows the frequency that agents ask for approvals/information/corrections on mistakes, etc. If there are too many exceptions, the president agent will hold a meeting based on the degree of the exceptions. During the meeting, all agents (president, managers and staff) must stop work. After the meeting, all current tasks will be approved, the work quality will be improved, and information will be shared thoroughly.

5.2 Initial Results

Figure 2 illustrates an initial scenario of a hypothetical construction enterprise comprised of six staff members, three managers and one president. Three different projects are awarded concurrently and will be processed. Tasks with different attributes will be generated by these three projects, based on a predefined TART table obtained from a case study. Behavioral rules of all individuals (the president, managers and staff) were described in above section. Parameters of the projects and every individual are shown in Figure 2. Also, organizational structures, including authority structure, work process and information flows, are illustrated.

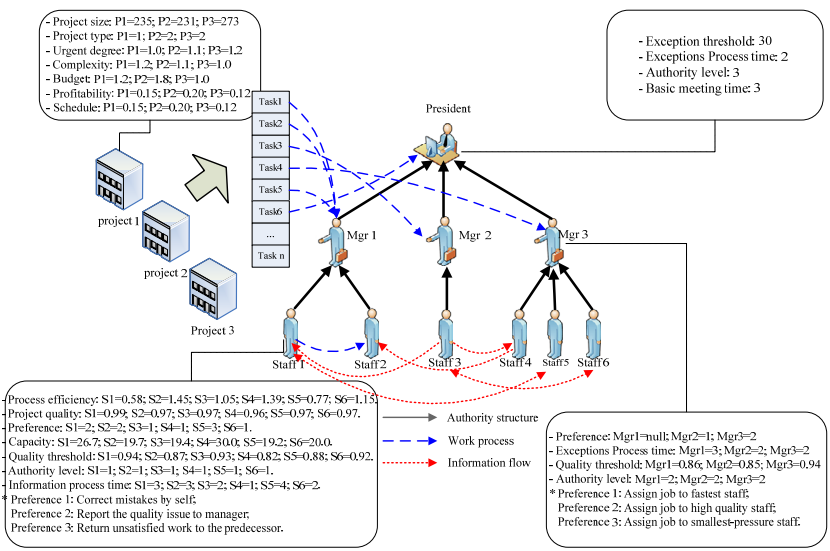
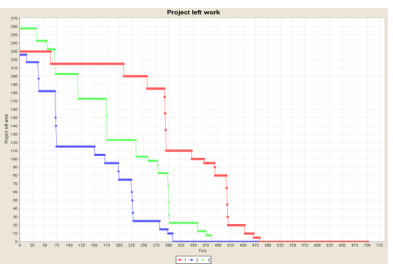


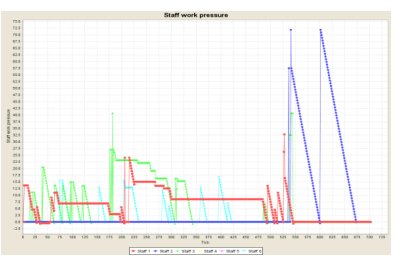
Fig. 2: A trial scenario

Figure 3 (a) illustrates unfinished work amount of the three projects along the time. This model can simulate the scenario where different projects are processed simultaneously, while former models could only simulate one project at one time. By comparing the simulation result and project deadline, decision makers can determine the maximum number of projects that the enterprise can afford. Figure 3 (b) illustrates the work pressure of every staff member during the projects. This indicator illustrates

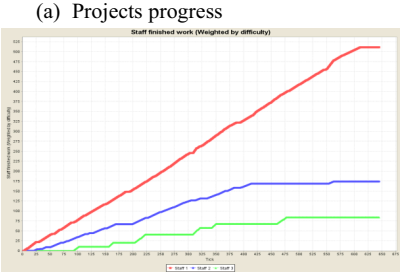
the potential needed time for processing all the tasks on hand. If the work pressure is too big for one staff member, he/she will stop working and report this exception to his/her manager, which increases ineffective work time. This indicator is helpful for assessing the current work arrangement. Figure 3 (c) illustrates the contribution of each staff agent, where the slope means the accumulative finished work, and the level part shows the idle time of each one. This indicator can be used to assess work efficiency. Figure 3 (d) shows the work error amount of one of the three projects (project number 1). Figure 3 (e) illustrates the effectiveness of three projects. Effectiveness is measured in the ration of effective work time with total work time. Exceptions will happen when processing each project, such as the unsatisfactory quality of the delivered work, authority issue, lack of information and excessive work pressure. As a result, some amount of time will be consumed to resolve such exceptions. Compared to the time used for processing tasks directly (effective work time), such time is called ineffective time in this model. The effectiveness indicator shows the percentage of effective work time. The developed initial model can reflect the dynamic feature of this indicator of every project.



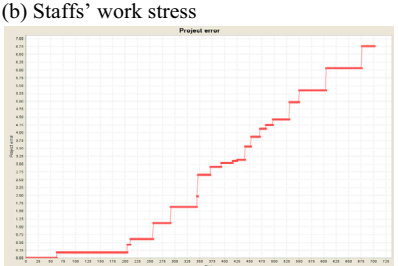
(a) Projects progress



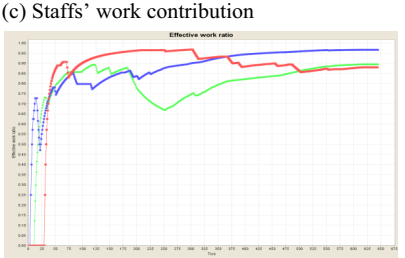
(b) Staffs' work stress



(c) Staffs' work contribution



(d) Accumulated work mistake (project 1)



(e) Work effectiveness of projects

Fig. 3: Initial results of the trial scenario

5. CONCLUSION

Increasingly, there is evidence that organizational factors are critical for the success of construction projects and organizations. However, few analysis tools exist for fully understanding construction enterprises. VOICE is proposed to fill this gap. Although not a substitute for field research, VOICE can help form hypotheses, sharpen theoretical relations, and set the agenda for more focused and productive empirical research. VOICE has the potential to have a transformative impact on our understanding of organizational natures of construction enterprises because it touches on several basic issues: (1) Providing a comprehensive micro-level analysis platform for understanding and managing the business complexity of construction enterprises; (2) Providing a user-friendly interface to practitioners, making the management more scientific, effective and efficient. With VOICE, decision makers can build their conclusions and decisions on reliable evidence and prediction so that mistakes can be avoided and better practices may be developed; (3) Providing a simulation tool to predict and validate the impacts of newly emerging business practices and innovative technologies, especially for construction enterprises that need to evaluate the risk to transform, to change strategy, to update technology and to reform business practices; and (4) "What-if" organizational design may be applied using the proposed platform.

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A Method to Develop and Optimize the Placement of Road Barriers in Emergency Evacuation for University Campuses

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Abstract

Disasters such as earthquakes and floods are sudden events that are difficult to predict, but have catastrophic consequences. A critical issue in disaster management is timely evacuation. University campuses face a unique challenge in developing effective emergency evacuation plans due to the complex site and high-dense buildings and population. This paper presents a method to optimize the placement of road barriers in emergency evacuation and assess the effectiveness via simulation. The main campus of the Western Michigan University (WMU) was chosen to implement and test the developed method. The placement of road barriers was optimized and the results were validated, using the Transportation Analysis and Simulation System (TRANSIMS). This system was also used to test the effectiveness of evacuation time to phased evacuation notification. It concluded that placing road barriers at appropriate locations could reduce the evacuation time by 20% or more.

Introduction

Disasters are sudden events that are difficult to predict and prevent, but have catastrophic consequences (Healy 1969). Disasters are categorized into natural disasters such as earthquakes, hurricanes, wildfires, severe storms, and floods, and manmade disasters including hazardous spills, terrorist attacks, and chemical explosions that are caused by human. Disasters cause the loss of lives and properties and have profound impact on our society. For example, the Tsunami occurred in 2004 killed over 225,000 people in eleven countries (Wikipedia 2009a). The hurricane Katrina in 2005 is among the deadliest disasters in the U.S. history. Over 1,800 people lost their lives and the damage was about $81.2 billion (Wikipedia 2009b).

Disaster management deals with a wide range of issues, focusing on maintaining control over disaster and emergency situations to help at-risk persons to avoid or recover from the impact of disasters (Disaster Management Center 1982). Among the many activities in disaster management, evacuation is a common strategy. In many

hazardous events the best option is to relocate threatened populations to safer areas (Cova and Johnson 2003). The key challenge in evacuation is to route evacuees to safety via optimal road paths under dynamic hazard and traffic conditions (MacGregor-Smith 1991, Southworth 1991).

Evacuation routing belongs to both the preparedness and response phases of the four emergency management phases defined by the Federal Emergency Management Agency (FEMA). Evacuation routes can be tested and evaluated via two approaches: mock exercises or drills, and simulation. Due to the nature of disasters and the cost or efforts involved, simulation is the preferred approach to conduct what-if analyses and assess various evacuation strategies. A number of simulation models have been developed to evaluate factors including routing, population distribution, road and intersection capacity, and human behavior, which contribute to road network clearance time (Han 1990, Southworth 1991, Tufekci and Kisko 1991, Urbanik and Jamison 1992, de Silva et al. 1993, Hobeika et al. 1994). These models are useful to model the evacuation of communities at risk to chemical stockpile sites, nuclear facilities, dams, and hurricanes. These macro-simulation models aggregate individual person and vehicle movement into macro-level parameters and consequently, lack the capabilities of incorporating detailed behavioral and management facets.

Emergency evacuations result in travel demand exceeding road network capacity, which causes traffic delays ranging from inconvenient to catastrophic (Cova and Johnson 2003). Strategies focusing on the optimal utilization of road network under extraordinary demand have emerged in recent years. Examples include counter flows, turn restrictions (Cova and Johnson 2003), traffic signal timing (Chen et al. 2006), and real time traffic guidance (Yue-Ming and De-Yun 2007). The basis for these strategies is the fact that most traffic delays occur at intersections (Southworth 1991) and therefore, reducing intersection conflicts will improve road network performance.

This paper presents a study that adopts the traffic control strategy of setting barriers at road intersections to control vehicle turns and to reduce intersection traffic conflicts, with the hope of improving the road network performance in emergency evacuation. In this study, a micro-simulation model was developed for vehicular traffic by using TRANSIMS to optimize the placement of barriers and to test the outcome. It is expected that using micro-simulation models can assess the road network performance more realistically and accurately. The developed methodology and models were tested in the context of university campuses in the United States, using the main campus of WMU as a representative case.

Significant Contributions

University campuses are among many communities that face dangers from disasters. A comprehensive literature review of emergency evacuation reveals that a university campus is treated as a “generic” community with their distinguishing characteristics neglected. Compared to industrial and residential communities, university campuses have certain key characteristics that cannot be sufficiently captured in the “generic” approach, but are critical to the success of evacuation routing: (1) highly dense population; (2) strong temporal variation in population distribution during school time (e.g. students move from one building to another to catch classes); (3) highly urbanized in terms of the density of buildings, parking lots and roads; and (4) the sparse distribution of hazardous materials. In addition, a road network on a university

campus is often one lane in each direction with many traffic calming devices. Traffic is mostly controlled via signs rather than signals. These distinguishing characteristics indicate the inappropriateness of treating university campuses as "generic" communities in evacuation routing. To our knowledge, there is very little research in this area. The study presented here has profound impacts by filling this gap.

This study also developed a method to optimize the placement of barriers via micro-level traffic simulation models (TRANSIMS models). The effectiveness was also evaluated using the same system to ensure the consistency. TRANSIMS is an agent-based traffic simulation tool developed by Los Alamos National Laboratory. It has the capability of capturing human behavior to certain extent and consequently, provides a more accurate and precise estimate of the road network performance under extraordinary travel demand. This study is among the first few studies to apply TRANSIMS in emergency evacuation routing and is believed to be the first one to apply TRANSIMS to university campus evacuation.

Methodology

The principal philosophy for this study was the utilization of TRANSIMS to simulate the network performance of road infrastructure under extraordinary travel demand that significantly exceeds the network capacity. Figure 1 provides a simplified version of the analysis flowchart. The overall procedure is described as below:

(1) Travel demand (number of vehicle trips) is determined based on individual building capacity and occupancy rate;
(2) Road network including physical road infrastructure and traffic control devices (signs and signals) are integrated to serve as the physical base for simulations;
(3) The travel demand and the road network resulted from the previous steps are combined to develop a TRANSIMS model and run simulation;
(4) Simulation results (network performance) are examined to identify problematic network links that face significant delays. Road barriers are set at appropriate locations to ease traffic that flows out of the problematic links. Information about the placement of road barriers feeds back to the original TRANSIMS model; and
(5) Steps (3) and (4) are repeated till either no further significant delays are detected or the placement of additional road barriers only leads to marginal improvement.

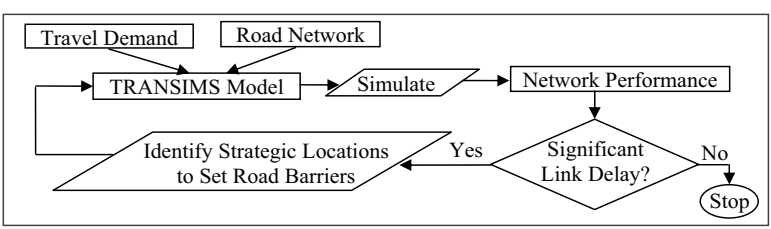


Figure 1. Flow Chart for Optimizing the Placement of Road Barrier

The method developed in this study helps to answer the following questions:

(1) How long does it take to evacuate the whole campus without any traffic guidance?
(2) Where to optimally place road barriers to shorten evacuation time?
(3) How efficient is the placement of road barriers in emergency evacuation?

In addition, the developed method can be used to conduct many what-if scenarios analyses in a sense that any traffic control/guidance measures are eventually reflected in the road network model and travel demand. For example, placing road barriers is treated as prohibiting certain turns. Also, phased notification can be incorporated by varying the time distribution of the vehicle trips in the travel demand.

TRANSIMS and Geographic Information System (GIS)

A key component in this study was the development of TRANSIMS models to simulate road network performance. TRANSIMS consists of a number of modules to accomplish all the tasks. An individual module can be viewed as an executable file and can be run with a control file that contains all the necessary information and parameters. Figure 2 illustrates a conceptual schema of the TRANSIMS framework. A TRANSIMS model can be developed using either the activity-based or trip-based approach. In this study, the trip-based approach was adopted. The embedded feedback mechanism indicates that the process is iterative.

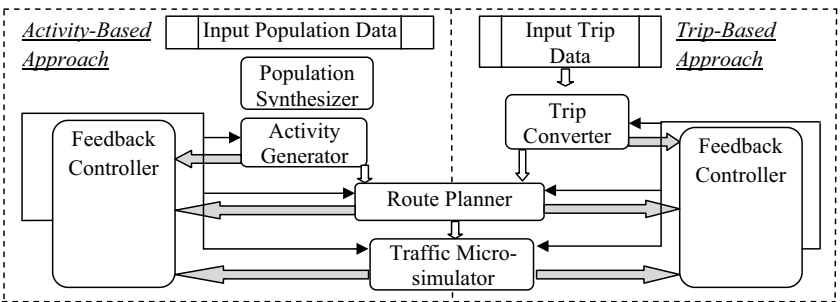


Figure 2. A Simplified Version of TRANSIMS Framework

WMU Case Study

In this study, the main campus of WMU was chosen to implement and test the developed method. This campus is representative of university campuses in U.S., most of which have complex infrastructure consisting of roads, parking lots, and buildings and a high-dense population that has a very strong temporal variation during the normal school time. Figure 3 provides an overview of the study area. The area above the major road running from southwest to the northeast is the main campus, on which this study focused.

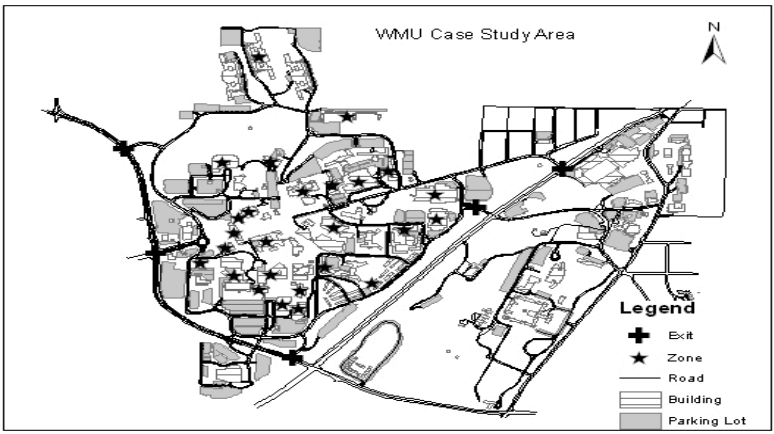


Figure 3. Overview of Case Study Area

Development of TRANSIMS Models

This section describes the development of TRANSIMS models for the WMU case study in detail. A total of six models were developed to evaluate the network performance in emergency evacuation when varying strategies were implemented, such as placing road barriers and phased notification. Figure 4 provides a detailed procedure in developing TRANSIMS models. Procedure details are described in the following subsections.

Travel Demand

The first step in developing a TRANSIMS model is to determine travel demand. In this study, the travel demand was determined by combining building capacity, class schedule, and parking capacity. Parking capacity was the constraining factor of travel demand of passenger cars. A number of buildings were visited during normal school time. It was determined that passenger car travel demand for each building is approximately 60 percent of the building capacity, which is the sum of capacities of rooms in that particular building.

TRANSIMS has its own mechanism of proportioning travel demand to activity locations and parking locations. For trip-based models, the travel demand shall be represented in the form of zone-to-zone trips. In this study, neighboring buildings sharing the same parking lot were combined to form an internal zone as illustrated in Figure 3. The travel demands of buildings in the same zone were summed to derive the number of trips that would originate from this particular zone. A total of 5 exits were also identified in Figure 3. These 5 exits, or external zones, are trip destinations. All trips originated in an internal zone were assigned to the closest exit. Table 1 lists the trip information in detail.

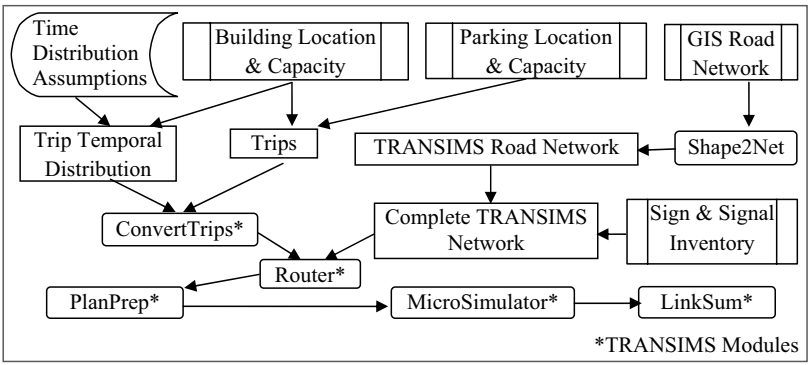


Figure 4. Detailed Procedure for the Development of TRANSIMS Models

Table 1. Travel Demand

Origin	Destination	Trips	Origin	Destination	Trips	Origin	Destination	Trips
1	28	73	10	29	567	19	30	108
2	28	56	11	29	70	20	28	900
3	28	774	12	29	1432	21	30	765
4	28	866	13	29	271	22	28	132
5	27	1289	14	31	27	23	30	210
6	28	681	15	27	122	24	27	49
7	28	112	16	27	81	25	30	62
8	28	14	17	31	493	26	30	30
9	29	882	18	29	240		**Total**	**10306**

The trips follow certain time distribution. The time it takes for a person to respond to an evacuation notification and to start the vehicle trip is affected by many factors. This study made a simplification by assuming that the time distribution of vehicle trips is determined by floor. It was assumed that (1) all vehicle trips of the first floor occupants occurred in the first ten minutes; (2) 25% of the vehicle trips of the second floor occupants occurred in the first ten minutes and the rest 75% occurred in the following ten minutes, or between ten and twenty minutes; (3) 25% of the vehicle trips for the third floor occupants occurred between ten and twenty minutes and the rest 75% occurred between twenty and thirty minutes; and (4) all vehicle trips of all forth and up floor occupants occurred between thirty and forty minutes. Table 2 lists the percentage of trips in four ten-minute time intervals.

Table 2. Temporal Trip Distribution

Start of Time Period	End of Time Period	Share/Percentage of Trips
12:00	12:10	0.57595
12:10	12:20	0.19900
12:20	12:30	0.16820
12:30	12:40	0.05685

Road Network

TRANSIMS needs a link-node road network. Having accurate road network data is critical to the development of valid TRANSIMS models. In this study, the road

network data were obtained from the physical plant of WMU and converted into a link-node structure via a GIS interfacing tool developed in another TRANSIMS study (TRANSIMS Manual 2007). Resulting text files were used as inputs to a TRANSIMS module entitled "TransimsNet", which converted textfile format link-node system into a network structure that was used in other TRANSIMS modules to complete traffic simulations.

Sign and Signal Locations

A field inventory of the locations of traffic signs, signals, and signal timing and phasing plans was collected. This field inventory was utilized to complete the construction of TRANSIMS network and verify and calibrate the resulting sign and signal data.

Route Planning, Micro-Simulation, and Network Performance

The TRANSIMS modules of Router, PlanPrep, MicroSimulator, and LinkSum were used to complete the development of TRANSIMS models. Router builds multi-modal travel plans with volume/capacity calculations to optimize the route selection. PlanPrep merges, sorts, and combines plan files when iterations are adopted. MicroSimulator simulates the vehicle movement on the TRANSIMS network based upon the travel plans. LinkSum summarizes and aggregates the network performance on a link-by-link basis so that network performance can be examined at both of the individual link and network levels.

Strategies for Setting Road Barriers

During emergency evacuation, a travel demand that greatly exceeds the network capacity is placed on the road, causing severe congestions. TRANSIMS reports such congestions by counting vehicle movement problems for each link. In our study, links with higher number of problem counts were given higher priority for placing road barriers to control traffic. Figure 5 illustrates the principle of placing barriers. A road barrier was placed to block left turns of the link with a severe congestion. Doing so forced the outgoing traffic to go straight or make right turn only and consequently, reduced traffic conflicts at the intersection. These left turn barriers were recorded in a turn prohibition table and fed into the Shape2Net step in the procedure outlined in Figure 4. The rest of that procedure was executed to test the effect. This step was repeated till the placement of additional road barriers either only marginally shortened or even increased the network clearance time.

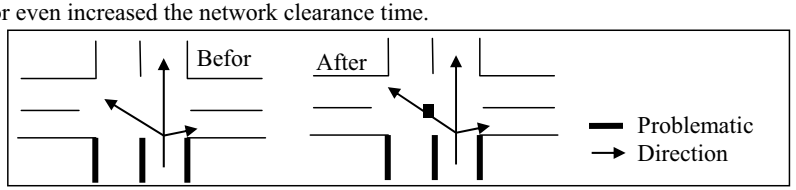


Figure 4. Placement of a Road Barrier to Control Traffic Flow

TRANSIMS Models

A total of six cases were investigated in this study.

(1) Case 1 assumed that trips went to the nearest exit (based on network distance) and no road barriers were in place.
(2) Case 2 was built upon Case 1 by following the procedure outlined in the section of Strategies for Setting Road Barriers. It could be viewed as having road barriers placed optimally. Table 3 lists the number of road barriers placed during the iterative procedure. Round 0 was the same as Case 1 and 10 most problematic links were identified. Placing 10 road barriers correspondingly lead to Round 1 model and so on so forth. Round 2 provided marginal benefit of adding additional 5 road barriers. Round 3 worsened the network clearance time. Round 2 was chosen to be the Case 2 model.

Table 3. Placing Road Barriers to Develop Case 2 Model

Iteration	# of Barriers	# of Problematic Links	Network Clearance Time
Round 0	0	55	2hr 14min
Round 1	10	51	1hr 16min
Round 2	15	36	1hr 8min
Round 3	20	56	2hr14min

(3) Case 3 was developed by incorporating a "virtual destination". This "virtual destination" was connected to all five exits by links that have a very large capacity, one-way traffic, and a long distance to remove the nearest distance assumption in Case 1 and Case 2. Having all trips destined at this "virtual destination", the bias of forcing trips going to the nearest exit was removed. A trip was considered to be complete as soon as it reached an exit. The network clearance time was determined by examining the link traffic volume for all links other than those links connecting exits to the "virtual destination".
(4) Case 4 was developed upon Case 3, following the road barrier set up strategies mentioned earlier. Case 4 can be viewed as having road barriers placed optimally.
(5) Case 5 was developed to evaluate the effects of phased notification. Phased notification could be building-based or floor-based. Building-based phased notification was determined to be of little help because (1) if the inner buildings (further away from exits) were notified earlier, then it caused more severe congestion to the portion of road network that is closer to exits; and (2) if the outer buildings were notified earlier, then the portion of road network that is further away from exits would be under-utilized. This thought was also validated in TRANSIMS models (not included herein). Case 5 evaluated the effects of floor-based phased notification: the first floor occupants were notified first, then the second floor occupants, the third floor occupants, and so forth. Table 4 lists the resulting temporal trip distribution.
(6) Case 6 was developed on Case 5 by placing road barriers at optimum locations.

Table 4. Temporal Trip Distribution

Start of Time Period	End of Time Period	Share/Percentage of Trips
12:00	12:10	0.5262
12:10	12:20	0.1990
12:20	12:30	0.1990
12:30	12:40	0.0758

Results

After developing six TRANSIMS models, traffic simulation was conducted for each case. Table 5 provides a summary of the distinguishing properties and the simulated network performance of each model. In addition to network clearance time, other performance measures including the total vehicle hours, total vehicle miles, total hours of delay, and total number of turns are included to provide a complete view.

Following is a summary of observations based upon Table 5 and Figure 5

(1) Comparing Cases 1 and 2 reveals that placing 15 road barriers to control the left turns of problematic links reduced network clearance time by 50%, reduced vehicle miles by 15%, reduced total vehicle hours by 30%, reduced hours of delay by 32%, and reduced number of turns by 29%.
(2) Comparing Cases 3 and 4 reveals that placing 10 road barriers reduced network clearance time by 20%, reduced vehicle miles by 26%, reduced total vehicle hours by 33%, reduced hours of delay by 34%, and reduced number of turns by 33%.
(3) Comparing Cases 1 and 3 reveals that after adopting the "virtual destination", network clearance time remained the same, but total vehicle miles were reduced by 20%. It indicates that travelers were intelligent in choosing exits to minimize the overall travel distance. However, this minimal travel distance did not affect the network clearance time. An increase in vehicle hours and hours of delays and a small decrease in number of turns were witnessed. This confirmed that total vehicle mile was not the only determining factor of network clearance time.
(4) Comparing Cases 2 and 4 reveals that adopting the "virtual destination" constrained the optimal set up of road barriers as indicated by the lesser number of road barriers in Case 4 and less significant improvement of the network clearance time. It was attempted to also set 15 road barriers in Case 4, but the resulting network evacuation time was 2hr 33 min (not shown in Table 5).
(5) Combining (3) and (4) leads to the suggestion of guiding evacuees to the closest exit based on the network distance.
(6) Comparing Cases 5 and 3 reveals that a floor-based, phased notification did not make improvement in network clearance time, even though it resulted in small decreases of vehicle miles, vehicle hours, hours of delay, and number of turns.
(7) Comparing Cases 6 and 5 reveals that by adopting the floor-based, phased notification, the benefit of placing ten road barriers was minimal.

Table 5. Simulation Results of TRANSIMS Models

Case	Virtual Destination	# of Road Barriers	Phased Notification	Network Clearance Time	Vehicle Miles	Vehicle Hours	Hours of Delay	Turns
1	No	0	No	2hr 14min	5090.97	730.07	654.22	16458
2	No	15	No	1hr 8min	4331.72	508.72	444.19	11705
3	Yes	0	No	2hr 16min	4064.83	841.18	780.61	14339
4	Yes	10	No	1hr 49min	3020.89	560.51	515.50	9590
5	Yes	0	Yes	2hr 19min	4013.12	782.25	722.45	14165
6	Yes	10	Yes	2hr 1min	2655.58	517.00	477.43	8089

Conclusions and Discussion

This study concludes that placing an optimal number of road barriers at strategic locations decreases the network clearance time significantly, as illustrated by the comparison of Case 2 to Case 1 and Case 4 to Case 2. If travelers are guided towards the nearest exit (based upon network distance), the developed methodology places 15

road barriers to block the left turns for the most problematic links. By doing so, the network clearance time is reduced by a significant percentage (50%). If travelers are given the option of choosing their own exits, the optimum placement of 10 road barriers reduces the network clearance time by 20%, which is still significant. In other words, these conclusions lead to the suggestion of assigning exits for travelers during emergency evacuation and placing road barriers at strategic locations.

It is also concluded that a floor-based, phased notification strategy does not work well either alone, or combined with the road barrier approach. The use of a single network performance measure might mislead our conclusions with regards of the network performance. For example, a minimum value of the total vehicle miles does not necessary means the shortest network clearance time.

It is realized that the study completed is very preliminary to address the campus evacuation routing problem. This study made many assumptions to simplify the problem. The authors recognize that campus evacuation is a very complex problem, involving not only the physical infrastructure, but also human behavior. There is a great room for further improvements and enhancements. This study simplified the building evacuation by developing a trip time distribution table to capture the outcomes of building evacuation. This simplification can be overcome by integrating TRANSIMS models with building evacuation models to acquire a more accurate temporal distribution of trips. This study focused only on vehicle evacuation. Yet in reality, not every person will bother to secure and drive his/her car. Rather, walking might be preferred. Many students come to school by bus. Focusing on a single transportation mode might not reflect the real scenario of campus evacuation. Rather, a multi-modal approach is more appropriate. Other limitations that provide future research directions include (1) the extent of reliance on TRANSIMS defaults such as activity locations and parking locations; (2) the more accurate incorporation of human response and behavior; and (3) the effects of not being able to put road barriers at the same time, i.e., ten road barriers might be placed in different orders.

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DEVELOPING OPTIMAL HAZARD INVESTMENT STRATEGIES

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ABSTRACT

There has been a significant increase in natural disasters that have negatively affected the U.S. economy in recent decades. The Government Accountability Office reported that the U.S. is not well prepared to manage large-scale natural disasters either through emergency response or financial relief. It is essential to develop integrated post-disaster investment strategies that avoid many of the pitfalls that have been observed following recent catastrophic events. This paper proposes a conceptual framework to build theoretical foundation and demonstrate technologies for creating a decision support system for optimizing stakeholders' resource allocation in natural hazards. The proposed framework will: (1) minimize the total costs associated with implementing such investment strategies and (2) maximize the uniformity of welfare distribution among all associated parties. This would provide broad members of the emergency management community as well as policy makers with easy-to-use preparedness and decision support tool, which would help in creating better societal financial resilience towards natural hazards.

KEYWORDS

Investment Strategies, Insurance, Post-Disaster Financial Relief, Multi-Agent Simulation, Multi-Objective Optimization.

INTRODUCTION

The development of this work is triggered through: (a) the increasing total costs associated with extreme natural events; (b) the challenges for effective natural hazards management; and (c) the urgent need for optimized hazard stakeholders' investment strategies. The Disaster Mitigation Act of 2000 now requires that to be eligible for Hazard Mitigation Grant Program (HMGP) funds, each state and local government must submit a mitigation plan to the Federal Emergency Management Agency (FEMA) describing how it is prioritizing mitigation actions so that its overall

mitigation strategy is cost-effective and maximizes overall wealth (FEMA 2003; Dodo *et al.* 2005). The development of optimized stakeholders' investment strategies can enhance the process of resource allocation prioritization in relation to natural hazard financial mitigation (Kunreuther *et al.* 2007).

BACKGROUND

A number of major impact assessment software systems have been developed to support disaster preparedness and recovery efforts. These systems include Hazards United States-Multihazard (HAZUS-MH) and MAEviz. HAZUS-MH is a hazard prediction software program developed by the Federal Emergency Management Agency (FEMA) under a contract with the National Institute of Building Sciences to estimate potential losses from earthquakes, hurricane winds, and floods (HAZUS-MH 2007; Pradhan *et al.* 2007). MAEviz is seismic risk assessment software developed by the Mid America Earthquake Center in cooperation with the National Center for Supercomputing Applications to estimate losses from earthquakes (Elnashai *et al.* 2008a; Elnashai *et al.* 2008b; MAEviz 2008). These loss estimation models provide increasingly comprehensive estimates of regional risk, but offer little guidance about how to use that information to make mitigation resource allocation decisions (Dodo *et al.* 2005). All these models can estimate losses in relation to structural damage, contents damage, time-based impacts, and only a small set of predefined mitigation alternatives can be considered, but they are not able to account for the stakeholders' side including costs of the alternatives, the budget, and the specific objectives and priorities of each stakeholder (FEMA 2003; Dodo *et al.* 2005; Grossi and Kunreuther 2006). Previous related research on mitigating financial impact of natural catastrophic is divided into four main approaches that include the following:

- Deterministic net present value (NPV) analysis was used where: Kappos *et al.* (1996); Kunreuther *et al.* (2001); Altay *et al.* (2002); Chang (2002); and Kuwata and Takada (2003) calculated the avoided loss in various hazardous situations as the difference of loss estimated with and without implementation of the mitigation alternatives.
- Stochastic NPV analysis was utilized where: (a) Englehardt and Peng (1996) estimated the probability distribution of benefits associated with revising the hurricane requirements in a South Florida building code and compared it with the cost of implementing the revision; (b) Werner *et al.* (2002) compared various levels of proposed seismic design or upgrade for port facilities in California based on both means and standard deviations of losses; and (c) Mostafa and Grigoriu (2002) examined the benefits of adding bracing elements to the water tank in a New York City hospital.
- Multi-attribute utility models were used where: (a) Nuti and Vanzi (1998) compared structural upgrading strategies for hospitals based on various performance indices for the response of the associated system of hospitals and (b) Opricovic and Tzeng (2002) compared post-earthquake regional reconstruction plans in Central Taiwan using a fuzzy, multi-criteria decision analysis approach.
- Optimization models were utilized where: (a) Shah *et al.* (1992) performed integer programming with a budget constraint to maximize the NPV of

earthquake mitigation investment; (b) Augusti *et al.* (1994) used dynamic programming to select structural mitigation alternatives for bridges in a highway network in Italy; (c) Researchers at the International Institute for Applied Systems Analysis (IIASA) have developed a spatial-dynamic stochastic optimization model to select the insurance policy design that best satisfies stated decision criteria, such as maximizing insurance company profits and minimizing the probability of insurance company insolvency (Ermoliev *et al.* 2000; Ermolieva *et al.* 2001; Brouwers and Hansson 2001; Brouwers *et al.* 2001; Brouwers *et al.* 2002; Brouwers and Verhagen 2003; Brouwers 2003-a; Brouwers 2003-b; and Brouwers *et al.* 2004); and (4) Dodo *et al.* (2005) developed a linear program for resource allocation in earthquakes that incorporates spatial correlation among spatially distributed mitigation alternatives, the range of possible earthquakes with their associated probabilities, and decision timing.

Meanwhile Dodo *et al.* (2005) is considered to be the most comprehensive study to address the problems of limited budgeting, dynamic investment scheduling, and resource allocation optimization for financial mitigation in natural hazards, all of the aforementioned valuable studies have only treated the problem through a non-dynamic aggregated simulation modeling techniques. The proposed research aims to build on previous research efforts by developing a transformative micro-level multi-agent stochastic optimization framework that is able to: (1) study financial mitigation of natural hazards from an integrated perspective that concurrently optimizes position of all interrelated stakeholders and (2) provide a dynamic investment mechanism to measure the costs associated with these stakeholders as a result of interdependencies, constraints, and uncertainties.

OBJECTIVES

The paper will model the extremely complex and highly interactive environments governing natural hazards using an innovative micro-level multi-agent stochastic optimization approach. This research will utilize well-founded techniques to: (1) compute the load distribution of insurance premiums; (2) create provisions of reinsurance; (3) minimize the total cost associated with implementing the anticipated resource allocation strategies; and (4) maximize the uniformity of welfare distribution among associated parties including property owners, the government, insurance/ reinsurance companies, and national recovery agencies.

DEVELOPMENT FRAMEWORK

The development of the framework associated with the development of an Automated Micro-Level Multi-Agent Stochastic Simulation Decision Support System for Investment Optimization in Natural Hazards (MASSIP) is based on theory formulation and model implementation.

1) Theory Formulation

To enable MASSIP to search for the optimal post-disaster resource allocation strategies, the authors will develop a comprehensive set of decision variables. These decision variables will be assessed on ex-ante and ex-post basis over time (t) where X

is the set of all feasible stakeholders' resource allocation strategies. Each candidate resource allocation strategy (x_i) will be defined and assessed using a set of input and output variables, as shown below in Figure 1.

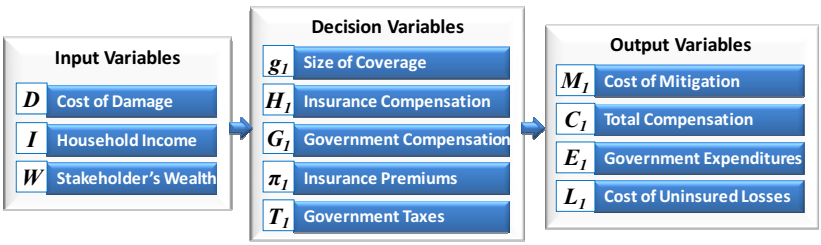


Figure 1: Variables for Resource Allocation Strategies

Two objective functions will be formulated for each candidate strategy to: (1) minimize the total costs using mitigation, vulnerability, damage, and loss functions as well as (2) maximize the welfare distribution using wealth transformation and uniformity distribution functions. These functions will be developed utilizing the scientific basis laid out in previous research studies including Brouwers and Hansson (2001), Brouwers *et al.* (2001), Brouwers *et al.* (2002), Brouwers and Verhagen (2003), Brouwers (2003-a), Brouwers (2003-b), and Brouwers *et al.* (2004).

MASSIP will be designed to support logistic, financial, or environmental constraints. For example, a financial constraint can be set to ensure that the government total expenditures (E) do not exceed a certain allocated amount. Moreover, MASSIP will utilize exploratory stochastic modeling and dynamic investment scheduling to account for the uncertainty of hazards occurrence and timing of stakeholders' resource allocation decisions, respectively (Ermoliev *et al.* 2000; Ermolieva *et al.* 2001; Dodo *et al.* 2005). Also, MASSIP will utilize exploratory stochastic modeling and dynamic investment scheduling to account for the uncertainty associated with hazards occurrence and stakeholders' resource allocation decisions.

The optimization problem is presented below in Equation (1), where the expected values (E) of the two objective functions are Ef(x, p, q) and EU(x, p, q) and the constraint(p) and uncertainty (q) functions are $h_i(x, p, q)$ and $g_i(x, p, q)$, respectively.

$$\begin{aligned} &\text{Find} && x \in X \text{ that minimizes } Ef(x, p, q) \text{ and maximizes } EU(x, p, q) \\ &\text{Subject to} && Eh_i(x, p, q) = 0;\ i = 1, \ldots, n \\ & && Eg_i(x, p, q) \leq 0,\ i = 1, \ldots, m \end{aligned} \qquad (1)$$

2) Model Implementation

As shown below in Figure 2, the framework associated with MASSIP will be designed to develop the following models: (1) stochastic hazards model; (2) multi-agent simulation model; (3) multi-objective optimization model; and (4) multi-attribute utility model.

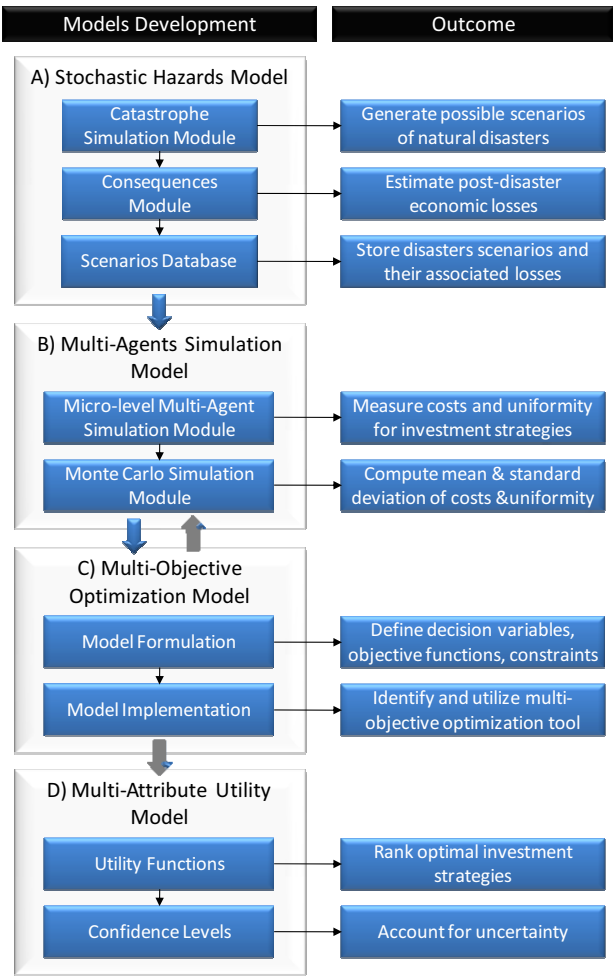


Figure 2: MASSIP Development Framework

A) Stochastic Hazards Model

The purpose of this model is to address the inherent uncertainty in the natural hazard problem. As the model is addressing the outcome of future investment strategies, these consequences must first be estimated instead of assessing the results by looking back at the outcome. To this end, the stochastic hazards model will internally apply stochastic simulation for natural catastrophes before communicating information with other models. This model consists of:

- *Catastrophe simulation module;* used to generate possible scenarios of natural disasters in the area of interest using vicinity and spatial models, which are fed through information provided from U.S Census and geographical information systems (GIS), respectively.
- *Consequences module;* utilized to estimate the economic losses as a result of each catastrophic event generated by the catastrophe simulator. It will benefit from currently available loss assessment software systems, such as HAZUS-MH and MAEviz.
- *Database of scenarios;* where each generated catastrophe and its associated economic losses are considered as one scenario and will be stored in the database of scenarios. These scenarios will be generated once for each optimization problem and will be used to evaluate and optimize possible investment strategies, as described in the following models.

B) Multi-Agents Simulation Model

The objective of this model is to evaluate possible investment strategies for the affected areas when they are subjected to any catastrophic scenario generated by the stochastic hazards model. As shown in Figure 1, this model will be composed of:

- *Micro-level multi-agent simulation module;* used to measure the total costs for possible investment strategies as well as the uniformity of welfare distribution among stakeholders' associated with applying each investment strategy for each generated catastrophe scenario. Three main agents will be used to represent the government, insurance/reinsurance companies, and property owners, where stochastic reinforcement learning techniques will be used to govern the agents' learning functions, such Roth-Erev, modified Roth-Erev, or Gibbs-Boltzmann.
- *Monte Carlo simulation module;* utilized to compute the mean and standard deviation of total costs and uniformity for each investment strategy for all generated catastrophe scenarios. In order to ensure practical computational time, this module will utilize parallel computing capabilities.

C) Multi-Objective Optimization Model

The objective of this model is to identify the Pareto optimal investment strategies. The development of this model consists of two main phases: (1) model formulation in order to define relevant decision variables, construct objective functions, and identify optimization constraints; and (2) model implementation in order to identify the most effective and efficient multi-objective optimization tool for this complex problem.

The model will be implemented using multi-objective genetic algorithms in order to account for the multi-objective nature of the problem and its huge search space. Robust algorithms, such as Non-Dominated Sorting genetic Algorithms II (NSGA2), will be used because of their important characteristics and superior performance compared to other multi-objective genetic algorithms (D'Souza and Simpson 2002; Deb *et al.* 2001; Deb 2005; Weile *et al.* 1996). The model will identify the optimal investment strategies using four main steps: (1) generating an initial population of

possible investment strategies; (2) sending the generated strategies to the multi-agent simulation model to evaluate their performance in minimizing the total costs and maximizing uniformity; (3) ranking the generated strategies using the constrained-domination principle to account for their compliance with all optimization constraints as well as their performance in achieving the optimization objectives; and (4) generating an enhanced population of strategies using selection, cross-over, and mutation operators. Steps (2) through (4) are then repeated until a predefined termination criterion is met and the Pareto optimal strategies are identified, as shown in Figure 3.

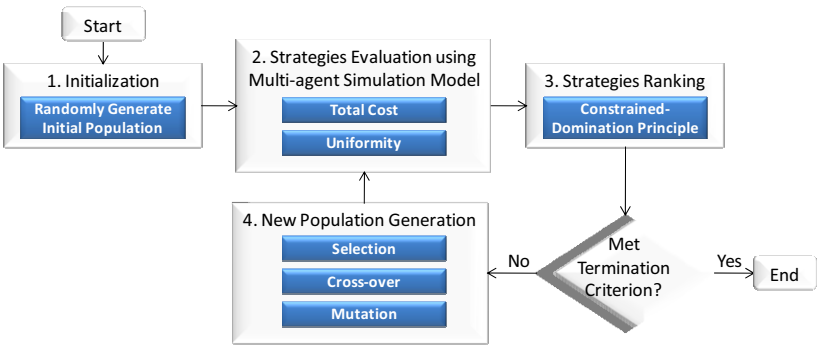


Figure 3: Example of Constrained-Domination Principle

D) Multi-Attribute Utility Model

The purpose of this model is to select an optimal investment strategy for implementation from the set of Pareto optimal strategies, which are generated by the multi-objective optimization model, as shown in Figure 1. Utility functions will be developed for the two main optimization objectives (i.e. minimizing the total costs and maximizing uniformity). These utility functions will also account for the level of uncertainty in the evaluated performance of each of the optimization objectives using their standard deviations, which are computed using Monte Carlo simulation in the multi-agent simulation model. Accordingly, the model will utilize multi-attribute utility theory in order to rank the Pareto optimal strategies based on their utilities and their confidence levels.

CONCLUSIONS

The proposed framework expressly differs from available disaster management models as it provides an explicit shift from the previously known aggregated simulation models for disaster mitigation, which have only partially succeeded in replicating the real world system governing natural catastrophes, to a more comprehensive decision support system, which is capable of capturing an integrated picture of the multivariate factors associated with natural hazards. MASSIP creates a series of intertwined stochastic, multi-objective optimization, and multi-attribute

utility models to provide an efficient decentralized communication across the system and more scalable simulation environment.

Moreover, it provides multi-fold benefits to society where the proposed system (i.e. MASSIP) can be used as (1) preparedness tool to foresee the expected integrated consequences of natural disasters in locations prone to catastrophic events; and (2) decision support tool for the choice of optimal resource allocation strategy that is suitable for a disastrous vicinity in the response and recovery phases of disaster management.

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Development of an Index to Rate the Completeness and Quality of Mitigation Project Definition

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Abstract

In the summer of 2008, two hurricanes made landfall along the Texas coast causing billions of dollars in damage. Texas received presidential disaster declarations, which resulted in the state receiving over $350 million in hazard mitigation funds. Over 500 requests for mitigation projects were submitted to the government from communities impacted by these disasters, but not all requested projects could be funded. As a result, those communities that submitted requests for well-defined mitigation projects were the primary benefactors of the federal mitigation funds. To better understand the factors that characterize a "well-defined" mitigation project, a study was initiated to develop an index for rating the completeness and quality of mitigation project definition. The study incorporated concepts from research on the quality of community planning and from project definition rating methods. A rating tool was developed to evaluate projects that have been successfully funded and to contrast them with projects that have been rejected. The rating tool consists of detailed descriptions of the project scope elements along with a method for scoring the completeness and quality of the project's definition. This paper presents the research results and the outcome from comparing six mitigation project definition packages.

***Keywords*:** project definition, rating, index, mitigation

Research Background and Problem Statement

In 2008, Hurricanes Dolly and Ike made landfall along the Texas coast, causing an estimated $23 billion in loss of life, injuries, and property damage. The damage caused by these two events exceeds all disaster losses in Texas during the past 15 years, making 2008 the most devastating year in Texas history. While these statistics are staggering, the number of communities that have struggled to recover following Hurricanes Dolly and Ike is equally disturbing. Reports indicate that the sheer magnitude of the destruction has resulted in slow recovery that anecdotally has been attributed to the lack of clear methods for prioritizing and implementing mitigation

and reconstruction projects at the community level (Oxfam America, 2008). This problem is especially acute in small communities that lack adequate resources to plan for, develop, and implement projects that will mitigate future disasters. Yet, *mitigation projects are especially critical for reducing future vulnerabilities of communities.*

To assist communities with mitigation efforts, several federal programs exist to provide funding for mitigation projects. Among the many types of projects that can be funded through federal assistance programs are public capital improvement projects, including bridge elevations, drainage improvements, structural hardening, and utility upgrades. In fact, capital improvement projects are *particularly* effective at reducing the vulnerabilities of *entire* communities, making them an especially attractive option to achieve local mitigation goals.

Following Hurricanes Dolly and Ike, over $350 million in federal mitigation funding became available, creating an unprecedented opportunity for communities to address their most critical vulnerabilities. Unfortunately, many communities that requested mitigation funding were unable to develop a viable project that was eligible for a subsidy, and this problem was especially acute for capital improvement projects in small communities. In fact, larger communities in Texas, which make up a small percentage of the total communities, have historically received a significant proportion of the available funding, while the large number of small communities have received a small proportion of funding (Table 1). Based on a recent field study, evidence suggests that larger communities in Texas have been the key benefactors of federal mitigation project assistance, and, furthermore, that this apparent bias may be occurring because these communities have access to engineering resources that are necessary for developing viable mitigation capital improvement projects. Unfortunately, smaller communities often do not have similar access to engineering resources, and as a result, they are less likely to develop viable projects that can be funded through much-needed federal subsidies (Menches et al. 2009).

Table 1. Percent of Communities that Received Mitigation Project Funding since 1989 (source: Texas GDEM Mitigation Section)

Community Population	Percentage of Cities with this Population	Percentage of Mitigation Capital Improvement Projects Awarded
0-10,000	60%	26%
10,001-20,000	6%	18%
20,001-30,000	29%	20%
30,001-100,000	4%	16%
100,001+	2%	20%

Consequently, federal mitigation policy may be inadvertently biased in favor of communities that already have access to mitigation project development resources, causing concern that the present policy may be distributing subsidies in an unintended way that limits small communities' abilities to reduce their hazard exposure. The problem of inequitable distribution of subsidies is not new and was hinted at in a landmark study conducted a decade ago by Godschalk, Beatley, Berke, Brower, and Kaiser (1999). The researchers cite the "scattershot nature of the projects" approved

for funding (p. 530) and propose that local governments should "operate mitigation implementation programs made up of coordinated and prioritized mitigation projects" (p. 532), but the study did not address the detailed and often complex process of developing and implementing mitigation projects. In fact, a decade later, countless communities continue to struggle with the development of mitigation capital improvement projects because they do not have the engineering resources to advance from a *mitigation idea* to a well-developed *mitigation project* that can be funded through federal subsidies. Hence, there is a critical need to address this complex process in order to ensure all communities have equal access to mitigation funding and equal opportunities to reduce their hazard exposure.

Hence, the current research is part of a larger effort to develop and test the effectiveness of a mitigation project development process that is fundamentally different from the public capital improvement project development process. The current research effort will provide tools that can be used by the researchers to investigate why specific projects were selected for funding, what characteristics of the project increased or decreased its chances for being selected for funding, or how and by whom were the successful projects developed. Ultimately, the researchers will use this data to develop a project development process that is uniquely suited for the development of mitigation capital improvement projects.

Research Goal and Objectives

The goal of the research was to develop a method and tool for evaluating the completeness and quality of mitigation capital improvement projects submitted for potential funding under the federal Hazard Mitigation Grant Program (HMGP). The rating tool will ultimately be used to identify the characteristics of projects that have been successfully funded and to contrast them with the characteristics of projects that have been rejected so that this information can be distributed to, and used by, communities as they prepare future mitigation projects. The rating tool, which consists of detailed descriptions of the project scope elements, has a secondary benefit of providing a checklist of items that comprise the project application package (i.e., funding request), which can be used by communities during the project development stage. The specific objectives of the research were to:

1. Develop a checklist of scope elements and associated detailed definitions that can be used by communities to develop high quality, complete mitigation project definition packages
2. Develop a rating method and tool that can be used by state officials to evaluate the quality and completeness of submitted mitigation projects for the purpose of selecting projects for funding through the federal Hazard Mitigation Grant Program
3. Demonstrate the effectiveness of the rating tool for comparing the completeness and quality of mitigation project definition packages

Research Methodology

The research methodology involved reviewing the State of Texas Hazard Mitigation Grant Program Comprehensive Application Package Instructions 2009 and several

completed mitigation project application packages to identify the elements that were required and recommended for inclusion in the project definition/application package. Furthermore, planning and project definition scoring methods were reviewed to develop a tool for rating both the completeness and the quality of mitigation project definition. Following this review, the researchers developed a list of mitigation project scope elements and detailed descriptions that could be used by communities to develop mitigation projects. The result was a checklist of items that should be included in a mitigation project application package in order to produce a quality package. After developing scope elements and descriptions, the researchers developed a quantitative rating system that was largely based on plan quality scoring techniques that are commonly used in the field of community planning. The rating system was implemented as a database tool, and eight projects were entered into the tool and were scored using the rating method. The results confirmed that the scoring system and tool can distinguish the quality and completeness among project packages.

Review of Existing Project Planning and Project Definition Rating Methods

The study incorporated concepts from research on the quality of community planning and from project definition rating methods. Research on the quality of community plans has evolved over the past decade, and was originated by Kaiser, Godschalk, and Chapin (1995), who defined plan quality as consisting of three core characteristics: (1) a strong factual basis, (2) clearly articulated goals, and (3) appropriately directed policies. To measure these three core characteristics, also referred to as plan components, a series of indicators were developed that allow for quantitative assessment and analysis of plan quality. For example, the "goals" component included information on economic goals (e.g., minimize fiscal impacts of hazards), physical goals (e.g., reduce property loss), and public interest goals (e.g., protect human safety). Each indicator that was developed to measure the quality of each plan component was measured on a 0 to 2 ordinal scale, in which 0 = not identified or mentioned in the community plan, 1 = suggested or identified but not discussed in detail in the community plan, and 2 = fully detailed or is a mandatory part of the community plan. Equal weighting was assigned to each plan quality indicator to avoid subjectivity. As described by Brody (2003), the measurement of overall plan quality was calculated by creating indices for each plan component and overall plan quality. There were three steps in the development of the index for each plan component. First, the scores for each of the indicators were summed within each of the plan components. Second, the sum of the scores was divided by the total possible score for each plan component. Third, this fractional score was multiplied by 10, placing the plan component on a 0-to-10 scale. Finally, a total plan quality score was developed by adding the scores of each component. Thus, a maximum score was determined, and the quality of various communities' plans could be contrasted by comparing their plan quality index score.

Berke et al. (1996) expanded the plan quality research by adding two additional factors that impact community plan quality: commitment to planning and community wealth. Berke later added population to the list of factors that impact plan quality (Berke 1998), and Burby and May (1998) further investigated the impact of planning

agency capacity on plan quality. Finally, Brody (2003) incorporated hazard mitigation measures into existing conceptions of what constitutes a high-quality plan. As noted by Brody (2003), the ability to code and measure indicators within a plan has made this technique a widely used instrument for quantitatively assessing the quality of planning efforts.

The standard for rating the completeness of project definition was established by Gibson with the development of the original Project Definition Rating Index (PDRI) (Gibson and Dumont 1996). Gibson first identified and categorized the critical elements that should be included in a capital project's scope definition package by reviewing company documents and conducting workshops with experts. Elements included design objectives, project schedule, site location, and numerous others. Each of the scope elements was then described in detail to ensure consistent understanding of the elements by all stakeholders. Furthermore, recognizing that not all elements will be equally important to overall project success, a series of workshops was conducted with experts to evaluated and assign a weight to each scope element based on its importance to project success relative to all other scope elements. Overall, 70 project scope elements were defined, weighted, and combined into an index that can be used to evaluate the completeness of project scope definition.

The current research combined the method of rating plan quality with the method of rating the completeness of project definition in order to develop a method for rating the completeness and quality of mitigation project application packages. These packages (1) should contain specific elements of project definition and (2) must achieve a relatively high level of quality in order to increase the community's chances for receiving federal funding to execute the mitigation project.

Development of Mitigation Project Scope Elements and Definitions

To develop mitigation project scope elements, the researchers interviewed state officials and reviewed the State of Texas Hazard Mitigation Grant Program Comprehensive Application Package Instructions 2009 and six completed mitigation project application packages. The instructions provide basic guidance on items that must be included in the project application package, but it does not describe the expected quality or the level of detail that is necessary to produce a high-quality project definition. From the instructions, and by reviewing project application packages, the researchers developed mitigation project scope elements as well as definitions of the elements that could be used by communities to develop a detailed project definition package and could also be used by state officials to rate the quality and completeness of mitigation project packages. Figure 1 displays an outline of the project scope elements, and Figure 2 presents an example of a mitigation project scope element, definition, and rating method.

Method to Rate the Quality and Completeness of Scope Definition

In Fig. 2, *completeness* and *quality* of scope definition are conceptualized as a combination of the responses to the Yes/No criteria (i.e., "Are the following items included in the Synopsis?") and the number of criteria that have been met.

SECTION I – ELIGIBILITY STATUS

A. ELIGIBILITY AND DECLARATION STATUS
- A 1. Eligibility of Entity and Project
- A 2. Conformance with Eligibility Criteria
- A 3. Location Proximate to Declared Area

SECTION II – STANDARD FORMS

B. APPLICATION FORMS
- B 1. State Project Application
- B 2. State of Texas Assurances
- B 3. Federal Application SF 424 and Assurance
- B 4. Engineering Checklist

C. DESIGNATIONS, CERTIFICATIONS, AND STATEMENTS
- C 1. Project Officer Designation
- C 2. Floodplain Manager Form
- C 3. Cost Share Certification
- C 4. Record of Environmental Consideration

SECTION III – MITIGATION PROJECT INFORMATION

D. PROJECT OBJECTIVES AND SCOPE
- D 1. Synopsis Statement
- D 2. Narrative Statement
  - D 2-1. Summary
  - D 2-2. Need for Proposed Action
  - D 2-3. Description of the Proposed Action
  - D 2-4. Discussion of Alternatives Considered
  - D 2-5. Coverage in the Mitigation Action Plan
- D 3. Cost Breakdown
- D 4. Proposed Work Schedules
- D 5. Flood Insurance Rate Map (FIRM) with Project Plotted
- D 6. Photographs of Project Area

E. ENVIRONMENTAL & HISTORICAL INFORMATION
- E 1. Description of Environmental and Historical Information

SECTION IV – MITIGATION PROJECT COST EFFECTIVENESS

F. BENEFIT COST ANALYSIS, RATIO, AND SUPPORTIVE DATA
- F 1. Benefit Cost Analysis & Cost Effectiveness Study
  - F 1-1. BCA Cover Sheet with Benefit-Cost Ratio (BCR)
  - F 1-2. Benefit Cost Analysis (BCA) Output
  - F 1-3 BCA Back-up Data and Assumptions

Figure 1. Mitigation Project Scope Elements

D 1. Synopsis Statement
A synopsis statement is a brief summary of project related information. It should include information about the project objective, cost, schedule, and benefit-cost ratio (BCR). Are the following items included in the Synopsis?

Yes	No	1. Project location
Yes	No	2. Problem definition (i.e., need for the proposed project and expected result)
Yes	No	3. Project description and scope
Yes	No	4. Estimated project cost
Yes	No	5. Benefit cost ratio (BCR)

SCORING:

0 = A Synopsis is not included
1 = A Synopsis is included but 5 items from above are missing
2 = A Synopsis is included but 4 items from above are missing
3 = A Synopsis is included but 3 items from above are missing
4 = A Synopsis is included but 2 items from above are missing
5 = A Synopsis is included but 1 item from above is missing
6 = A Synopsis is included and no items from above are missing

Figure 2. Mitigation Project Scope Element Definition and Rating Method

As the number of criteria that have been achieved in the project definition/application package increases, the completeness likewise increases, and as a result, the quality overall increases. Hence, the scoring that has been assigned (i.e., "0 = A Synopsis is not included" or "1 = A Synopsis is included but 5 items are missing") is a reflection of both completeness and quality.

As shown in Fig. 1, there are four sections of a mitigation project definition/ application package: (1) eligibility status, (2) standard forms, (3) mitigation project information, and (4) project cost effectiveness. Hence, completeness and quality of scope definition is conceptualized as consisting of unequal weighting of these four sections based on how important the content of each section is to the overall application package. Experts at the state hazard mitigation office were queried to determine which weights were assigned to each section of the application package. Based on their response, eligibility status was assigned a weight of 30%, standard forms was assigned a weight of 10%, mitigation project information was assigned a weight of 30%, and project cost effectiveness was assigned a weight of 30%.

Together, these four sections of the mitigation project definition/application package enable a local community to develop a viable scope of work for a mitigation capital improvement project. Furthermore, within each section of the project definition/application package, individual indicators (scope elements) further specify the concept of completeness and quality of scope definition. The following process was used to develop an index score for each *section* of the project definition package.

1. Each individual indicator (scope element) received a raw score using a rating system similar to the one identified in Fig. 2.
2. The raw scores assigned to each indicator within a section were summed to determine the total points assigned to all indicators (scope elements) within each section.
3. The sum of the assigned raw scores was divided by the sum of the total possible scores for each section.
4. This fractional score was multiplied by 100 to standardize the section score on a more intuitive 0-100 scale.

The measure of *overall* project definition/application completeness and quality was derived as follows:

1. Each section standardized score was multiplied by its section weight.
2. The weighted standardized section scores were summed to arrive at an overall project definition/application weighted score.

Ultimately, the scores can be used by state officials to compare the quality and completeness of submitted mitigation projects so that they can select the highest quality projects for funding.

Initial Assessment of Mitigation Project Definition Completeness and Quality

To test the scoring method, six mitigation project definition/application packages were examined. Index scores were developed for each of the four sections of the packages and an overall Completeness-Quality Score (CQS) was established. The results are presented in Table 2 (section scoring) and Table 3 (overall scoring). The applicants are identified in rows, and the project definition/application package sections are identified in columns. Future research will involve conducting a reliability analysis to evaluate the utility of the score index as a measure of project definition completeness and quality.

Applicant and Project Information

The applicant and project information is summarized in Table 3. Two of the six applicants were cities, three were counties, and one was a drainage district. All of the projects were intended to mitigate the impacts of flooding, and the types of requested projects included four culvert replacements or installations, one channel construction, and one general drainage improvement project. The projects ranged in value from $253,000 to $902,000.

Mitigation Project Definition/Application Completeness-Quality Analysis

Table 2 displays the unweighted scores for the four application sections. Each row in the table represents the scores received by one applicant. Both the raw score and the standardized score are displayed in the table. At the bottom of the table, the total possible raw score for each section is shown. For example, the first applicant received two points out of three for Section I, 16 points out of 18 for Section II, 54 out of 65 points for Section III, and six out of seven for Section IV. Table 3 displays the standardized scores for each section. For example, Section I has a weight of 30%; hence, the total weighted standardized score possible is 100 x 0.30 = 30. The first applicant received a weighted standardized score of 20 for Section I. The total

possible overall weighted score is 100. The first applicant received a total overall weighted score of 79.5. Comparatively, the first applicant had a relatively high overall standardized weighted score (79.5), whereas the fourth applicant had a low overall standardized weighted score (28.0). The fourth applicant specifically needs to

Table 2. Mitigation Project Definition Completeness-Quality Section Scores

Applicant No.	Scores	Raw and Standardized Scores				Raw Score
		SECTION I	SECTION II	SECTION III	SECTION IV	
APP.1	Raw Score	2	16	54	6	78
	Std. Score	66.7	88.9	83.1	85.7	324.3
APP.2	Raw Score	2	13	31	3	49
	Std. Score	66.7	72.2	47.7	42.9	229.4
APP.3	Raw Score	2	14	12	2	30
	Std. Score	66.7	77.8	18.5	28.6	191.5
APP.4	Raw Score	1	8	20	1	30
	Std. Score	33.3	44.4	30.8	14.3	122.8
APP.5	Raw Score	2	9	18	3	32
	Std. Score	66.7	50.0	27.7	42.9	187.2
APP.6	Raw Score	2	12	9	1	24
	Std. Score	66.7	66.7	13.8	14.3	161.5
Mean Raw Score		1.8	12.0	24.0	2.7	40.5
Standard Deviation		0.41	3.03	16.55	1.86	20.22
Max. Raw Score		**3**	**18**	**65**	**7**	**93**
Max. Std. Score		**100**	**100**	**100**	**100**	**400**

Table 3. Mitigation Project Definition Completeness-Quality Weighted Standardized Scores

Applicant No.	Scores	Weighted Standardized Scores				Total Raw Score
		SECTION I	SECTION II	SECTION III	SECTION IV	
		Weight: 30%	Weight: 10%	Weight: 30%	Weight: 30%	
APP.1	Std. Score	66.7	88.9	83.1	85.7	324.3
	Wt. Score	20.0	8.9	24.9	25.7	79.5
APP.2	Std. Score	66.7	72.2	47.7	42.9	229.4
	Wt. Score	20.0	7.2	14.3	12.9	54.4
APP.3	Std. Score	66.7	77.8	18.5	28.6	191.5
	Wt. Score	20.0	7.8	5.5	8.6	41.9
APP.4	Std. Score	33.3	44.4	30.8	14.3	122.8
	Wt. Score	10.0	4.4	9.2	4.3	28.0
APP.5	Std. Score	66.7	50.0	27.7	42.9	187.2
	Wt. Score	20.0	5.0	8.3	12.9	46.2
APP.6	Std. Score	66.7	66.7	13.8	14.3	161.5
	Wt. Score	20.0	6.7	4.2	4.3	35.1
Mean Standard. Score		61.1	66.7	36.9	38.1	202.8
Standard Deviation		13.6	16.9	25.5	26.6	69.2
Max. Score	**Raw**	**3**	**18**	**65**	**7**	**93**
	Standard.	**100**	**100**	**100**	**100**	**400**
	Weighted	**30**	**10**	**30**	**30**	**100**

Table 4. Applicant and Project Information

No.	Entity	Event Mitigated	Type of Project	Cost
1	County	Flood	Culvert replacement	$294,000
2	Drainage District	Flood	Drainage improvements	$902,000
3	City	Flood	Install storm sewers	$458,000
4	City	Flood	Install storm sewers	$715,000
5	County	Flood	Elevate road/install culverts	$253,000
6	County	Flood	Channel construction	$665,000

improve the completeness and quality of the benefit-cost analysis in order to compete more effectively for federal grant funding.

Conclusion and Future Research

The researchers have developed a method to rate the completeness and quality of mitigation project definition, and it is envisioned that this data will be used in three important ways. First, communities will use the information to develop better, more complete, and higher quality projects for submission to federal grant programs. Second, the state mitigation officer will use the information to rate the completeness and quality of projects and applications so that they can select the best projects to receive federal grant funds. Finally, the researchers intend to collect additional data and to further refine the scoring method. A validity and reliability analysis will be conducted to determine the importance of each indicator to the total index score.

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OPTIMIZING ALTERNATIVE HOUSING PROJECTS IN THE AFTERMATH OF NATURAL DISASTERS

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ABSTRACT

In 2006 the U.S. Congress appropriated $400 million to the Department of Homeland Security to support post-disaster alternative housing pilot programs as a possible substitution to the highly criticized temporary housing programs. One of the main objectives of these programs is to provide quick and permanent housing solutions to displaced families. Decisions on alternative housing should be carefully analyzed because of their significant impacts on (1) socioeconomic welfare of displaced families; and (2) available budgets for post-disaster housing recovery. This paper presents the development of an optimization model capable of identifying the optimal alternative housing plans that maximizes the net social benefits of these programs. This is achieved by striking a balance between the added social benefits to displaced families provided by alternative housing and the corresponding associated costs. An application example is analyzed to demonstrate the use of the proposed model and its capabilities in maximizing net social benefits.

KEYWORDS

Optimization, Alternative Housing, Temporary Housing, Post-Disaster Recovery, Net Social Benefits.

INTRODUCTION

The large scale and catastrophic impacts of Hurricanes Katrina and Rita (2005) challenged the statutory supposition that temporary housing assistance will generally not be required for more than 18 months (FEMA 2008). In fact, temporary housing continued to be used for up to 44 months after Hurricane Katrina (FEMA 2009a). This prolonged use of temporary housing and its associated impacts on the displaced households led the US Congress to appropriate $400 million to the Department of Homeland Security (DHS) to support alternative housing pilot programs in order to explore the possibilities of providing more permanent housing solutions (FEMA 2009b). The Alternative Housing Pilot Program (AHPP) encourages innovative solutions that can lead to permanent affordable housing (FEMA 2006). In addition, these innovative housing solutions need to be quickly deployed to house families

residing in mass-care emergency shelters. Accordingly, alternative housing should play the role of both temporary and permanent housing.

Among the main objectives of AHPP is to evaluate the efficacy of non-traditional housing alternatives for potential future use after large-scale natural disasters. Evaluating and maximizing the efficacy of post-disaster alternative housing is an important objective because of the long-term nature of alternative housing relative to the traditional temporary housing. Decisions on alternative housing projects can have significant and long-term impacts on multiple parties, including (1) social and economic impacts on displaced households, because housing plays a key role in determining the socioeconomic welfare of its residents (Quercia and Bates 2002; Shlay 1995); and (2) impact on post-disaster recovery plans often executed under tight budgets, because of the additional resources needed to provide alternative housing solutions. Accordingly, decisions on alternative housing need to be carefully analyzed in order to account for its multiple and significant impacts.

Various aspects of temporary housing and post-disaster housing recovery were studied and reported in the literature (Barakat 2003; Bolin 1982; Bolin 1993; Bolin and Stanford 1991; Chandler 2007; Comerio 1997a; Comerio 1997b; Comerio 1998; FEMA – CUSEC 1998; Fox 2002; Golec 1983; Johnson 2002a; Johnson 2002b; Kamel and Loukaitou-sideris 2004; Quarantelli 1985; Quarantelli 1995; Peacock et al. 2006; El-Anwar et al. 2008; El-Anwar et al. 2009a; El-Anwar et al. 2009b; El-Anwar et al. 2009c; El-Anwar et al. 2010b). Despite the significant contributions of the aforementioned research studies, there is little or no reported research on maximizing the net social benefits of alternative housing projects after natural disasters. Accordingly, there is a need for novel research methodologies to evaluate and optimize decisions on alternative housing taking into account its multiple impacts on society. The objective of this paper is to present the development of a prototype optimization model capable of identifying optimal decisions on alternative housing that would maximize the net social benefits to both the displaced families and emergency management and aid agencies. The following sections provide a brief description of the model formulation and implementation followed by an application example.

MODEL FORMULATION

An optimization model is formulated in order to maximize the net social benefits of post-disaster alternative housing. The model is designed to answer the following important questions: (1) What is the optimal number of displaced families to be provided by alternative housing instead of the traditional temporary housing? (2) Which candidate alternative housing projects should be provided and what are their optimal sizes? (3) Which temporary housing projects should be substituted by the alternative housing projects? And (4) how to quantify and optimize the impact of these decisions on the net social benefits of displaced families and emergency management and aid agencies? The following sections briefly describe the formulation of the decision variables and optimization objective that are designed to address these research questions.

Decision Variables

The decision variables are designed to represent (1) the number of families that should be provided by alternative housing; (2) the alternative housing projects selected and their sizes; and (3) the temporary housing projects that will be fully or partially substituted by alternative housing projects. To this end, the decision variables are divided into increments of families (e.g. 10 families). The total number of increments (I) is equal to the total number of families that can be housed in the potential alternative housing projects (N) divided by the increment value. Each increment of families (i) is represented by two decision variables representing (1) which alternative housing will house those families and (2) which temporary housing project will be substituted in return, as shown in Figure 1. Accordingly, the total number of decision variables is equal to twice the total number of increments. For example, for an increment of 10 families and if N = 5,000, then there will be 500 increments and 1,000 decision variables.

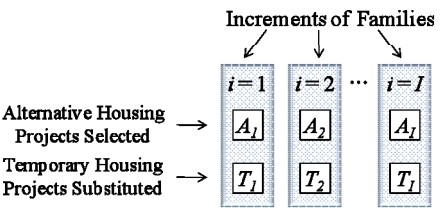


Figure 1. Decision Variables

The first group of decision variables (A_i) represents which alternative housing project is selected for housing the corresponding increment of families (i). For example, if the increment is set to 10 families and decision variables A_1 = 7 and A_2 = 5, this means that the first 10 families will housed in alternative housing project #7, where as the second 10 families will be housed in alternative housing project #5. If no alternative housing project is selected for that increment of families (i.e. A_i = 0), then these families are going to be housed in traditional temporary housing.

The second group of decision variables (T_i) represents which temporary housing projects will be fully or partially substituted by alternative housing. In the previous example, if A_1 = 7 and T_1 = 3, it means that the first 10 families will be housed in alternative housing project #7 instead of temporary housing project #3.

Optimization Objective

The main objective of the proposed model is to maximize the net social benefit of alternative housing projects to displaced families and emergency management and aid agencies. In order to evaluate and maximize the net social benefit, the model is designed to compute two important metrics: (1) the social benefits metric (SB), which represents the value of added social benefits by providing alternative housing to displaced families in substitution of traditional temporary housing; and (2) the total change in cost metric (TCC), which accounts for the added cost associated with providing alternative housing as well as the corresponding savings from fully or partially substituting originally planned temporary housing projects. Accordingly, the

optimization objective of the proposed model is to maximize the net social benefit (*NSB*), as shown in Equation (1).

$$\text{Maximize } NSB = SB - TCC \tag{1}$$

Where, *NSB* is the net social benefit of alternative housing projects; *SB* is the social benefits metric; and *TCC* is total change in cost metric. In regard to computing the social benefits metric, previous research studies have proposed indexes to quantify the socioeconomic impacts of temporary and alternative housing on displaced families, such as the socioeconomic disruption index (*SDI*) and the social welfare index (*SWI*) (El-Anwar et al. 2008; El-Anwar et al. 2009c; El-Anwar et al. 2010a; El-Anwar et al. 2010b). These indexes can account for important social metrics, including (1) employment and educational opportunities at the housing location; (2) housing quality; (3) housing delivery time; (4) capacity of housing location to support healthcare and safety needs for displaced families; and (5) access to public transportation and essential utilities and services (El-Anwar et al. 2008; El-Anwar et al. 2010b).Therefore, the model enables decision-makers to assign a social welfare index for each temporary housing project included in the original temporary housing plan (*SWI(T)*) and for each candidate alternative housing project (*SWI(A)*). Accordingly, the social benefits metric (*SB*) can be computed using Equation (2).

$$SB = \sum_{i=1}^{I} \left[SWI(A_i) - SWI(T_i) \right] \times V_{SWI} \times f \tag{2}$$

Where, *SB* is the social benefits metric; *I* is the total number of increments of families; $SWI(A_i)$ is the social welfare index for the i^{th} increment of families that will be housed in alternative housing project A_i; $SWI(T_i)$ is the social welfare index for the i^{th} increment of families that would have been housed in temporary housing project T_i if alternative housing was not provided; V_{SWI} is the monetary value of the social welfare index, which is an input by the decision-maker; and *f* is the value of the increment of families (e.g. 10 families).

In order to compute the total change in cost metric (*TCC*), the model accounts for four types of costs: (1) the initial cost ($C_1(A_i)$) of providing each alternative housing project A_i, which covers the costs of design, permits, mobilization, etc.; (2) the cost ($C_2(A_i)$) associated with increasing the size of an alternative housing project to accommodate an increment of families, which covers the cost of the construction or installation of new housing units, additional land acquisition, etc.; (3) the initial cost ($C_1(T_i)$) of providing each temporary housing project T_i, which is needed to compute the savings in case of fully substituting temporary housing by alternative housing; and (4) the cost ($C_2(T_i)$) associated with increasing the size of a temporary housing project to accommodate an increment of families, which is needed to compute the savings in case of partially substituting temporary housing by alternative housing. Accordingly, the model computes the total change in cost metric (*TCC*) using Equation 3.

$$TCC = \sum_{i=1}^{I} \left[C_1(A_i) - C_1(T_i) \right] + \sum_{i=1}^{I} \left[C_2(A_i) - C_2(T_i) \right] \times f \tag{3}$$

Where, *TCC* is the total change in cost metric; *I* is the total number of increments of families; $C_1(A_i)$ is initial cost of providing alternative housing project A_i, and it is accounted for only once when the alternative housing project is initiated; $C_1(T_i)$ is the initial cost of providing temporary housing project T_i, and it can be subtracted only once to reflect savings in case of fully replacing temporary housing project T_i with alternative housing; $C_2(A_i)$ is the cost associated with increasing the size of alternative housing project A_i to accommodate an increment of families; $C_2(T_i)$ is the cost associated with increasing the size of a temporary housing project to accommodate an increment of families, and it is subtracted to reflect savings in case of partially substituting temporary housing project T_i with the alternative housing project A_i; and *f* is the value of the increment of families (e.g. 10 families).

MODEL IMPLEMENTATION

The proposed model is designed to identify the optimal decisions on alternative housing that would maximize the net social benefit to displaced families and emergency management and aid agencies. Non-Dominated Sorting Genetic Algorithm II (NSGA2) is used to implement the proposed model because of its (1) superior performance compared to other genetic algorithms (D'Souza and Simpson 2002; Deb et al. 2001; Weile et al. 1996); and (2) unique characteristics such as fast non-dominated sorting and elitism (Deb et al. 2001; Deb 2005). The model is implemented in four main steps: (1) initialization phase, in which a population of random solutions is generated, where each solution represents a possible combination of assignments of increments of families to candidate alternative housing projects and the substituted temporary housing projects; (2) solutions evaluation phase, where the optimization objective is evaluated for each solution based on the computed net social benefit, as shown in Equation (1); (3) ranking phase, in which all the solutions are ranked based on the value of their net social benefit; and (4) population generation, where a new improved population of solutions is generated. Phases 2, 3, and 4 are then repeated until a predetermined number of generations are completed.

APPLICATION EXAMPLE

An application example is presented to demonstrate the use of the model and its capabilities in maximizing the net social benefits. In this example, a configuration of 20 temporary housing projects are planned to house 5,520 displaced families. There are 10 candidate alternative housing projects that are being considered for substituting some of the temporary housing projects with a total capacity of 2,340 families. V_{SWI} is assumed to be $54,000 and the increment of families is assumed to be 20 families. Therefore, there are 117 increments of families that can be housed in alternative housing (2,340 families ÷ 20). Accordingly, there are 234 decision variables that need to be optimized (twice the number of increments as previously explained), and the search space for this problem is approximately 1.16×10^{274}.

The model is used to maximize the net social benefit by identifying the optimal decisions regarding (1) which alternative housing projects should be selected and with what capacities (which is represented using 117 decision variables); and (2) which temporary housing projects should be partially or fully substituted (which is represented using the remaining 117 decision variables). The model is used to search

for near-optimal solutions for this problem with a population size of 1,000, crossover probability of 0.9, and mutation probability of 0.00095.

Figure 2 shows the rapid improvement of the net social benefits (in dollar value) for the optimal solutions identified until a predetermined termination criterion of 1,000 generations. The results illustrate the ability of the proposed model to identify optimal decisions on alternative housing that would maximize the net social benefits to both the displaced families and emergency management and aid agencies.

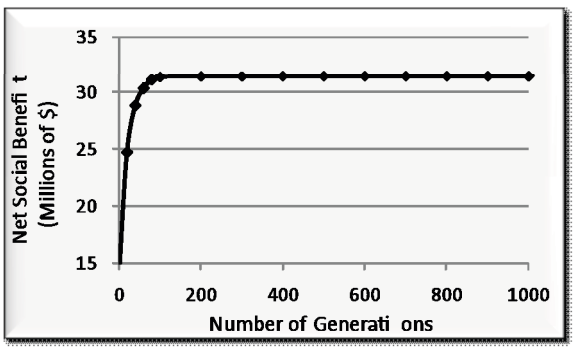


Figure 2. Optimization Results

Figure 3 shows the average rate of improvement in the net social benefits per generation, where the average rate is measured every 20 generations for the first 100 generations and then every 100 generations afterwards. The results show that the rate of improvement starts at high values and then decreases until it approaches convergence approximately after 400 generations.

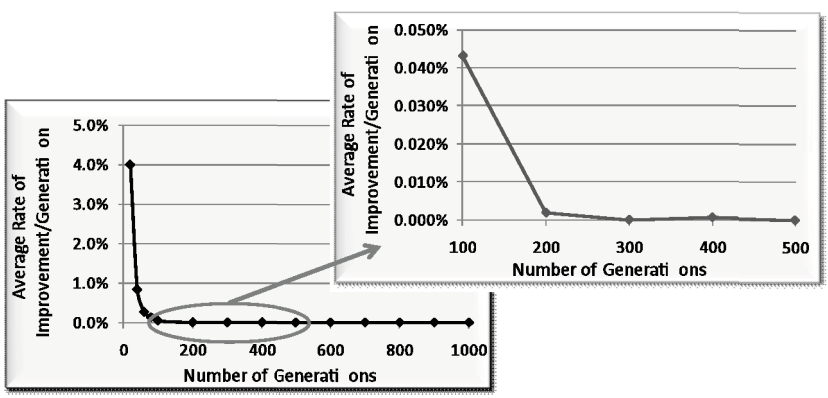


Figure 3. Average Rate of Improvement per Generation

CONCLUSION

An optimization model is developed to support decision-makers in planning for post-disaster alternative housing projects. The decision variables in the developed model

are designed to represent (1) the number of families that should be provided by alternative housing; (2) the alternative housing projects selected and their sizes; and (3) the temporary housing projects that should be fully or partially substituted by alternative housing. The objective of the model is to maximize the net social benefit for displaced families as well as emergency management and aid agencies. In order to quantify and maximize the net social benefit, the paper presents the development of two new important metrics: (1) the social benefits metric (*SB*); and (2) the total change in cost metric. The model is implemented in four main steps using Non-Dominated Sorting Genetic Algorithm II. An application example is presented to demonstrate the use of the model and its unique capabilities in identifying optimal plans for alternative housing that would maximize the net social benefits. The model is currently being expanded to consider other important objectives; including quantifying and optimizing the impacts of alternative housing projects on host communities. Moreover, future research will investigate economic methods to compute the monetary value of the social welfare metric, such as utility theory, in addition to willingness to accept and willingness to pay methods. The presented model should prove useful to emergency management agencies at the state and federal levels and can be used to support officials and decision-makers in planning for alternative housing projects after natural disasters.

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Vulnerability Assessment of Critical Infrastructure, Associated Industries, and Communities during Extreme Events

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Abstract:
Critical infrastructure play an important role in functioning of industries and communities and also responding against natural disasters to reduce their impacts (i.e., routes and bridges for evacuation and public buildings for sheltering). Due to global warming, there is an increase in the frequency of extreme weather events which pose a high risk of functional and structural failure of critical infrastructure. Recent natural disasters (i.e., Hurricane Katrina, 2008 Midwest Flood, etc.) have exposed the vulnerability of critical infrastructure in the U.S. Therefore, it is important for the emergency-related agencies to identify and fortify the vulnerable critical infrastructure ahead of time to significantly reduce the potential damage due to floods. In this paper a decision support system (DSS) using Bayesian Network theory and System Dynamics Simulation method is presented for vulnerability assessment of critical infrastructure. This DSS has been developed to support emergency agencies and industries to prepare customized mitigation strategies and plans for preparedness, response, and recovery using the criticality and vulnerability analyses.

1. Extreme Events and the Role of Critical Infrastructure

Critical infrastructure plays a very important role not only for sustaining industries and communities but also in properly responding against natural disasters to reduce their impacts. Critical infrastructure are considered as life support networks that are essential to sustain the normal activities of the industries and communities, such as production, delivery, and supply chain issues for industries, as well as commuting to work, school, church, healthcare, etc., for communities. Moreover, at the occurrence of natural disasters, the critical infrastructure such as routes and bridges for evacuation support activities for disaster response and recovery.

Thus, if critical infrastructure are damaged due to natural disasters, they in turn affect the services and activities of industries and communities as well as disaster response during disasters. Natural disasters, such as the recent floods in Atlanta and the Midwest (2008), Hurricane Ike in the Gulf coast region (2008), and the earthquake in Sichuan, China (2008), caused severe damage to critical infrastructure and associated industries and communities. The estimated damages due to Hurricane Ike are a staggering $27 billion, third worst in the U.S. after Hurricane Andrew (1992) and Hurricane Katrina (2005). In the case of Katrina, eight (8) percent of the affected population were isolated due to broken levees in the Gulf Coast areas and could not be evacuated whereas about 1,330 were killed or reported missing (Homeland Security and Counterterrorism 2006). Similarly, if the emergency-related agencies in Sichuan had identified and fortified the vulnerable critical infrastructure (i.e., communication networks and main routes) ahead of time the damage and impacts due to earthquake could have been significantly mitigated (New York Times 2008).

The reasons that cause these failures of critical infrastructure are closely related to the conditions of critical infrastructure. The majority of infrastructure throughout the U.S. has been weakened due to age and deteriorated conditions making them vulnerable to natural disasters. For example, the 2009 ASCE Report Card for infrastructure gives an average grade of D to U.S. infrastructure, which signifies a need for urgent rehabilitation.

2. Previous Research of Natural Disaster Impact Analysis

Since critical infrastructure play significant roles during the occurrence of natural disasters, preparedness and mitigation strategies should include identifying and fortifying vulnerable infrastructure based on their interrelationship with the associated industries and communities. In previous research conducted by the authors (Hastak et al. 2008, Oh 2008) this interrelationship has been defined through a basic cell model (Fig 1). However, the inter-relationships that Hastak et al. (2008) emphasized is mainly focused on technical issues, such as critical infrastructure affected by floods, level of inter-relationship, and industrial distribution in the affected areas. However, to understand the inter-relationship between critical infrastructure, industries, and communities, it is important to define their relationships and impacts considering various economic, social and technical factors.

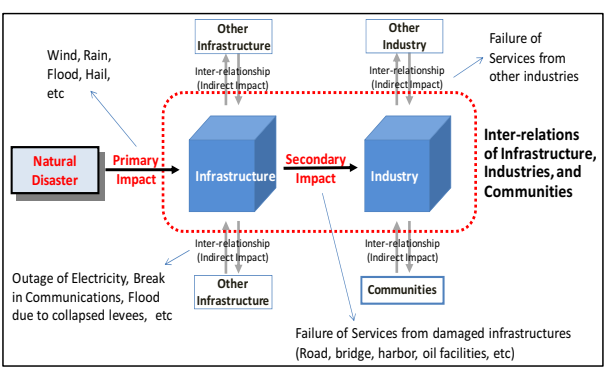


Figure 1: Disaster Impact Mechanism (Basic Cell Model) (Hastak and Oh 2008)

Economic Impacts: Burrus et al. (2002) have used full-day

equivalents lost (FDEL) as a metric for measuring the cumulative impact of frequent business interruption in low-intensity hurricane regions. Whereas, Lian et al. (2007) applied mathematical methods to measure the impact on companies through their input-output (I-O) exchange of goods and services. The model analyzed the interdependency among the industry sectors of the economy and the indirect ripple effects of initial perturbations to the critical infrastructure systems. Rose et al. (2007) also established economic factors to measure the impact of natural disasters focusing on regional economics that are highly dependent on electricity. Computable general equilibrium (CGE) simulation method was applied using factors such as output loss of downstream/upstream customers/suppliers, output loss to all firms from decreased customers, etc. Most of these models are complex and time consuming and combine economic and engineering data along with time based information to generate results (Mantell 2005, Moteff et al. 2003). Hence models that could give quick input-output results providing with an upper end of total loss are most beneficial to emergency response decision making team as they would provide an extent of disaster effects over a region in a short period of time.

Social Impacts: Current research methods can gauge economic gains and losses but are unable to capture the degraded life quality after the floods (Tapsell et al. 2002). With an increase in socioeconomic losses due to natural disasters more emphasis is being placed on improved risk management strategies that consider both social as well as monetary loss (Munich-Re 2007). They have developed a Social Flood Vulnerability Index (SFVI) consisting of three social characteristics and four financial-deprivation indicators to measure the impact of floods on communities. Lindell and Prater (2003) illustrated the relationship of physical and social impacts of natural disasters on communities and emphasize the need for research to identify social and economic characteristics of communities such as type of commercial, industrial or agricultural business, skilled or unskilled workers, etc. and demographic factors such as age, gender, low-income employees, etc. This will help in anticipating the needs beforehand and effective disaster response can be initiated. However, these models do not capture the social and economic impacts caused by failure of infrastructure interrelationships.

Technical Impacts: Rinaldi et al. (2001) observed interdependencies among infrastructure and their importance and influence over functioning of industries. They have provided with a conceptual framework which shows a broad range of interrelated factors and system conditions using “six dimensions” such as infrastructure characteristics, state of operations, types of interdependencies, environment, coupling and response behavior, and type of failure. Chang et al. (2002) provided a loss-estimation decision framework based on Monte Carlo simulation. In addition, Chang (2003) pointed out the significant fact that loss of critical infrastructure, such as electric power, water, transportation, and other lifeline infrastructure systems can have far-reaching societal impacts. Based on this analysis, McDaniels et al. (2007) further characterized infrastructure failure interdependencies in terms of the sectors affected and the consequences for society. In addition, Simpson et al. (2005) have proposed a framework to measure resiliency of community against the risks of multiple hazards using fragility curves at building and infrastructure network level.

These achievements of various researchers have been a foundation to develop a new framework, which was suggested by Oh and Hastak (2008). They introduced a disaster impact analysis model based on inter-relationships of critical infrastructure and associated industries/communities and measured the magnitude of natural disaster impacts on communities and industries. The key components of this framework are vulnerable infrastructure (which are likely to be affected by a natural disaster), the main industries and communities in the affected area, and their varied inter-relationships. Besides, FEMA (the Federal Emergency Management Agency) has developed a GIS-based tool, Hazus-MH as an emergency management tool, to estimate the loss due to disaster impacts on communities. This model has a merit of visualization of the disaster area, however, it also has a shortcoming not to simulate the changeable conditions according to the timeline of a flood. For example, as the flood water rises, the conditions of main routes may change and some of them would fail to sustain their original purpose (i.e., transportation). Thus, experts may not be able to establish safe routes to reach and evacuate isolated people at the right time during a flood. In addition, most previous research focus on the response stages of 'mitigation strategies' and 'recovery after disaster' for communities. As a result, there may not be any support for disaster response during the disaster. Therefore, there is a need for a support system that can identify critical infrastructure for quick response and recovery such as evacuation, functioning and sustenance of communities and industries as well as identify critical vulnerable infrastructure for long term mitigation and rehabilitation strategies. The current paper has addressed these needs with respect to flood disaster.

3. Research Objectives

Therefore, the general objective of this research is to develop a decision support system for identifying region specific disaster mitigation strategies based on the inter-relationships between infrastructure and communities and associated industries in terms of technical, social, and economic dependencies. The model should be able to facilitate the decision making of the local emergency agencies and industries in developing better plans and strategies to maximize the use of available resources and infrastructure for sustaining the community and industrial activities during natural calamities. Where, the inter-relationships are identified in terms of the dependency of communities and associated industries on critical infrastructure.

4. Framework of Decision Support System

Plans and mitigation strategies for reducing the impacts are important at a wide-range of levels in terms of communities, industries, local and federal governments, etc. Thus, various entities, such as city managers, emergency management agencies, industrial experts, and community leaders, should be able to generate plans and mitigation strategies according to their purposes after data collection is complete. The information they need will be similar and can be derived based on the analyses of the collected data. For example, the purpose of disaster preparedness for a city manager and emergency managers in industries would be to identify vulnerable critical infrastructure from their view points. Thus, the information that should be identified for developing the mitigation plans and strategies includes:

- Identification of critical infrastructure for protecting or sustaining industries and communities in terms of the technical, social, and economic aspects (criticality)
- Identification of vulnerable infrastructure or vulnerable parts and sections of the critical infrastructure (vulnerability)
- Impacts on industries and communities if vulnerable infrastructure fail during a disaster (severity or level of impact).
- Mitigation plans to protect industries and communities or reduce the impacts.

Criticality implies, for example, how much a company is dependent on critical infrastructure in terms of its business activities. Vulnerability addresses the threats or potential hazards to industries or communities in disaster situations and can vary according to the condition of infrastructure. Severity implies the extent of damage or impact when a disaster occurs in communities or near industries (Oh et al. 2009a, 2009b, and 2009c). Thus, criticality, vulnerability, and severity can be key metrics for the framework of the decision support system to understand how critical infrastructure, industries, and communities are inter-related in terms of the impacts of natural disasters and how the natural impact can be measured.

5. Data Collection

Data collection efforts included survey questionnaires, interviews, and site-investigations. 65 complete survey questionnaires were collected from the affected areas in the Midwest area focusing social and economic data from residents. 19 interviews were conducted to collect technical, social, and economic data from affected communities as well as experts who were responsible to operate and maintain the critical infrastructure in the affected areas. Industrial experts were also interviewed to obtain information about the critical facilities and infrastructure to sustain their functions and services. This data collection effort was successfully conducted with support from NSF through a NSF SGER project that aimed to collect ephemeral data due to the 2008 Midwest floods. During the NSF SGER project, authors focused on critical infrastructure and the impacts on associated industries and communities through damaged critical infrastructure. Timing of data collection was very important for ephemeral data; however, it was also true that most relevant data was obtained from interviews and survey questionnaires due to limited accessibility to the affected areas at the occurrence of floods.

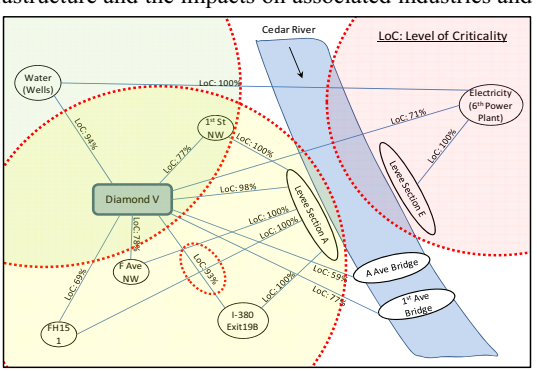


Figure 2: Zone of Influence and Network Structure of Inter-relationships with the Level of Criticality (LoC) of Diamond V (Cedar Rapids, Iowa)

Case Study: The example illustrated below has been developed using a case

study conducted for Diamond V during the NSF SGER study. Diamond V is a feed ingredient supplier in Cedar Rapids, Iowa that provides natural yeast culture products. Figure 2 illustrates Diamond V as a node with all interrelated infrastructure. It falls under the zone of influence of several adjacent critical infrastructure as shown in Figure 2.

6. Criticality Assessment

Criticality is the dependency of a community or an industry on a critical infrastructure in terms of their daily routine activities and it is important to measure the level of criticality (inter-relationship) between critical infrastructure, industries and communities. The level of dependency needs to be established by the community or industry since they understand best the role played by a particular infrastructure in their environment with respect to technical, social, and economic aspects. Thus, based on zone of influence analysis the users can determine the criticality of each infrastructure (Fig. 2). For example, Zone of Influence of Levee Section A covers the entire area of west side of the river including Diamond V, I-380 exit 19B, etc. In addition, the level of dependencies can be established through interviews and the final level of criticality (LoC) can be calculated using the decision tree analysis (Oh et al. 2009). Finally, the network structure (or zone of influence of inter-relationships) that illustrates all the inter-relationships and the level of criticality (LoC) can be represented as shown in Figure 2 (For the details of Criticality assessment, please, refer to Oh, Deshmukh, Hastak, and Dietz. (2009).

7. Vulnerability Assessment

The purpose of vulnerability assessment is to provide emergency-agencies and associated individuals appropriate information for preparing better mitigation strategies from a long-term perspective. It is also very important for them to facilitate their activities regarding the use of temporary methods/tools for mitigating the impact in time and the responses (i.e., evacuation, search and rescue, protecting infrastructure, etc.) during the occurrence of floods. Therefore, the vulnerability assessment should provide the level of vulnerability for each infrastructure based on the varied timeline (long-term and just before/during/after) of the flood. For example, if it is successful to predict the level of vulnerability of an infrastructure as a flood develops, it will be easy for them to react against the flood to mitigate the potential damage that the infrastructure may cause. However, measuring the level of vulnerability is complicated due to unpredictability of flood events and the characteristics of infrastructure. During a flood, critical infrastructure such as levees and bridges are likely to be affected in the primary impact stage. Whereas, in the secondary stage, other adjacent (or indirectly inter-related) infrastructure will be affected by the damaged infrastructure as well as the flood water (Oh et al. 2008). Thus, the level of vulnerability will vary according to the impact stages and the type of infrastructure.

For determining the level of vulnerability, two types of information are important: probability of failure (or inundation) of each component (critical infrastructure, associated industries, and communities) due to a flood; and the extent of potential damage to them. It is noticeable that the probabilities of failure of the infrastructure are linked (or chained). For example, the probability of inundation of a road near a

levee section depends on the probability of overflowing of the levee section. That is, if the probability of levee failure increases, then, the probability of failure of the road also increases. This conditional probability indicates the probable state of a variable that is dependent on the state of another variable.

Bayesian Network for Calculating Probabilities of Failure: A Bayesian network (or a Bayesian belief network) therefore can be applied to calculate the probability of failure for each component (i.e., infrastructure, industry, and community). The Bayesian network consists of nodes that are connected with directional arrows that represent conditional dependence relationships between those nodes. Bayes' theorem is used to recalculate the probability about the state of a node depending on the evidence introduced for another node in the Bayesian network (Jensen 1996, McCabe et al. 1998, and Bayraktar 2006). There are several software packages available to facilitate modeling using Bayesian networks. Figure 3 illustrates an example of Bayesian network using the network structure of Diamond V (refer to Fig. 2). The model described in this paper is created using GeNIe 2.0, a free software provided by the Decision Systems Laboratory of the University of Pittsburgh (http://dsl.sis.pitt.edu).

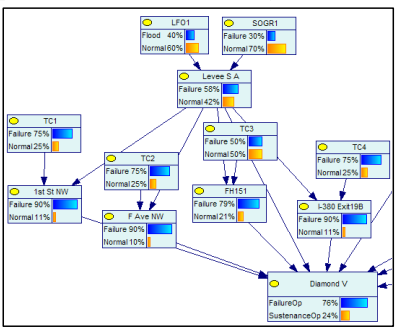


Figure 3: Example of Bayesian Network (Diamond V in Cedar Rapids, Iowa)

The figure shows three types of nodes: prior nodes of input probability (LFO (the likelihood of flood occurrence), SOGR (the State of Good Repair), and TC (Topographical Condition)), intermediate nodes of infrastructure (levee sections, roads (streets and avenues), bridges, and a power plant), and the end node (Diamond V)). The probability of failure (or flood) of Diamond V is affected by the prior probabilities from the adjacent infrastructure. Thus, its probability can be calculated by Bayes' Theorem using all prior probabilities from infrastructure as shown in Figure 3. In order to simulate the probability of failure for each component, i.e., infrastructure, industries, and communities, System Dynamics can be used.

Simulation based on System Dynamics: System Dynamics Simulation method has been used to simulate the vulnerability assessment of critical infrastructure, associated industries, and communities. The characteristics of the vulnerability assessment module are: (1) the system is very complex and mixed with many components and varied factors; (2) the components are inter-related with fixed level of criticality; and (3) the system should be structured in a macro level representing the components (i.e., infrastructure, industries, and communities). Thus, among the varied simulation methods, System Dynamics (SD) was considered the most appropriate for this research. SD can be considered as a set of rules (i.e., equations) that defines how the system is being modeled. In this paper, the vulnerability assessment module has been established using the case of Diamond V as an example of SD modeling (Fig. 4 shows a partial model). A free software, Vensim PLE Software, was used as a tool for the simulation.

There are three types of variables in the model: constant, auxiliary, and level. The sources of flood water (surface water, flood water-1, and flood water-2) and other information (topographical conditions, water pressure, SOGR, etc.) are examples of constant variables which provide basic information of the flood and the conditions of infrastructure as initial values. The box nodes are all auxiliary variables except Diamond V which is a level variable. Auxiliary variables calculate the vulnerability combining the values from constant variables and transfer the result to associated auxiliary and level variables. Thus, the impacts from the flood can be transferred to associated infrastructure and industries through the middle infrastructure which were expressed as auxiliary variables.

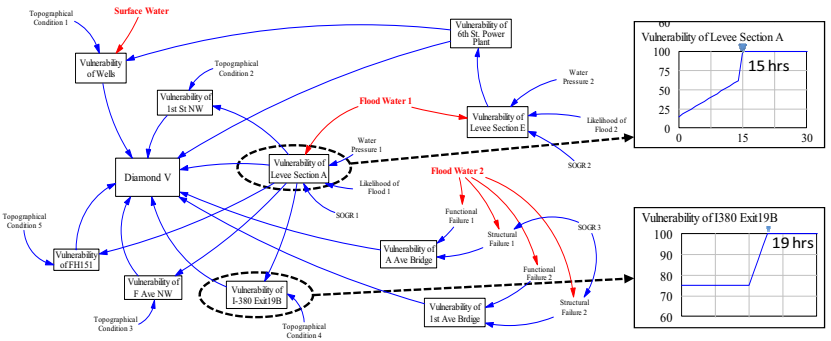


Figure 4: Example of a System Dynamics Simulation (Diamond V, Cedar Rapids, Ia)

The vulnerability of any infrastructure would be influence by its physical characteristics, for example, bridge elevation, levee height, and type of material and construction. For example, the vulnerability of Levee Section A which comprised of functional and structural failure could be determined by the conditions of related factors, such as Flood Water-1 and SOGR (Fig. 4). As Flood water-1 increases according to the rising water for 15 hours, the vulnerability of Levee Section A also increases. However, Flood Water-1 indicates that the flood water overflows at 15th hour and its vulnerability becomes 100% at that point. In sequence, the vulnerability of Levee Section A also gets to the point of 100% at 15th hour. Similarly, the vulnerability of each critical infrastructure can be evaluated through simulation. Each variable (infrastructure) shows its vulnerability change according to the timeline of flood. For example, as shown in Figure 4, the vulnerability of I-380 Exit19B increases rapidly when Levee Section A fails and the flood water runs on the ground for 4 hours, and it becomes 100% when the flood water reaches the exit at 19th hour.

8. Significance of the Results and Conclusion

The criticality and vulnerability assessments of the DSS identify critical infrastructure as well as its vulnerability to flood events. In the response stage, this information can be used for immediate actions to preserve life, property, and the environment. For example, main routes for evacuation can be examined through the vulnerability analysis before the flood water overflows. In addition, the assessment modules will help examine the conditions of critical infrastructure, such as levees, flood walls, and

dams, which are significant to protect industries and communities. The Department of Homeland Security defines the three stages of disaster response as: preparedness, response, and recovery (DHS, 2004). Preparedness includes wide range of activities to prevent/mitigate the impact of disasters, thus, it requires relevant data (i.e., technical, social, and economic) for hazard assessment, infrastructure assessment, planning, and training personnel. Thus, mitigation plans may include proper or emergent protection methods for safeguarding those important infrastructure. Additionally, knowledge about the vulnerability of critical infrastructure to natural (and or manmade) disaster can also be used for developing infrastructure rehabilitation strategies tied to the capital improvement program for the city or the industry.

After the flood water recedes, the efforts of recovery and rehabilitation of damaged industries/communities/infrastructure will follow. Rehabilitation of damaged infrastructure will be decided through criticality and severity analyses results in terms of the level of serviceability of a specific infrastructure. The mitigation strategies can be enhanced by combining the functions of the proposed DSS and the tools that were previously developed, such as Hazus-MH because it has the functions of direct and indirect loss estimates and visualization with GIS, while the proposed DSS provides criticality, vulnerability, and severity analysis based on inter-relationships and time-based mitigation actions during disaster occurrence.

In conclusion, data for disaster impact analysis in terms of social, economic, and technical aspects will be collected for facilitating and improving preparedness against the impact of natural disasters. Based on the data, factors for impact measurements and a framework for the simulation based decision support system will be developed. The decision support system will allow development of customized strategies and plans for each affected area. Eventually, a better understanding of the impact of disasters on infrastructure and the associated industries and communities would assist emergency-related agencies in identifying appropriate disaster mitigation strategies.

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2D VISION TRACKING METHODS' PERFORMANCE COMPARISON FOR 3D TRACKING OF CONSTRUCTION RESOURCES

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ABSTRACT

In construction sites, tracking personnel, equipment, and materials is necessary in many applications such as asset management and progress monitoring. Vision tracking as a tracking technique has two unique capabilities which make it ideal for tracking on large scale, congested construction sites; tracking from a distance and tracking multiple elements from a single camera. 2D tracking results can be obtained through each camera and the 3D positions can be calculated by calibrating multiple cameras. 2D vision tracking methods vary and each method has unique capabilities, but little is known about the appropriateness of each method for tracking construction resources. This paper presents an evaluation of these methods that aims to identify the one most suitable for 3D tracking in construction sites. To satisfy this goal, 2D tracking methods are categorized, metrics are identified and performance of two categories of methods is evaluated based on these metrics. This evaluation has been used to find some preliminary results that can ultimately help with selection of the most suitable category of 2D vision tracking methods for construction applications.

KEYWORDS

Vision tracking, Image processing, Computer vision, Comparison

1 INTRODUCTION

In construction sites, tracking project related entities (e.g. personnel, equipment, and materials) is necessary in many construction applications such as progress monitoring, activity sequence analysis, productivity measurements, locating resources, and safety management. One potential capability of 3D vision tracking is that it can track tens of hundreds of objects that are present in the view of a camera without installation of any tags on them. 3D vision tracking is expected to be cost-effective and time-effective in large-scale, congested construction sites, where a large number of entities are required to be tracked. This is because of the low cost of cameras and also less pre-processing time needed to install cameras compared with other tracking methods that require installation of tags on each entity being tracked.

3D vision tracking results can be obtained by applying epipolar geometry that can calculate the depth information of objects using 2D vision tracking results (i.e. x,y information) from two or more cameras (Brilakis et al., 2008). The effectiveness of 3D vision tracking methods is directly related to the performance of 2D vision tracking since accurate positions (x, y) of objects being tracked are required for optimum 3D vision tracking results. Therefore, it is necessary to find a proper 2D vision tracking method out of the methods that currently exist to see which one can satisfy construction resource tracking needs and be adaptable to the construction site environment. Since little is known on how these methods compare for this environment, a scientific approach to select an appropriate 2D vision tracking method that can fit construction industry's requirements can greatly enhance 3D tracking results.

There are a variety of 2D tracking methods with different capabilities and specifications in terms of the way of initializing the tracking (i.e. manual or automatic), the processing time, and their effectiveness in terms of handling occlusion, object size, etc. These aspects, along with complications that are in the nature of construction sites (e.g. existence of many different types of entities with high similarity in terms of shape and color (Brilakis et al., 2008)), make the selection of a proper 2D vision tracking method for construction applications a challenging task.

This paper presents a comparative study of existing tracking methods to find the most suitable one for construction site 3D tracking. To accomplish this objective, 2D tracking methods are categorized, studied and compared. A brief literature review shows that there are many different approaches and algorithms under each category of trackers, which results in enormous number of 2D tracking methods. This makes the literature so vast and no attempt can be nor will be made to review them comprehensively. Here, the authors have just tried to look at the main categories of trackers and tested some selected methods under each category to find the most optimum one for the purposes of 3D tracking in construction sites.

The comparison of 2D tracking methods is based on identification of criteria that can affect the efficiency of on-site tracking in construction sites which vary in terms

of their characteristics (e.g. size, complexity, congestion). These criteria have been set up as metrics (i.e. performance indicators) to evaluate and compare tracking methods for construction applications. Two categories of tracking methods (contour-based and kernel-based) were tested based on the number of frames each method can track. Preliminary results revealed that kernel-based tracker is capable of tracking more number of frames in each case.

2 VISION TRACKING

Object tracking has attracted a lot of interest and attention in the field of computer vision because of the large number of applications it has as well as availability of high performance computers and inexpensive digital video cameras. To achieve vision tracking, there are two main steps that must be accomplished. The first step is detection of objects of interest, which can be done manually or automatically depending on the method selected. This step has also been referred to as characterization or initialization step (Marfil et al., 2007). The second step is tracking of the detected objects and prediction of their changes in terms of position and shape in the succeeding image frame, which is also known as localization of targets (Marfil et al., 2007).

2D vision tracking is not sufficient for the general applications of tracking in construction industry and 4D information is required, i.e. 3D spatial coordinates over time. For instance, to avoid collisions at construction sites, the entities' precise position (i.e. 3D) is needed in real time to calculate the relative distance and velocity of objects. In vision tracking, cameras can be used to obtain 2D positions of objects in each camera's view. By integrating information collected from multiple cameras and applying epipolar geometry, it is possible to evaluate the depth information of objects (Brilakis et al., 2008). Consequently, obtaining reliable 3D tracking results depends on the results of 2D tracking. Therefore, selection of a 2D tracking method that is robust to domain specific variations of construction sites and produces valid tracking information is essential. 2D vision trackers can be classified as contour-based, kernel-based, and point-based trackers (Yilmaz et al., 2006). A brief review of each method is brought below.

2.1 Contour-Based Trackers

Many tracking methods use silhouette or contours to track objects by estimating and updating the region or boundary of the target in the current frame and comparing that with the results obtained from the previous frame (Nguyen et al., 2002). Contour-based tracking methods use a variety of algorithms; they may track parameterized contours and non-parameterized contours (Nguyen et al., 2002). Parameterized methods approximate the contour using a parametric model (e.g. B-Splines) or detect the contour by minimization of some energy function (i.e. snake model). Non-parameterized contours are basically represented as boundary of a

region (e.g. geodesic contour model) (Nguyen et al., 2002). The strength of the latter approach is that it can be used to represent the contour of an arbitrary shape (Nguyen et al., 2002) and as a result they have been used in most contour-based tracking methods of recent years.

Algorithms employed in contour-based trackers could use "photometric variables" (e.g. intensity, color, texture), "geometric variables" (e.g. edges, lines, corners), or a combination of both (Freedman 2004). It is argued that trackers that use photometric variables are more advantageous to geometric trackers because they are more reliable in the presence of illumination variations and cluttering and also they take into account the rich amount of information existing in the images (Freedman 2004). Based on literature, it could be safe to say methods that use non-parametric contours and photometric variables are more favorable to use because they are more robust to illumination variations as well as occlusion. The main advantage of contour-based trackers is that they can detect the exact contour, which is useful in applications where exact posture of the target is needed. Occlusion and illumination variations may not be handled as good as other categories of trackers.

One approach to achieve contour-based tracking is employment of variational frameworks (Yilmaz et al., 2006). These frameworks basically integrate variety of information for image segmentation Rousson and Deriche (2002). Bertalimo et al. (2000), Rousson and Deriche (2002), and Cremers (2003) presented different variational frameworks combining different information (e.g. motion estimation and shape regularization in Cremers (2003)). The framework proposed by Rousson and Deriche (2002) is a dynamical framework that works based on a Bayesian model. This method has shown very good results for image segmentation and contour evolution of different objects in a variety of backgrounds.

2.2 Kernel-based Trackers

Kernel basically refers to the shape and appearance of the object (Yilmaz et al., 2006). As a result, these trackers are also referred to as region-based or appearance-based methods. These methods compute and update the motion of the kernel in each frame based on the regions' information such as color and texture (Marfil et al., 2007). Color histogram generally plays an important role in these methods since color is a good feature to distinguish objects' regions and enables to manage partial occlusion (Marfil et al., 2007). However, the tracker may get confused if objects of similar colors are occluded by each other. Since these methods do not take any "a priori" knowledge of the objects' appearance into account, initialization of tracking a new object has to be performed manually.

Two sub-categories of kernel-based trackers are template and density-based appearance models, and multiview appearance models (summarized in Table 1 below). Template-based models take into account both color histograms and spatial information. The basic concept of template tracking is finding the region that best

matches with the template that is determined in the first frame (Marfil et al., 2007). One approach to do this is mean-shift procedure, which basically is an analysis technique that works based on the comparison of histograms of the object, Q, with the window approximated around the location of that object, P (Yilmaz et al., 2006). Bhattacharya coefficient is used in this approach to measure the similarity of the two histograms. Templates and density-based trackers are advantageous because of their simplicity and low computational cost. However, they are not suitable if the pose of objects change considerably in each frame (Yilmaz et al., 2006).

2.3 Point-based Trackers

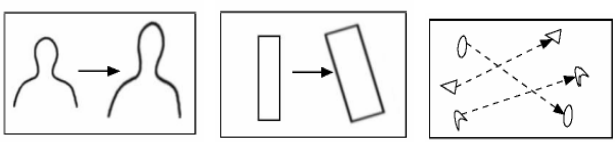
In point-based trackers, objects are represented by some limited points, which are detected and tracked in consecutive frames (Yilmaz et al., 2006). In image frames that objects appear larger, the more points may be demanded for successful identification of the object, which could affect processing time and also when multiple points are employed, grouping of points that belong to the same object becomes an important problem (Yilmaz et al., 2006). Also, it is important to select and keep appropriate feature points that can effectively represent the objects. Yilmaz et al (2006) have divided point-based methods into two categories of deterministic methods and probabilistic methods. In general, point-based trackers using multiple points are beneficial to characterization of non-rigid objects provided that the locations of the feature points are flexible. Also, these trackers are suitable for tracking extremely small objects which can be represented by a single point, but they have more tendencies to fail in the presence of occlusion as well appearance and re-appearance of objects (Yilmaz et al., 2006).

2.4 Summary of Methods

The following table presents a summary of tracking categories outlined above. This table is based on the literature review and especially the survey of object tracking methods done by Yilmaz et al. (2006). It should be noted that the general strengths and limitations listed in this table are addressed and handled by some subcategories/approaches and it cannot be concluded that a category has such limitation regardless of the algorithm or method used. For example, although tracking multiple objects cannot be handled by most kernel-based trackers, there are some algorithms that can track multiple objects.

Table 1: A summary of Main Features of Object Tracking Methods

Category	Main Purpose	General Strength(s)	General Weakness(es)	Performance Evaluation	Sub-categories	Approaches (examples)
Contour-based	Tracking exact contour (object shape)	Ability to represent variety of shapes	handling occlusion and object split and merge	precision and recall	Contour-evolution	Variational Methods
					Matching Shapes	Histogram
kernel-based	estimating object motion (region and direction)	handling occlusion	handling multiple objects	precision and recall	Template-based models	Mean-shift
				distance b/w estimated and actual	Multi-view models	SVM Tracker
Point-based	tracking small objects (single point tracking)	tracking small objects	Handling occlusion and appearance & re-appearance	Precision and recall based on generation of point trajectories	Deterministic	MGE Tracker
					Statistical	MHT filter



(a) (b) (c)

Fig. 1: Representation of different categories of trackers. a) contour-based b) kernel-based and c) point-based trackers from Yilmaz et al., (2006).

3 COMPARISON MATRICS

Construction sites have some unique characteristics, which should be considered when it comes to object tracking, because they affect the appearance of objects in the view of the cameras. The scale of construction sites, the congestion, the clutter, the variety of objects with high similarity in terms of color and shape, the illumination as well as the illumination variations and the existence of both rigid and non-rigid objects (e.g. equipment and workers) that enter and leave the site are the main characteristics of most construction sites. Therefore, to find the most suitable 2D tracking method, one needs to know how well each of these factors can be handled. To satisfy this, a list of metrics that are based on these characteristics is proposed here to evaluate and compare the 2D vision tracking methods presented previously. These metrics are based on the ability of the tracker to handle: 1) occlusions, 2) small objects, 3) objects of different types, 4) illumination variations; 5) absolute value of illumination, and also 6) processing time.

Occlusion refers to the state when an object is partially or fully blocked by itself or another object. In construction sites, there is constant movement of equipment,

materials and personnel. As a result, it is extremely important to select a method that can continue to track objects even in the presence of occlusions. Self-occlusion is a common problem of contour-based methods especially when tracking non-rigid objects. It should be noted that one way to handle and control occlusions is by picking the right position to install cameras. By installing the cameras in higher levels, it is possible to minimize complete occlusion of objects; partial occlusions can be handled well by some methods (e.g. kernel-based).

Small objects can be defined as distant objects that appear to be small in the view of the camera and also those that have smaller dimensions compared to other objects (e.g. hardhats vs. bulldozers). Construction sites vary in size and some objects appear to be very small in the view of camera. Also, some objects move away from the camera and become small in size. Therefore, it is important to select a method that can track small objects and also be able to handle changes in scale.

The types of objects in construction sites refer to their rigidity and non-rigidity of objects. Rigid objects (e.g. wheel loaders, backhoes, steel beams) do not make severe changes in their poses. Therefore, their appearances are adequately predictable. On the other, non-rigid objects (e.g. workers) change their poses dynamically. This makes their appearances in the subsequent frames unpredictable. In most construction related applications, there is no need to track the whole body of a worker. As a result, it is possible to overcome the difficulty of tracking non-rigid objects by tracking a rigid part of their belongings (e.g. hard hat).

Illumination variations are related to changes that occur in lighting conditions. Such variations can affect tracking results because they can significantly alter the appearance of objects in the view of the cameras. Illumination variations are common at open, large-scale and congested construction sites, where shadows and light reflections (from other equipment or adjacent buildings) are present. Therefore, the ability to handle illumination variations is an important factor to be considered.

The absolute value of illumination is another factor related to lighting conditions. Absence of light or presence of strong illumination can affect tracking results depending on how severe each case is. Working hours at construction sites can start from very early hours in the morning when it is still dark and go on until very late hours of the day. Also, construction site locations vary geographically from very illuminated sites at deserts to light reflecting sites by oceans. Therefore, it is important to select a tracker that can perform accurately at different light levels in different locations and during the course of a day.

Processing time can be defined as the amount of time it takes a tracker to process one image frame and send the results to the user. After receiving and processing video data, the tracker should be able to transfer the accurate information to the user in a specified amount of time. For instance, when tracking for safety management, after the tracker detects a short distance that could result in a collision between a bulldozer and a worker, it should warn the worker before the collision occurs. Different

applications have different requirements for 2D vision tracking methods' processing time and the tracker that has less response time than the requirement should be selected.

4 RESULTS AND COMPARISON

The performance of tracking categories was tested and evaluated based on the metrics discussed in the previous section. For comparison purposes, a kernel-based method was selected that uses the Bhattcharyya coefficient as similarity measure and the mean-shift algorithm to carry out the optimization based on a method presented by Comaniciu et al., 2003. Also, a variational framework was selected as a contour-based tracker. Rousan and Deriche (2002) used a Bayesian model to develop their variational method and the authors combined this framework with a knowledge-based segmentation algorithm presented by Haker et al. (2001). These methods were implemented and tests were performed using videos that were taken at construction sites.

Some frames from preliminary tracking test results are shown in Fig. 2 below. In the first row of images, the worker (non-rigid object) is being tracked using the contour-based method. This worker could be tracked for 10 frames until he was occluded by another worker and then the tracking failed. On the other hand, the result from the kernel-based method shows that this method could still track the worker in the equivalent frame and even the subsequent frames. In the second row of images in Fig. 2, a bulldozer that is moving away from the camera is being tracked. The results show that the contour-based method loses the target in frame 2500 while the kernel-based tracker keeps tracking for another 6000 frames (until the object comes to the camera). The last row of images shows the results of tracking of a backhoe's bucket. Complete deformation of the bucket in the view of the camera can be observed in these images. The results revealed that the kernel-based method could track the bucket for 723 frames while the contour-based lost it in frame 101. It should be noted that illumination varies in each frame and affects the appearance of the target in the view of the camera. Therefore, both methods can handle illumination variations to a good degree. The difference in the processing time of these methods was not that significant and as a result it is considered to be a neutral criterion for the purposes of this evaluation and comparison.

To evaluate the performance of tracking methods, it is possible to measure the accuracy of each method by calculating their precision and recall as mentioned in Table 1 in section 2.4 above. It is also possible to assess the performance of tracking methods based on the number of frames successfully tracked to obtain some preliminary results. The authors have closely watched the frames and recorded the number of frames the object can be tracked using each tracking method. A summary of this comparison is shown in Table 2 for each case and criterion.

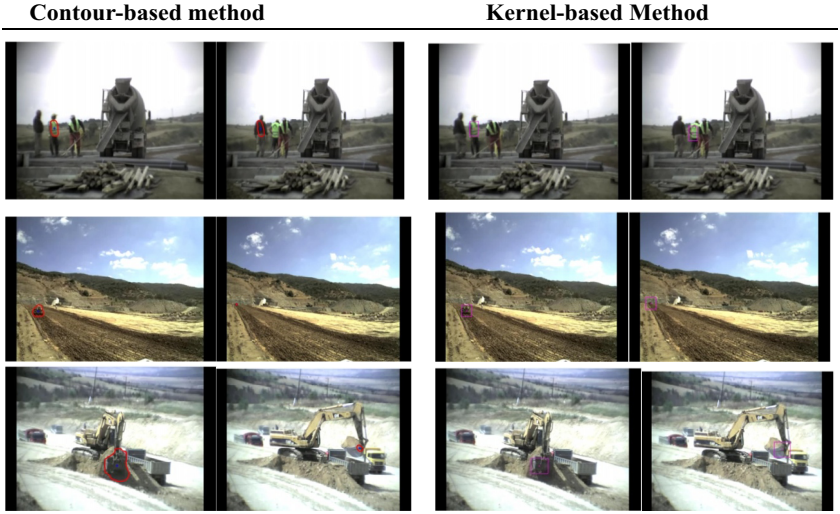


Fig. 2. Preliminary results of tracking in real construction sites.

Table 2. Number of frames successfully tracked.

	Kernel-based (Mean-shift)	**Contour-based (Variation method)**
Occlusion (e.g. worker shown in images a-d)	115	102
Small object and also scale variation (e.g. road roller shown in images e-h)	8564	2500
Object type and quick deformation (e.g. bucket of a backhoe shown in images i-l)	723	101
Illumination variation (e.g. bucket of a backhoe shown in images i-l)	723	101

5 CONCLUSION

Tracking objects in the construction sites is essential in many applications such as progress monitoring, activity sequence analysis, productivity measurements, locating resources, and safety management. These applications require the results of 3D vision tracking over time while calculating the depth information of objects (the 3rd dimension) depends on the results of 2D vision tracking. Selecting the best 2D vision tracking method for construction applications faces some challenges and difficulties. First of all, there are a number of 2D vision tracking methods with different capabilities and specifications. In addition, construction sites have unique tracking requirements, which must be considered in order to select a 2D tracking method that performs optimal under restrictions of construction sites.

This paper presented a systematic approach to compare different categories of 2D

vision tracking methods to find the most optimum one for 3D vision tracking purposes. The 2D vision tracking methods were first categorized and each was briefly described. The characteristics of construction sites that can interfere with the performance of these vision tracking methods were recognized and comparison metrics were set up based on them, to measure the performance of each category in relation with construction site requirements. One method from contour-based and another from kernel-based trackers was selected and implemented. A number of tests under different conditions of construction sites were performed to observe the performance of each tracking algorithm. The methods were compared based on the number of frames each tracker could successfully track. The preliminary results of this comparison revealed that kernel-based methods are more reliable between the two categories of trackers tested for construction related applications.

Future work will focus on measurement of accuracy of each method under each condition. Point-based methods will also be implemented, tested and compared with the results obtained in this study. Ultimately, the preferred 2D tracking method will be used to implement 3D vision tracking systems by employing epipolar geometry algorithm.

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A Decision Support System for Integrating Corrective Maintenance, Preventive Maintenance and Condition-based Maintenance

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Abstract

This paper presents a framework of decision support systems for facilities maintenance management (FMM) with the objective of integrating facilities maintenance management, real-time project management, condition monitoring systems and building information models. Multi-faceted views of maintainable assets are designed to meet the requirements of any potential functional extensions or systems integration. Basic processes for asset management, Corrective Maintenance (CM), Preventive Maintenance (PM), and Condition-based Maintenance (CBM) are implemented in a Web-based FMM prototype system. The generic aspects of the system lay in the fact that: 1) all sources of maintenance work, ranging from manually entered CM orders and system generated PM orders to individual maintenance projects, are normalized and manipulated as projects and tasks; 2) the allocation of various kinds of resources, including equipment, materials, trades, contractors, and tools, is optimized using the proposed algorithms.

1. Introduction

Every company is dependent on "facilities" (also called "assets" or "equipment") that keep the business in business – be it a computer, a centrifuge, or a megawatt transformer. For specific enterprises whose asset replacement cost or equipment failures contribute to a significant part of their operations, efficient facility maintenance management is a top management concern. Downtime in any network, manufacturing, or computing system ultimately results not only in high costs, but also in customer dissatisfaction and lower potential market share.

Facility maintenance is always a matter of equipment uptime and the cost to support that uptime (Hoke and Craig 2008). In a manufacturing organization, the role of facility maintenance is easily neglected since it is a subsidiary stream supporting the main-stream production events. However, facility management in the construction

industry has a higher expectation and it constitutes a separate element in FIATECH's Capital Projects Technology Roadmap (FIATECH 2009), in which "real-time facility and project management, coordination and control" provides a fully integrated facility planning and management system. Built facilities always require large capital investment and a relatively high maintenance and operation cost. Critical facilities like municipal infrastructures, power plants, and airports, have stricter demands on health and safety, a bigger impact on society, and much less tolerance for failures.

Based on the basic concepts of Corrective Maintenance (CM), Preventive Maintenance (PM), Condition-based Maintenance (CBM), and the philosophical relationships between them, this paper presents a framework of decision support systems for facility maintenance management (FMM-DSS). Integration issues and technologies are discussed for integrating the FMM system with real-time project management, condition monitoring systems and building information models. A prototype system for FMM-DSS has been developed using a number of leading edge Java and Web-based technologies and it will be presented at the end of the paper.

2. CM, PM and CBM

The essence of the "run-to-failure" **corrective maintenance** approach is to replace a part with a new part only when it is out of function. It is a traditional method for facility maintenance which is surprisingly, still popular in present. Failure happens in reality no matter how you want to avoid them; so an organization should always have CM processes in place as an emergency plan to handle unexpected failures. The downside is that it always implies facility downtime, low customer satisfaction and is not a programmable operation in terms of time and cost. However, depending on the criticality of facilities, and how we can accept the consequences of a failure, CM is the most economical solution among the three maintenance strategies.

Preventive maintenance involves the planning of periodical replacements of parts, scheduling at regular time intervals, independently of whether the component is still performing satisfactorily or not. PM introduces a way to facility maintenance operations that allows some sorts of controllability into the plate, including planning and scheduling of routine maintenance work of assets. Accompany with explicit definitions of maintenance intervals (frequencies), periodic maintenance jobs (for example, inspections, or routine replacements) can be pre-scheduled and budgeted. However, if the PM intervals are not fine-tuned with asset conditions, PM may lead to "deficient" or "superfluous" maintenance. Failures cannot be totally avoided in theory and in practice in that they might still happen between the intervals.

Condition-based maintenance rationalizes prevention, because the physical variables that determine the symptoms of a failure are monitored. CBM has proven capable of aiding facility managers in identifying anomalies early enough to minimize the impact of operational interruptions; avoid expensive failures, including collateral damage; and significantly reduce the cost of maintenance. Many leading companies in the manufacturing, process, paper, and power generating industries have shifted the majority of their maintenance tasks from time-based preventive to condition based. Other similar terms such as "predictive maintenance" and "pro-active maintenance" can be categorized to CBM since they all continuously monitor variables and make maintenance decisions based on the collected condition data.

Table 1 summarizes the pros and cons for the three maintenance strategies.

Table 1: Pros and cons of CM, PM and CBM

Corrective	**Preventive**	**Condition-based**
Run to failure	*Fix it routinely before it breaks.*	*Don't fix it if it is not going to break.*
+ Facility is not over maintained + No initial investment + Low costs – High risk of secondary failure – Unscheduled and possibly long downtime – High cost of spare parts – Overtime and labor arrangement – Safety hazardous	+ Maintenance is controlled + Fewer catastrophic disasters + Stored parts and cost can be controlled + Unexpected failures should be reduced – Facilities are maintained when there is no fault – Unscheduled breakdowns cannot be avoided	+ Unexpected failures are reduced + Parts are ordered when needed + Maintenance is performed when needed + Facility life is extended – High initial investment – Additional skill is required – High operation cost – Extra instruments need to be maintained

Notes: "+": pros; "-": cons

Although it sounds like the evolvement of facility maintenance management practices from CM to PM to CBM is an improvement process, the reality is that ALL three must co-exist within an organization. For example, as PM and CBM cannot screen out failures theoretically, an organization must have a formal procedure in place to handle emergent breakdowns and the subsequent consequences. Also because CBM is costly and requires high skill sets and advanced technologies, few organizations can afford CBM solutions on all assets.

Hosseini (2009) has a vision that maintenance departments should gradually transform to maintenance systems and he believes that the ultimate goal is to achieve "performance-oriented" systems that are integrated with "operation" and "support" systems. We advocate this "system" viewpoint in that an optimal facility maintenance program should be a balanced distribution of CM, PM and CBM that meets the organization's high level strategic business plans.

3. Related Work

A good number of commercial facility maintenance software tools are available on the market, which can largely be categorized into enterprise-scale asset management (EAM) and specialized computerized maintenance management systems (CMMS). The most famous EAM software is SAP Plant Maintenance (SAP 2009). The main catalyst for SAP PM's success lies in the fact that it is seamlessly integrated into the existing SAP ERP kingdom in both operating and financial aspects. The selling point of CMMS systems (for example, MAXIMO 2009) is their essence and user-friendly features that are specific to the facility maintenance management domain.

In order to somehow standardize the methodology and processes toward CBM, an early effort by Hassanain et al. (2003) proposed a comprehensive framework model to formalize and standardize the business processes of asset maintenance management in which asset management is divided into five major processes: 1) identify assets; 2) identify performance requirements; 3) asset performance; 4) plan performance; 5) manage maintenance operations. The MIMOSA's up-to-date Open Systems

Architecture for Condition-Based Maintenance (MIMOSA 2009) specifies a standard architecture and framework with seven layers (namely, data acquisition, data manipulation, signal processing, condition monitoring, health assessment, prognostic, and decision support) for implementing condition-based maintenance systems. .

In past decades, CBM technologies have been successfully applied to manufacturing, construction, chemical, power, and process industries. A large volume of academic research work has been done in the area of CBM on a variety of topics. Based on the literature review, we noticed that the developed CBM systems are usually separate modules for condition assessment (Zhang et al. 2006; Luan et al. 2006), risk analysis (Narasimhan 2008), wireless and mobile sensing (Emmanouilidis et al. 2009; Sun 2009) of specific facilities or components, for example, diesel generation units (Luan et al. 2006), power distribution (Pathak et al. 2007), and aircraft (Narayanamurthy and Arora 2008). Very little effort has been made to integrate practical asset management and CBM systems in a general purpose. Our goal of FMM research is to build a fully integrated decision support system at both strategic and operational managerial levels that provides full-scale optimization for a balanced blending of maintenance strategies. The resultant system also aims to facilitate the integration of the FMM system with other AEC/FM elements in FIATECH through building information models (BIM) and process technologies.

4. An Integrated Decision Support Framework for FMM

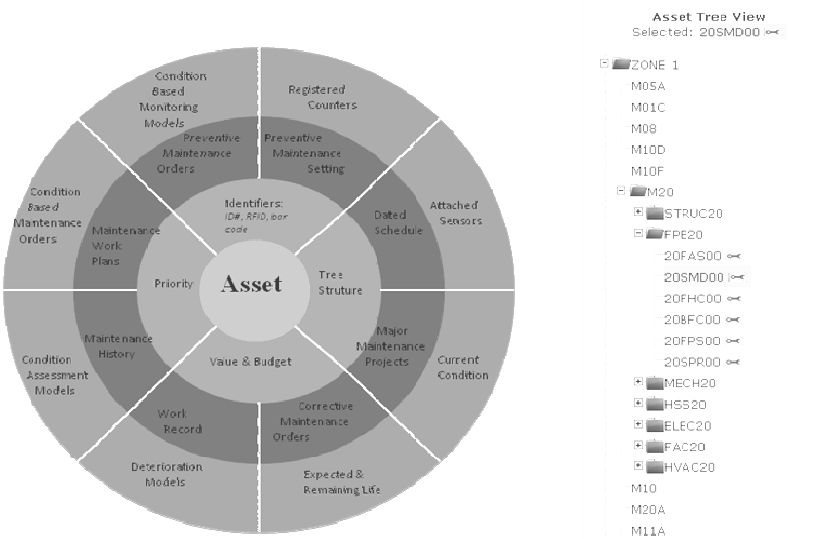


Figure 1: Asset information wheel and the tree structure

We propose a general decision support framework for facility maintenance management (FMM-DSS), in which information and business processes are all centered upon an entity - "asset". The term asset is equivalent to "facility" or

"equipment" in other systems. Figure 1 gives an overview of the general concept of an asset that contains information at three layers.

1) Basic information

The most important item in the basic information is the identification. Apart from the unique ID# that is referred to by the FMM system, an asset has other ways to distinguish itself in various environments; for example, RFID, bar code, and the GUID in BIM models. "Parent-children (1:n)" relationship is used to describe a tree structure and multiple roots are allowed in the hierarchy. In an asset tree, we distinguish two types of entities: "maintainable" and "functional" assets. The "functional assets" can be organized at different layers to group assets into sub-systems or physical maintainable assets; it is equal to the concept of "functional locations" in other EAM or CMMS systems.

2) Maintenance information

Maintenance information is a set of data that defines the rules for maintenance as well as the planned, pending, and past maintenance orders (MO). Regarding the three types of maintenance strategies, we distinguish three types of MOs - CMO, PMO and CbMO. Each maintainable asset can have multiple pre-defined rules/options (called "PM setting") for carrying out its preventive maintenance activities. A PM setting contains the following information:

- Temporal type: periodic or scheduled
- Work type: inspection, minor repair, major repair or replacement
- Work content (trade or skill, e.g., plumbing)
- Cyclic intervals: time-based and/or counter-based
- Shifting flexibility
- Default start time
- Duration and cost
- Project template
- Resource requirements (equipment, trades, materials, tools, contractors)

3) Life cycle condition-based information and models

The information and processes at this level are focused on "condition" as to record and assess the current and future condition of an asset. With deterioration models and condition assessment models in place, life-cycle condition information can be calculated based on real-time data collected from condition monitoring systems and the planned and past maintenance data. This level of information or models can be an integral part of FMM-DSS or more likely, reside in other distributed systems and integrate with the FMM-DSS using integration techniques (Section 5).

Since preventive maintenance is so far the only one of the three maintenance strategies that is programmable and controllable, the processes related to PM are the easiest to standardize and implement. Commercial EAM or CMMS packages already set good PM practices and they are comparable in PM capabilities. The general PM planning process we developed can be divided into six major steps, as shown in Figure 2.

Among all assets defined, the preventive maintenance planning only calculates maintenance work due in the next planning cycle for "maintainable assets" according to their pre-defined PM settings. The PMOs are generated by either resuming a brand new maintenance cycle or adding cyclic intervals to the last maintenance order in the

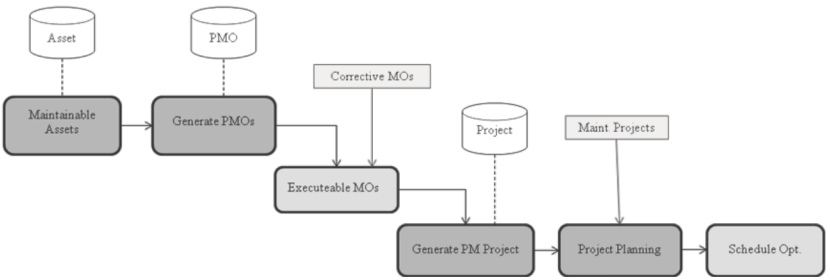


Figure 2: Preventive maintenance planning process

past planning cycle. The "executable MO" and "Schedule Opt." are two major decision points where decision supports are very much required. The objective of selecting executable MOs is to find an optimal collection of PMOs for the next PM planning cycle, based on priority, condition, remaining life, deterioration trend, and life-cycle cost leveling against a limited maintenance and operating budget base. The purpose of schedule optimization at the operational level is to maximize the performance and productivity of an organization through optimizing the daily production and maintenance activities. Multiple objectives can be considered, for example, the greatest resource utilization, lowest cost, and shortest makespan. In Figure 2, the CM and CBM processes are smoothly merged into the main FMM planning flow. Corrective MOs, entered manually by the user directly, become directly executable in the system because the decision of whether it needs to be done is already made. The same decision applies to the CbMOs generated by condition monitoring systems.

In CMMS, "task list" function is provided to group maintenance tasks, but actually it is just a simple checklist-style reminder which cannot handle complex relationships nor consolidate external resource constraints required by the industry. To settle this dilemma, we combine the PM planning and project planning in the FMM-DSS framework, which treats them equally as "projects". Treating all MOs as projects provides a good unification for maintenance orders and maintenance projects, which is one of the most distinguishing features of our framework. Complex relationships and constraints can therefore be defined on tasks and project scheduling techniques can easily be applied to resolve complex problems. We have completed significant R&D work in project management and project scheduling for aircraft periodical maintenance management in a past project (Hao et al. 2009a; 2009b).

5. Integrating FMM with Condition Monitoring Systems and BIM

Condition Monitoring (CM) is a maintenance process where the condition of equipment is monitored for early signs of impending failure. Equipment can be monitored using sophisticated instrumentation such as vibration analysis equipment or the human senses. Where instrumentation is used thresholds can be imposed to trigger condition-based maintenance activity. In reality, the scope CBM is largely dependent on requirements from specific facilities and specific industries; there is no standardized condition monitoring hardware and software tools that can consolidate all kinds of needs from different CBM models. Also, even the choice of performance

indicators, theoretical modeling and algorithms are customized to the maintained assets. For these reasons, the condition monitoring systems are better to exist as stand-alone systems rather than native modules in the FMM-DSS framework. The integration of FMM-DSS with condition monitoring systems may happen at any of the top five layers in the OSA-CBM model (MIMOSA 2009) depending on the scope of the specific condition monitoring systems. If the generation of CbMOs is taken as the final output, the latest integration point would be the "executable MOs" in Figure 2. Another aspect that condition monitoring can contribute to the FMM is to assist with deciding the optimal PM strategies or settings. Traditional preventive maintenance practice is implemented through the fixed calendar-based maintenance intervals. How to determine these intervals is a pure experience-based exercise; and once decided, they are never changed. However, with dynamic condition information, one can reasonably envisage that the PM activities can be carried out smartly, in varied intervals, based on the condition of the actual facility. Sun et al. (2008) believed that the optimal PM interval is dependent on the total expected cost index, PM performance and types of PM strategies.

Building information models (BIM) provide a 3D representation of a building and contain database storage mechanisms for properties about all of the elements of the building. When one believes that BIM is a catalyst propelling the AEC industry through its biggest evolution since the introduction of the personal computer, it is hard to imagine that facility management in the 21st century will remain the same (Valentine and Zyskowski 2009). The benefits that BIM can bring to FM include:

- 3D visualization. Using the geometry information embedded in BIM's 3D models, the FMM can easily present facilities relative to their residing environment. The visualization can be very useful in designing and verifying space changes, facility movements, and renovation projects. Also linking with RFID, sensing and tracking systems, visualization would be useful in the locating and tracking of movable facilities, as well as the movement of maintenance work resources, such as materials, equipment, and people.
- Exchange of information between FMM and other up-stream systems. For facilities maintenance information other than 3D models, none of the other systems would have a better knowledge than a FMM system. Therefore, when considering what kind of interaction will be needed for integrating FMM and BIM, firstly, we need to think of what information will benefit FMM from up-stream processes and reversely, what information other processes might utilize if FMM data is available.

Most of the existing work for integrating BIM and FMM suggests a totally centralized BIM solution for facility management, where BIM provides a simple, centralized facility management data solution in one relational database (Motamedi and Hammad 2009). In contrast, we rely on a different loosely-coupled integration approach such as Web services and agents for integrating FMM, BIM and other systems along the AEC/FM processes. Please refer to our previous publication (Shen et al. 2009) for a comprehensive review of systems integration and collaboration technologies in AEC/FM.

6. Implementing the FMM Using the MVC Architecture

A prototype of the proposed FMM-DSS framework is developed as a pure Web-based application based on the popular Model–View–Controller (MVC) design pattern to maximize the modifiability, extensibility, and reusability of the code. Struts 2.0 framework (Apache 2009) was adopted for the MVC implementation. Other leading edge Java and Web-based technologies used in the development were: *Java EE, JSP, Tomcat, MySQL, Hibernate*, *jQuery*, *AJAX*, and *Yahoo!UI*, to name a few.

Asset management constitutes an asset browser showing an asset tree on the left and a tabbed view on the right. Each tab is implemented as a separate *JSP* page for populating the corresponding aspect of asset information on the screen. The asset management user interface with asset "ASPM-> ZONE1->M20->ELEC20->20DIE02" and the "Plan" tab opened is shown in Figure 3.

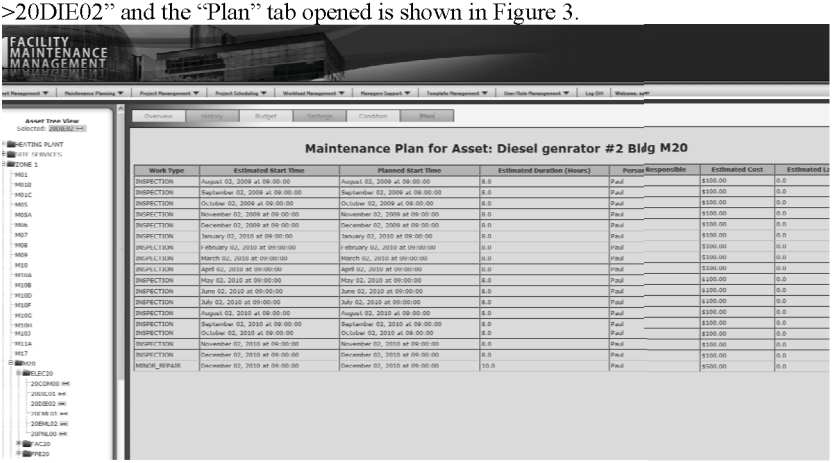
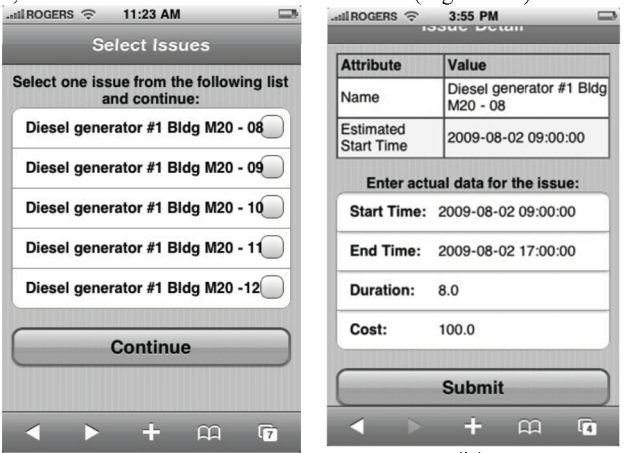


Figure 3: User interface – asset browser

Both corrective and preventive maintenance processes are implemented in the FMM-DSS system. The PM planning is executed for a given year and the strategic decision for prioritizing maintenance activities is currently implemented as a manual selection process. Research of optimization models at this layer is one objective of our future work. The optimization of maintenance activities at the operation level is done through a Workload analysis module. This module is designed to analyze and balance the resource workload (i.e., materials, tools, equipment, craftspeople, and contractors) for all maintenance activities in a given time period. The developed meta-heuristic based optimization algorithm (Zhu et al. 2010) can perform conflict detection, schedule coordination, schedule repair, and schedule optimization.

A set of user interfaces is developed for the iPhone's Safari using iUI (2009) to enter actual information for maintenance orders at the job site. When a user accesses the system's website through an iPhone, the system can automatically recognize the device and display a specific set of iPhone pages from the correct server directory. After a user is logged in, a to-do list of MOs assigned to this person's work trades are shown on the touch screen (Figure 4-a). After the user selects a maintenance item

from the list, he/she can then view the detailed description of the work and after the work is done, enter the actual information of the work (Figure 4-b).



(a) (b)

Figure 4: User interface – iPhone – work list, work details and actual work recording

7. Conclusion

Based on the basic concepts of the three facility maintenance strategies, CM, PM, CBM, this paper presents a decision support framework for facility maintenance management (FMM-DSS) that aims at integrating facilities maintenance management, real-time project management, condition monitoring systems, and BIM. Multi-faceted views of assets are designed to meet the requirements of potential functional extensions and systems integration. Meanwhile, preventive maintenance orders and maintenance projects are unified in the FMM-DSS where they are equally treated as "projects". This feature allows complex relationships and constraints to be defined on or between activities within a maintenance order.

Loosely coupled integration technologies such as Web services and agents are preferable for gluing FMM, BIM, and condition monitoring systems together. Using a number of leading edge Java and Web-based technologies, a prototype FMM-DSS system has been developed for asset management, preventive maintenance planning, maintenance order management and workload analysis.

Our future work on FMM-DSS will be focused on research and development of decision support models for CBM related processes as well as the strategic prioritizing of maintenance activities that accommodate operational data deducted from condition monitoring, condition assessment and prediction models. The integration of the FMM prototype with other application systems using Web services technologies is another topic that we are currently undertaking to investigate the integration framework for asset life-cycle maintenance and management.

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A GIS Framework for Construction Equipment Request and Deployment During Emergency Response

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Abstract
Efficient request and deployment of resources such as construction equipment is vital to urban search and rescue operations during emergency response. Based on the lessons learned in recent disasters, collecting, prioritizing and distributing of resources are urgent to life-saving operations. Construction equipment is required for shoring of structures, selective debris removal, and lifting of heavy building components. Infrastructure restoration, such as the transportation network, also needs construction equipment to support its operations to bring back services to facilitate disaster response efforts. A Geographic Information System (GIS) framework is presented to expedite equipment management. Within the framework, automation of data collection, transfer and processing for fast decision-making via computer networks, geospatial services and mobile devices is proposed. With the framework deployed, lifesaving operations are expected to have better performance provided with the appropriate equipment.

INTRODUCTION

Distribution of resources, such as heavy construction equipment, is critical to efficient and effective urban search and rescue (US&R) operations during disaster response. On September 11, 2001, the 9/11 terrorist attacks killed 2,819 innocent people, injured more than 6,290, and caused over $105 billion of economic loss (NYM, 2009). Supply of highly demand equipment was insufficient during the disaster response phase, challenging the ability of first responders (Gasiorek-Nelson, 2002). On May 12, 2008, a magnitude 7.9 earthquake struck Sichuan, China. Disaster response operations such as civilian search and rescue missions were hampered due to massive demand not being fulfilled by insufficient amount of equipment (MSNBC, 2008). Without appropriate construction equipment, first responders were forced to

dig for survivors with their bare hands (MSNBC, 2008). The earthquake caused over 69,197 deaths, left 18,222 people missing, and injured 374,176 people (China View, 2008). During disaster response, it is imperative to have efficient and effective equipment distribution to facilitate lifesaving operations (Sullum et al., 2005).

Management of geographically distributed resources has been recognized as one of the most important but challenging tasks in disasters (SBC, 2006; 9/11 Commission Report, 2004). Challenges include identification, assignment and delivery of resources. For example, after 9/11, the authorities were not fully aware of available resources and their deployment. As a result, resources were distributed inefficiently, which compromised the response operations. In order for disaster response efforts to be more effective, resource distribution challenges must be addressed.

Distribution of resources during disasters has been characterized by various shortcomings that inhibit efficient and effective decision-making (NRC, 1999). These decision-making challenges range from prioritization of limited resources and vehicle route selection, to resource location tracking (SBC, 2006; 9/11 Commission Report, 2004). Supply of resources, such as construction equipment (which supports shoring up damaged buildings and selective debris removal in a disaster zone), is usually unable to meet the demand in large-scale disasters. This could lead to additional damage within the disaster zone (Gentes, 2006; Bissell et al., 2004). "***Throughout the government, nothing has been harder for officials than to set priorities, making hard choices in allocating limited resources***" (9/11 Commission Report, 2004). Efficient prioritization and distribution of resources is critical in maximizing the effectiveness of the disaster response efforts.

CURRENT LITERATURE

Without successful resource distribution, disaster response activities including US&R may not be carried out efficiently and effectively. The following sections lay out the challenges within current practice and the available technologies to address these important issues.

Challenges in Current Practice

Challenges relate to resource distribution identified in disaster response operations include: deficiency of command and control, lack of spatial information and services, limited situational awareness, insufficient transportation planning, deficient information interoperability, and lack of resources tracking. Requirements that may improve current resource distribution operations can be derived thorough understanding of these challenges.

Access to heavy equipment is critical to disaster response operations (Gentes, 2006; SBC, 2006; Kevany, 2005; Bissell et al., 2004). Heavy equipment is a necessity during operations such as 1) rapid debris clearance of the transportation network so that first response teams can reach blocked hazard zones, 2) careful lifting of damaged structural elements in conditions when human power is not sufficient, and 3) selected debris removal to clear structural materials which facilitates void space searches and tunneling under collapsed buildings (ELANSO, 2009). However, in major disasters the social infrastructure is not always able to provide immediate supply of heavy construction equipment to support disaster response operations (Gill, 2007; Fessler, 2006). The delay in rescue operations could result to more casualties

(Bissell et al., 2004). Heavy equipment, which supports critical lifesaving activities, should be efficiently located, assigned and distributed to meet the urgent demands of critical disaster response operations.

Vehicle route selections are inefficient due to lack of traffic information. After disasters, condition of the transportation network is highly unpredictable: blockages, such as road debris, bridge collapse, and hazardous zones influence traffic conditions (Kwan and Lee, 2005). As a result, response resources may reach to the disaster zone with great delay. As time is considered the most important factor in terms of lifesaving during disasters, delay of response time could lead to unnecessary casualties (Gill, 2007). Therefore, traffic conditions should be updated in real-time and taken into account for decisions such as safest route selection and shortest traveling time for efficient resource deployment.

Cohesive inter-organization collaboration is needed for effective disaster response. Resources owned by each jurisdiction need to be visible and available to the incident command. Due to lack of command and control during a major disaster, the coordination of resources across different organizations is extremely challenging (Gill 2007; Meeds, 2006). During Hurricane Katrina, between the logistics management systems of the state and federal government, there did not exist an electronic interface for communication and coordination. Resource requests from the state level to the federal level were input by hand. With no tracking mechanism in place, the state was unable to follow up on resource requests, resulting in significant time delays (Holguin-Veras et al., 2007). An electronic interface, supporting collaboration among different jurisdictions, should be established to reduce time delay in disaster response.

Available Technologies

Vast amounts of research related to disaster management are potentially adaptable to address challenges of effective disaster resource distribution. This research focuses on heavy construction equipment distribution during disaster response operations and will seek to integrate the following technologies:

GIS is an essential tool for mapping locations, visualizing dynamic conditions, and making decisions in disasters (Kataoka, 2007). Geospatial data and tools are useful in response to disasters; Real-time data fusion and analysis can be achieved through GIS during the response phase for fast decision-making. A significant quantity of research has been conducted in GIS that focused on areas such as shortest path analysis (Han et al., 2007; Kwan and Lee 2005; Tsai 2002), data visualization (Cutter, 2003; Pundt and Brinkkötter-Runde, 2000), and risk management (Elnashai et al., 2008; Zerger and Smith, 2003). However, GIS for emergency management with rapid capability and access of data and tools that work under difficult circumstances of US&R have rarely been addressed (NRC, 2007).

Radio Frequency Identification (RFID) and Global Positioning Systems (GPS) are popular technologies for location tracking of resources. GPS has been widely deployed for vehicle tracking (Guan et al., 2008; Lu et al., 2007), while RFID products have been broadly applied to warehouse inventory (Oh and Park, 2008; Zeng et al., 2008). GPS and RFID could provide important location information of available resources to emergency management agencies (EMAs). As a result, decision-makers could have better visibility and control of the overall logistics

distribution such as construction equipment deployed for disaster response. However, full potential of these technologies has not yet been reached. For example, tracking of logistics was unsatisfactory during Hurricane Katrina; the Federal Emergency Management Agency was not able to keep track of their assets (SBC, 2006).

Decision models have been formulated (El-Anwar et al., 2008; Elnashai et al., 2008; Kung et al., 2008), along with research conducted in supply chain and logistics (Balcik et al., 2008; Lodree Jr. and Taskin, 2008; Ozdamar and Yi, 2008). The objectives of those models include logistics distribution with multiple resource types and quantities, facility and target locations with special conditions, and vehicle capacity issues for split deliveries. These models are formulated so that decision-makers and first responders can best utilize available information and assets for effective disaster responses. The efficiency of solving these models affects the response time, while the accuracy of real-time input data affects the correctness of the output decisions. Proper graphical visualization is needed to convey and represent the analyzed information to decision-makers and first responders. However, automation of decision-making is yet not deployed in disasters response (Suchyta et al., 2006).

To efficiently solve decision models, exploration of robust natural systems that have been recognized with well-organized systematic behavior, is expected to contribute to this research. Decision models based on entomology produces fast collective decision-making (Seeley and Visscher, 2004). In the selection of a new hive for example, the self-organization capability of a honeybee colony is highly efficient and effective. The scout bees leave the hive to search for profitable alternative locations for their hive. When bees return, each scout enters the dance floor inside the hive to pass on information of a potential new hive and recruit others to support the selection of that potential location. A “more profitable location” dance will be propagated throughout the dance floor. Eventually, a majority of bees will converge to the “best” dance (i.e., the most profitable location). Thus, the dance is completed with the whole colony agreeing on the new hive (Seeley et al., 1991). A distributed model that showed great potential for decision-making in complex and dynamic contexts based on the behavior of honeybees’ foraging is proposed for disasters (Aldunate et al., 2005). Such entomology-based models will be explored and are envisioned to be adopted to facilitate critical decision-making such as equipment prioritization and distribution during disasters.

Various types of resources are required for Urban Search and Rescue (US&R) operations while conditions of the transportation networks are highly unpredictable. These challenges make resource distribution problems complex. Traveling Salesmen Problems (TSPs) are transportation planning problems for resource distribution. Ant colony optimization (ACO) algorithms have been discovered and used to solve TSPs (Blum, 2005; Dorigo and Stützle, 2004). Disaster resource distribution problems are envisioned to be formulated into TSPs with special characteristics, such as split delivery, dynamic depot locations, limited truck capacities, equipment and technician matching, and demand prioritization. ACO can be run continuously and adapt changes in real-time to produce close to favorable solutions. This is of interest in the proposed research due to the dynamic and chaotic characteristics of disasters. Research on ACO algorithm for solving logistics problems in disaster relief

operations has been proposed (Han et al., 2007; Yi and Kumar, 2007). Yi and Kumar (2007) use a meta-heuristic of ACO algorithm for distribution of multiple types of resources. Different types of transportation tools are selected and the capacity of different type of vehicles is incorporated in their model. While this model is considered valuable to the proposed goal, some shortcomings were not addressed in the original work. Decision to set priority of demand was not determined in real-time, traffic conditions were not monitored in real-time, and delivered resources were not tracked for further deployment. Han et al. (2007) use an ACO algorithm to solve shortest path problems in firefighting operations considering traffic conditions. However, incident response prioritization is not considered and road conditions are not real-time updated. The aforementioned research will serve as the base of knowledge for decision-models for equipment distribution in disasters.

In the previous sections, challenges in current resource distribution operations and available technologies have been discussed. Existing systems such as HELIOS (Fritz, 2008) and IRIS (FEMA, 2008) have been developed for supply chain management. However, resource tracking technologies and resource distribution decisions are not adequately considered. Although they serve as a centralized logistics request medium, real-time disaster data collection and information visualizations are not currently complete. Therefore, this makes critical decision-making difficult. Challenges described in the previous sections revealed that a cohesive framework for data collection, analysis, and visualization is necessary for an efficient and effective construction equipment distribution during disaster response.

APPROACH

Responders with better situational awareness —of the impact caused by disasters, where critical resources are, and locations of potential infrastructure damages— are able to respond more efficiently to lifesaving tasks (NRC 2007). An infrastructure for information sharing and decision-making to increase the performance of resource distribution operations is of great importance. As a result, a collaborative framework automating construction equipment distribution is expected to greatly improve current first response activities in disasters. The goal of this paper is to establish such a framework to expedite the process of resource request and deployment. Resources that are taken under consideration include professional personnel and construction equipment, which can be generalized to other types of resources.

The architecture of the framework is shown in Figure 1. The following discusses the three layers the framework is composed of: a front-end layer (data collection and visualization), a middleware layer (communication medium for information dissemination), and a back-end layer (data management and decision-making) for construction equipment distribution.

Front-end: The front-end provides a flexible and general interface for the framework to support future integration with IT plug-ins such as 1) automated inventory, 2) deployed resource tracking, 3) traffic condition monitoring, and 4) on-field resource request and their data transmission. The formalization of the front-end facilitates data acquisition to be further analyzed by decision-models in the back-end. Geospatial equipment inventory based on the MapServer with PostgreSQL database (Peña-Mora et al., 2009) and a mobile client for equipment request implemented in C# (Chen and

Peña-Mora, 2009) currently serve as the source of data input. Once more system components for data acquisition is integrated through this layer, decision-makers and logistics managers can easily and efficiently locate professional personnel and construction equipment, monitor traffic conditions, keep track of deployed equipment, and receive on-site equipment requests for rescue operations.



Figure 1 Five-tier Architecture

Middleware: The middleware provides a level of abstraction so that the layers above and below need not be fixed to a particular communication medium. The communication medium selected will be treated no differently from the upper and lower layers as a result of this level of abstraction. The communication medium is interchangeable to suit the condition at the moment. For example, with the absent of infrastructure based communication, the mobile ad hoc network (Aldunate et al., 2006) will be chosen. The abstraction is still under development and different policies to determine what network to use in different scenarios will be tested. In addition, communication medium with information policies (Kostoulas et al., 2008) such as priority, trustworthiness, and security are envisioned to advance communication for first responders. This layer provides a foundation for digital communication to the collaborative resource distribution framework.

Back-end: The back-end is composed of 3 sub-layers: a *spatial data and service fusion layer*, a *decision support core*, and a *visualization and interaction platform* to support efficient and effective disaster response. *The spatial data and service fusion layer* serves as a façade to separate the *middleware* and *decision support core* and processes input data in the desired format for flexible communication. Decision models, such as fastest and safest route selection and equipment prioritization, reside in the *decision support core*. Complex decisions that involve various parameters are to be made in disaster scenarios. However, these decisions are often too complex to be solved by computers in a satisfactory amount of time. As a result, special formulations for such decisions are to be investigated to meet requirements such as running time, accuracy, and other policies. A distributed decision-making model inspired by honeybees' foraging behavior has been formulated and studied (Aldunate et al., 2005). The honeybees' decentralized learning is envisioned to be formed as an efficient heuristic, to expedite the operation of equipment deployment.

The *visualization and interaction platform* provides decision-makers and first responders with 1) better situational awareness of the disaster and 2) better communication medium to convey information and ideas to others. Through GIS, geospatial operations can be efficiently conducted for fast visualization to support decision-making and effectively communicate with various stakeholders involved in the response operations. For example, a GIS system implemented in C# with ESRI's ArcGIS Engine and a MySQL database is in place for transportation planning in disaster response (Chen and Peña-Mora, 2009). It has a graphical representation embedded for the spatial information. Decisions suggested by the *decision support core* can also be showed graphically to decision makers through this visualization environment. Thus, decisions can be made more efficiently and effectively with a better vision of the overall picture with more stakeholders involved. Information can also be propagated to the *front-end* and shown to first responders through the *communication medium layer* to PDAs for better situational awareness.

With this framework, decision-making such as equipment distribution during disaster response is more efficient. First responders use PDAs to request resources on-site. Through the *communication medium layer*, decision models take the input data and suggest analyzed decisions to decision-makers through the visualization component. Final decisions will be sent to the equipment for deployment. As a result, an automated process for equipment request and deployment for disaster response.

CONTRIBUTION AND FUTURE WORK

A flexible framework is presented in this paper for further integration with existing IT components. Various type of information can be plugged into the framework to facilitate automated decision-making. Once integrated, time overhead for data transmission, input, and output will be reduced. Information can be shown to decision-makers and first responders more comprehensively. This results in better decision-making and situational awareness, which further leads to more effective disaster responses. Future work will be directed towards further integration of systems into the framework and testing. Brian Brauer, Stuart Foltz, and Scott Nacheman, field experts in disaster response operations, will provide practical insights based on their expertise and experience in response to the 9/11 terrorist

attacks, Hurricane Katrina and Rita. Through collaboration with these first response exports, testing of the framework will refine and shape the framework to become deployable in disaster response scenarios. In addition, efficient decision models are to be formed and integrated to support critical decision-making.

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Visually Scheduling Construction Projects

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Abstract
This paper presents a simple, flexible and intuitive approach for activity sequencing and project scheduling. Several construction scheduling professionals were consulted during development of this approach. The most important attribute desired by the industry professionals was flexibility to rapidly revise activity definitions and relationships allowing fast schedule modifications and what-if analysis. Considering the needs and suggestions of construction industry professionals and using the latest visualization technology, a graphics application was developed using Microsoft DirectX Graphics Library. The application interfaces with Revit CAD software to extract a building project's geometry and material information which is then used to create a virtual prototype of the project. Users can walk inside the virtual building for visualization of the project and sequencing project activities by selecting tasks and predecessors. The application interfaces with MS Project and provides an intuitive and flexible method to digitally transfer activity information to the schedule. The visual approach presented in this paper attempts to increase scheduling efficiency by incorporating the findings of modern cognitive theories that suggest human brain interacts more effectively with 3D virtual worlds than a long list of project activities and textual content.

Introduction and Background

Project schedules are the primary tools for communicating the thinking and planning by the management team to all the stakeholders in a construction project. Any advances in project scheduling technology can result in substantial improvements in management efficiency and more wide-spread application of scheduling in construction projects. Sequencing of construction activities is done by reviewing 2D CAD drawings, compiling a long list of construction activities and visualizing the logic mentally which causes heavy cognitive load on a scheduler's memory and

reduces efficiency. It requires special skills and experience to read 2D drawings and relate it to the schedule. Such schedules force planners to visualize and interpret the activity sequence in their minds. Also, some planners will have different interpretations of the same schedule, which makes it difficult to communicate and discuss whether a certain problem actually existed or not (Wang 2007). This miscommunication causes schedule delays and results in monetary losses. Thus there is a need of systems which provide visualization at early planning phase and communicate same idea to all the stake holders.

Construction project scheduling involves choosing a set of actions, arranged chronologically, that will achieve some given goals (Navinchandra, Sriram, Logcher 1988). Traditional network based tools employing critical path methods (CPM) and project evaluation and review techniques (PERT) algorithms can help in analyzing a plan, not in generating it. The definition of activities and their predecessors must be provided to such systems by a human planner (Kartam and Levitt 1990). One of the crucial problems faced when generating a construction schedule is to produce an adequate sequencing of activities involved (Echeverry, Ibbs, Kim 1991).

The scheduling process involves a number of steps including: (1) breaking the project down into a number of activities and estimating activity durations, (2) transferring activity information to scheduling software, (3) developing project logic or the sequence that activities will be carried out during construction and (4) scheduling project activities. The new 3D CAD software and scheduling programs have substantially reduced the time and efforts necessary for performing steps 2 and 4 in the scheduling process. However, step 3 or project logic development is still a tedious process that involves sorting and organizing a long list of project activities. During the past two decades a considerable amount of research has been conducted in activity sequencing and construction project scheduling. Various systems have been developed by researches to computerize the process of sequencing and project scheduling. These systems have migrated from the early AI planning systems to knowledge-based planning systems and ultimately to model based planning systems (F.B. Alami, J.C. Kunz, M. Fisher, 1998).

Construction Planex developed by Hendrickson, Gorostiza, Rehak, Miller and Lim (1987) was a frame-based hierarchical system for scheduling construction projects. Navinchandra, Sriram and Logcher developed a program for Generation of Hierarchical networks for construction (GHOST, 1988). Their methodology generates or modifies the topology of construction activity networks. It starts with a general network and subdivides it into sub activities. N.A. Kartam and R.E. Levitt (1990) studied intelligent planning of construction projects (SIPE) and proposed sequencing to be done based on common principles or constraints such as “supported by” or “enclosed in”. Their approach relies on structural support and generates a network. Echeverry, Ibbs and Kim (1991) proposed formalization of sequencing knowledge for construction scheduling by developing a knowledge-based prototype system. Cherneff, Logcher and Sriram (1990) developed BUILDER which integrates CAD with construction schedule generation. It consists of two main knowledge modules

(KMs) first "Draw" for creating and interpreting architectural floor plans and "Planner" for producing construction schedule.

It is common knowledge that no two schedulers develop the same schedule for the same project since each of them makes different assumptions, selects different construction methods and represents the schedule at different levels of details (Fisher, Aalami 1996). A rule-driven approach or constraint-based schedule logic may not be flexible enough to accommodate every scheduler's style.

Researchers at the Center of Integrated Facility Engineering at Stanford University have carried out a considerable amount of research for automating sequencing of construction activities and developing knowledge-based environments for scheduling. Fischer and Aalami (1995) demonstrated scheduling with computer interpretable construction method models. The feasibility study of 4D in commercial construction by Koo and Fisher in 1999 showed that 4D modeling helps in analyses concerning cost, productivity, safety and resource allocation. It is also helpful in the integration and collaboration among project team members and supports early detection of problems. 4D visualization systems require a project schedule before they can produce a graphical simulation of the project's construction process. It is a tool which facilitates effective visualization but it does not make scheduling easier nor reduces the work involved when manually entering project tasks. Planners mostly use 4D visualization tools as a means of visualizing and comparing, rather than implementing different decision alternative (Waly, et.al, 2002).

The graphical application developed in this study is named Visual Scheduling Application (VSA) and provides a visual, interactive and flexible approach to construction project scheduling. VSA allows visualization of the project at an early planning stage and accommodates scheduling style of every scheduler. Construction scheduling experts were involved during requirement analysis and development phases of VSA. According to the industry professionals consulted, the most important attribute in a sequencing-scheduling application is flexibility to rapidly revise activity definitions and relationships. This would accommodate various scheduling styles and simplifies schedule modifications and what-if analysis. They suggested an approach that minimizes manual data entry by digitally transferring information from a building model to a scheduling program allowing them more time for critical thinking and evaluation of alternative solutions.

In VSA, information extracted from a building's Revit CAD file is used to create a 3D virtual model of the building. Using a first-person camera, the scheduler can navigate the virtual building and select a building element or a group of elements by pointing to the elements. A selected building element or group of elements may be designated as an activity or an activity predecessor. The selected information can then be digitally transferred to a scheduling program. According to the modern cognitive theories, visual approaches reduce memory load. This means developing project logic while walking inside the virtual prototype of the project exerts less stress on

scheduler's memory than working with a long list of activities that requires building a mental image of the project.

Visual Scheduling Application Architecture

VSA is developed for two-way communication between Revit Architecture 2009 for model information extraction, Microsoft Project for schedule preparation and a database for project information storage. The VSA application and its components are shown in Figure 1 and are discussed in the following sections. VSA interacts with Revit for extracting project geometry and element material information. The extracted information is saved in a database. Using the extracted information and Microsoft DirectX graphics library a virtual prototype of the project is created (Van Verth, Bishop 2004). This allows users to interact with the virtual environment by navigating inside and around the 3D model. Input Devices facilitate navigation and interaction with the 3D model once it has been created by the graphics engine. The common input devices used for interactive visualization are keyboard, mouse, game pads and gloves which facilitate navigation in the 3D model. Game pads make navigation easier and have been used by many visualization applications such as video games to provide easier navigation. Gloves are usually used in immersive visualization where a user can grab or move objects in the virtual environment. The graphics engine developed in this research uses keyboard and mouse as input devices.

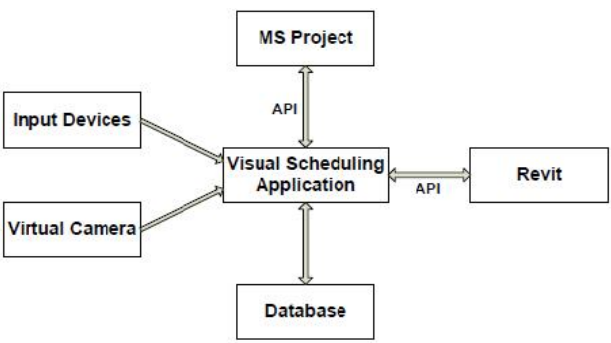


Figure 1-Visual Scheduling Application Architecture

The application uses perspective view to project a 3D model. Both ambient and directional lighting is used to make elements visible. In order to view objects in the virtual world, it is necessary to present the notion of the viewer. This could be the main character's viewpoint in a first person shooter, an over the shoulder view in a third person adventure game, or it could be a zoomed out wide shot in a strategy game. These properties can be encapsulated into a single entity commonly called virtual viewer or camera (Van Verth, Bishop 2004). Virtual viewer or a camera is a combination of the position of the eye and direction in which the viewer is looking. This controls which object lies in the current view. To provide interactive visualization VSA accesses and manipulates a lot of data which is stored by the

application in a database. Figure 2 shows a snapshot of a portion of VSA database. This database saves information about project, elements, faces, material, vertex indices and coordinates in the form of tables and provides fast access to element information. VSA interfaces with Revit using Revit API and C# programming language. Interaction with Revit using its API offers a direct, dynamic link between the application and Revit. Revit API facilitates extraction of information from a model and allows querying the model or modifying model elements. The visualization application extracts not only the geometry of building elements but also their material properties. In order to facilitate visual scheduling of project elements, interaction with Microsoft Project is also implemented using Microsoft Project API. This provides a two way communication with Microsoft Project; that is, the visualization application can send element information to Microsoft Project and it can read schedule information from Microsoft Project.

Methodology

The Visual Scheduling Application allows grouping of 3D elements into construction assemblies, creating activity tasks visually, and visual sequencing of the activities. Using a virtual building as an interface to project scheduling mimics very closely how an individual interacts with the 3D world and how human brain perceives and processes information. A VSA user interacts with a 3D visualization window, a Revit element extractor window, and a dialog box to review information before sending it to the scheduling software.

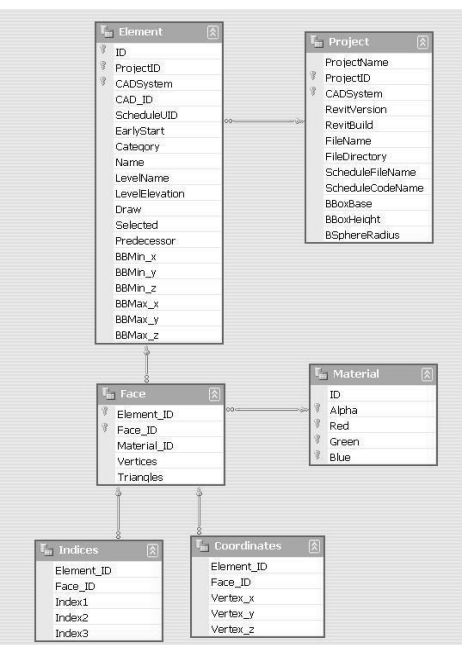


Figure 2: A snapshot of a portion of the VSA database

Visualization of the project can be done by navigating around or inside the building using an orbit camera or a walk camera. The orbit camera allows user to navigate around the building and have a bird's eye view of the building. Walk camera allows the user to walk inside and around the building. An element to be scheduled as an activity or as a predecessor can be selected by pointing to the element and clicking the mouse. For ease of selection, the program provides an option which allows the user to select similar items on the same level or in the whole building. For example, if an activity consists of all windows on level one, user does not have to select individual windows one by one.

When an element is selected, VSA highlights it to allow fast detection of all selected elements. VSA uses different colors for elements selected as an activity and element selected as a predecessor. Elements selected as an activity turn pink on selection whereas elements selected as a predecessor turn blue. An element hidden underneath other elements can be viewed and selected as an activity or a predecessor by temporarily removing the elements that cover it. For example, slab-on-grade and back fill cover wall and column footings in buildings. To expose building footings during a walkthrough, the user can temporarily remove slab-on-grade and backfill for exposing the hidden elements and scheduling them. Figure 3 shows interior of a building where footings are hidden underneath slab-on grade and backfill and Figure 4 shows interior of the same building after removal of slab-on-grade and backfill.

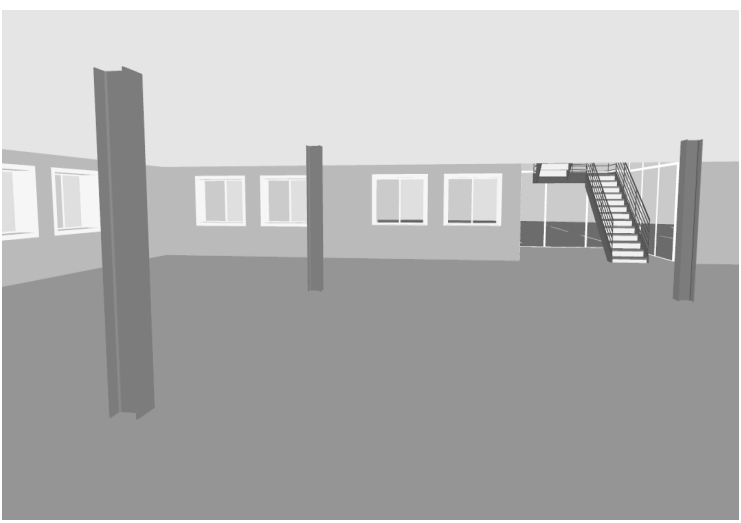


Figure 3: Interior view of a 3D Model

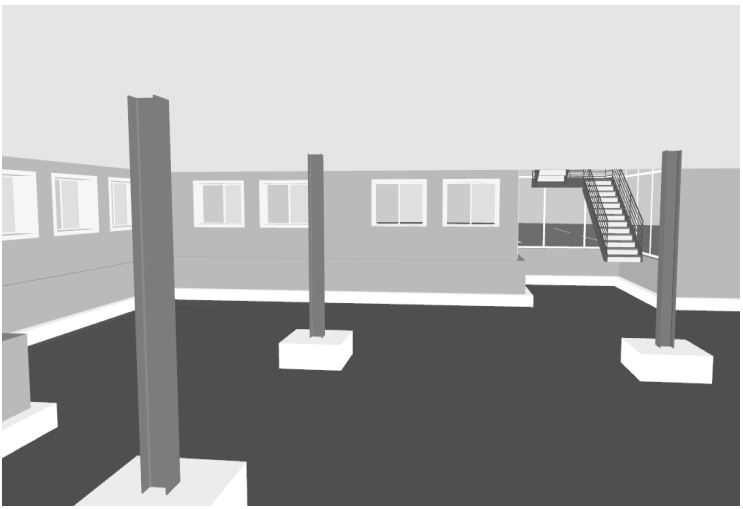


Figure 4: Interior view after removal of slab-on-grade and backfill

After an activity and its predecessor(s) are selected, the information can be submitted to the scheduling program. Figure 5 shows a dialog box for reviewing the building elements selected to represent an activity and its predecessors. As Figure 5 shows, the scheduler can assign a name and duration to a new activity. The dialog box also allows the user to select an appropriate relationship between the activity and its predecessors from a drop-down list and specify a lag time between the activity and its preceding activities.

To make the schedule organized VSA uses work breakdown structure. A project manager can setup a custom work breakdown structure before starting a schedule. Before an activity is submitted to the scheduling software, the scheduler can assign it to an activity outline. As Figure 5 shows, the selected activity outline structure appears at the bottom of the Activity Review Dialog Box. The outline structure shown in Figure 5 is based on CSI format.

After reviewing/editing activity information in the Activity Review Dialog Box, the information is digitally transferred to the scheduling software. Figure 6 shows a snapshot of a portion of a project schedule created with VSA.

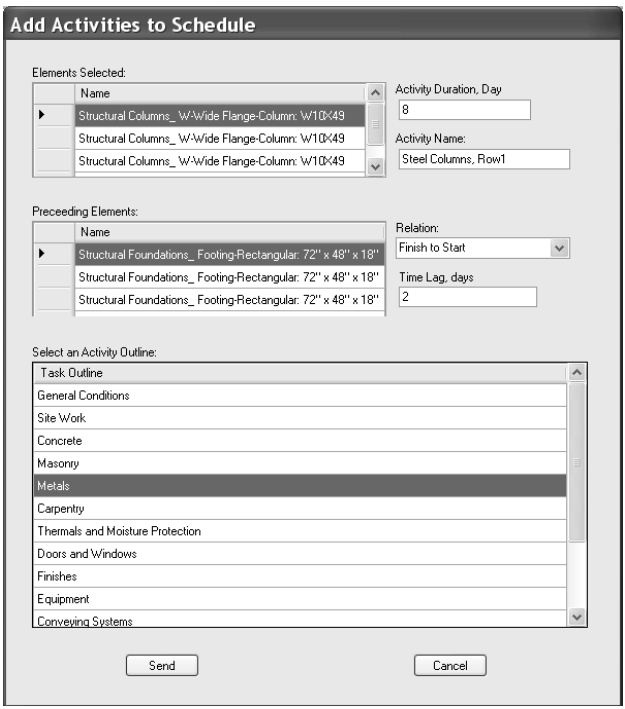


Figure 5: Activity Review Dialog Box

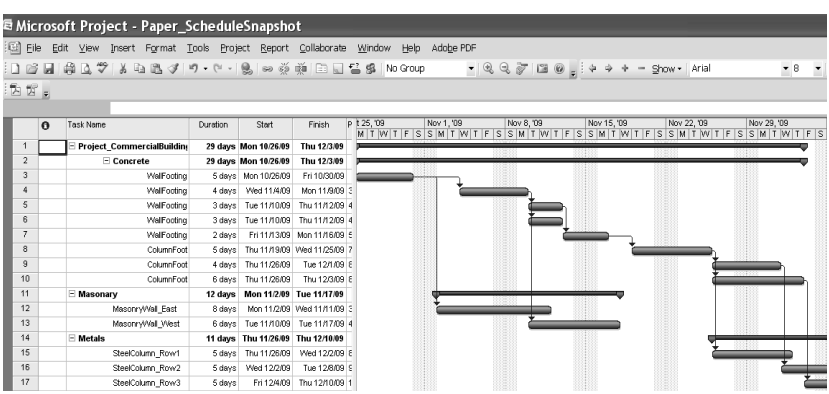


Figure 6: A snapshot of a portion of a schedule created using VSA

Summary and Conclusion

With growing complexity of projects, it is not easy to properly schedule a project by visualizing it mentally. Visual Scheduling Application (VSA) provides a visual approach to activity sequencing thereby making the process more intuitive and simple. VSA was developed based on discussions with construction industry professionals to make it responsive to the needs of construction project schedulers. Application flexibility and ease of re-defining project activities and activity relationships were identified as the most desired attributes for a scheduling application. VSA provides an interactive, visual and flexible approach to activity sequencing and project schedule. It allows visualization of the project before starting the planning and scheduling process. In this approach the scheduling process is reduced to: (1) walking inside a virtual model of the building being scheduled, (2) selecting the element(s) to be included in a new activity and activity predecessor(s) and (3) executing a command that sends the activity information and an estimate of its duration to the scheduling software. In other words, scheduling a building is reduced to a simple excursion inside the building. The project logic is developed while walking inside the project. This approach minimizes manual data entry by digitally transferring project activity information from the CAD model to the scheduling software and exerts fewer loads on scheduler's memory than working with a long list of activities that requires building a mental image of the project. The visual scheduling approach was demonstrated to a few professional schedulers; their feedbacks have been very positive.

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Assessment of Internet Based Systems for Construction Product Information

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Abstract

In the Architectural, Engineering, and Construction (A/E/C) industry, construction products constitute a large proportion of the total cost of construction. In recent years, the range of construction products has grown substantially that users are facing difficulties in selecting products that fit their projects' needs. Due to wide availability of the internet, web-based construction production information (CPI) providers have become very popular as a new source of CPI acquisition. This study identified a typical business operating structure of this new industry sector and also investigated various factors that are critical for successful operation of the business in the A/E/C industry in the United States, through extensive literature reviews, investigations of CPI websites, and three independent surveys of CPI users, web-based CPI providers and construction product manufacturers. The findings of this study will allow stakeholders to find areas to improve in order to continue to grow in this industry sector.

Introduction

In the Architectural, Engineering, and Construction (A/E/C) industry, construction products constitute a large proportion of the total cost of construction. Depending on the project type, construction products account for almost 30-45% of the total construction cost (Hildebrandt 1988). In recent years, the range of construction products has grown substantially that users are facing difficulties in selecting products that fit their projects' needs. Information about various construction products is required at different stages during the life cycle of a project by many project participants including the owner, architects, specification writers, interior designers, cost estimators, contractors, specialty contractors, cost engineers, etc. Traditionally, construction product information (CPI) has been obtained through product catalogs, product manufacturer's distributors, professional magazines, and word of mouth. However, since the internet has become widely available for product information acquisition, internet search engines and internet based CPI providers have rapidly replaced the traditional methods. Specifically, the internet based CPI providers offer strong benefits to both CPI users and construction product manufacturers (CPMs) such as one-stop access to various product information, comparison of different products of same function, quick update on information about new and existing products and the availability of statistics about the visitors of each product information page. These internet based CPI providers have created a promising niche market in the A/E/C industry, in which the CPI providers typically generate revenue by collecting fees from CPMs and in return, the CPI providers upload and maintain the product information of the manufacturers.

This paper investigates this emerging market in terms of two aspects; a) business structure of this unique market and the flow of product information in the web-based CPI systems, and b) critical factors for successful operation of the web-based CPI business in the A/E/C industry through literature reviews, expert interviews, and collection of opinions of stakeholders using three questionnaire surveys.

Web-Based CPI Business Model and CPI Flow

In total, 11 companies were identified as business entities which provide CPI through the internet in the U.S. as of Spring 2009. The research team physically visited two major leading companies in this business sector for interviews and the others were contacted by phone for interviews to identify the characteristics of this industry, business operating models and the flow sequence of product information from the manufacturers to users. Figure 1 illustrates a business operating model of a typical internet based CPI provider.

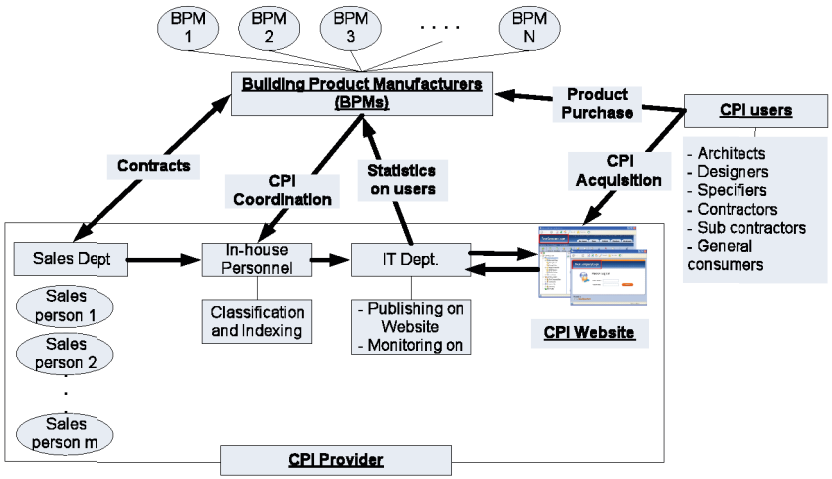


Figure 1. Business Model of Internet Based CPI Providers

A typical web-based CPI provider's business structure consists of sales personnel that make contact with the CPMs and establish contracts between the two parties. These contracts are typically made on annual basis and the manufacturers pay the CPI providers in a form of membership fees. The membership fees have different fee structures based on the number of products advertised and uploaded into the CPI provider's website. Some CPI providers charge special fees if the manufacturers request for easily visible advertisements on the websites. The in-house personnel of the CPI providers collect the product information from the manufacturers and categorize the products abiding to the Construction Specification Institute (CSI) format. It is important to note that none of the current CPI providers redevelops the product information sheets that are obtained from the manufacturers. It is on the contract that the accuracy of the data belongs to the manufacturer's responsibility and the CPI providers are not liable for it. An important role of the in-house personnel is to index the products. Key words and search words are extracted from the collected product information. Some CPI providers identify these key words manually using experienced employees and some others use an indexing computer software program to automate this process and reduce the associated cost.

The product information is then received by an Information Technology (IT) department to put onto the website. The IT department constantly manages the websites and updates new and revised product information onto the websites. The IT department is also responsible for recording the amount of hits a manufacture receives on their products and providing these useful statistics and the perception of the users on the site to the manufacturers. The websites are typically set up by using a server that stores various product information data. The users are able to access the server through various web links found in the website. The Computer Aided Design and Drafting (CADD) models and Building Information Models (BIM) of products

and specification sheets are stored here and are accessed by weblink without referring to the manufacture's website. This enables a user to find many different product specifications without leaving the CPI provider's website. The users are directed from the CPI website if they choose to place a purchase order on an item or they request additional information that is not located on the CPI provider's site. It is noteworthy that no web-based CPI providers currently offer a function to facilitate product purchase orders for the users or the website visitors. It is also important to note that most users of CPI in the design stage such as architects, interior designers, specification writers and cost estimators are not actual buyers of the products. The actual purchase of products takes place in the construction stage. Currently, the major point of attraction or the benefits of these web-based CPI providers for the CPI users are limited to providing information of various construction products under one roof for easy access and comparison of the products of same function.

Questionnaire Surveys

Three independent questionnaire surveys were conducted during summer and fall 2009 to identify the main factors of the CPI market that contribute to its success. The research team investigated the differences on opinions on these factors between stakeholders in the CPI market. These three questionnaires include one for CPI providers, another for CPMs, and the last for CPI users who visit CPI websites. These questionnaires were developed through discussions within the research team and literature review. The potential survey participants for CPI providers and users were selected using an online search. The potential survey participants for CPMs were found from CPI websites. Four popular divisions of the CSI format were considered for surveying CPMs including: concrete, steel, wood and doors, and windows. The survey forms were sent to the participants via email using Microsoft Word or an alternate PDF format after confirming their willingness to participate in the survey via telephone.

Method for Analyzing Survey Data

The survey questionnaires consisted of a set of questions with a 5 point likert scale. The following equation was used to convert the respondents' ratings to questions with five different answer options into a percentage format:

$$Percentage(\%) = \left\{ \sum_{i=1}^{n} \frac{(X_i - 1)}{4} \right\} x \frac{1}{n} x100 \qquad \text{(Equation 1)}$$

Where, X_i = option chosen by the respondent (rating 1 to 5), n = total number of survey respondents on the question

Survey Results and Discussion

The questionnaire surveys were performed to determine the differences of opinion in each group. There were, in total, 11 CPI providers contacted and encouraged to

participate in the survey. Out of the 11 CPI providers, the research team obtained 7 responses. The survey of CPI users resulted in 31 collected responses. The result of the final group, CPMs, was 27 collected responses.

Frequency and Preference of methods to access and advertise CPI

The two groups (CPI users and CPMs) were assessed in terms of the frequency and preference of the methods that they are currently using to access CPI (CPI users) and advertise their products (CPMs). The methods that were evaluated include catalogues, professional magazines, product sale agents/distributors, direct contact with the manufacturers or customers, web-based CPI providers, and Internet search engines.

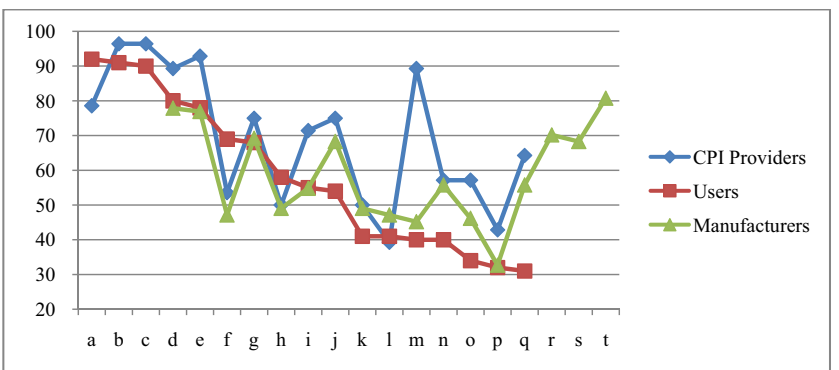
Table 1. Methods to Access and Advertise CPI

Methods		CPI Users		CPMs	
		Frequency (%)	Preference (%)	Frequency (%)	Preference (%)
Non-internet based methods	Catalogue	45	42	49	46
	Professional Magazines	25	22	39	30
	Distributors/ suppliers/ Sales agents	56	51	58	59
	Direct contact with manufacturers or customers	58	56	75	73
Internet based methods	Web-based CPI providers (sweets networks, reedconstructiondata, etc.)	69	67	73	60
	Internet search sites (Google, yahoo) / Company's website	75	62	84	75

Table 1 shows that the user group frequently uses and highly prefers the internet based methods compared to other traditional methods. The manufacturer group uses and prefers the internet based methods and also the method of direct contact with customers. This indicates that the mode of access and advertisement of CPI has significantly shifted to the internet based methods with extensive availability of the internet. CPI users are at least 11% and at most 50% more dependent upon the internet methods than other methods. This dependency on the internet based methods is higher for CPMs. CPMs use the internet based methods at least 11 % and at most 45% more in advertising their products than other non-internet based methods.

Important Factors for Using CPI Websites

Figure 2 shows the factors that the three groups (CPI providers, CPI users, and CPMs) think are important in using CPI websites. For CPI users and CPI providers, basically the same list of factors was provided. For CPMs, three additional factors (factors r, s, and t) were included as potential reasons to hire web-based CPI providers for advertizing their products. Three factors (a, b, and c) were not included in the questionnaire as they are not directly relevant to the manufacturers. In developing a comparative chart in Figure 2, a line for each group was used to easily capture and compare the differences between the responses of different groups even though these data points are not a trend or continuous data. The factors are sorted in descending order based on the CPI users' responses.



Legend:	
a: Accuracy of information, quality	k: Product installation video clips
b: Easier to retrieve information	l: Product delivery information
c: Ease of navigation on the website	m: Product reviews
d: Regular updates about products	n: Finished construction photos, power point presentation
e: Provision for acquiring additional information of the product (by contacting the manufacturer)	o: Cost saving availability/information
f: Comparison with other products	p: Public forum for discussion of products
g: Amount of information (variety of products)	q: Customer feedback system
h: Online technical support/Customer service	r: Users/Customers recommendations
i: Various search options	s: Economical
j: Supporting files (CAD files etc.)	t: More visibility

Figure 2. Important Factors for Using CPI websites

The major factors that attract the three groups in using the CPI websites are different shown in Figure 2. The CPI users who participated in the survey reported the top five important factors to visit the CPI websites as: a) accuracy of information/quality, b) easier to retrieve information, c) ease to navigate, d) regularly updates about the products, and e) provisions for acquiring additional information. The results indicate that quick and easy access to construction product information along with accurate product information is the key to maintaining current users and attracting potential

users to the websites. It means that users are seeking the most updated accurate information about construction products and various features and functions that help quickly obtain required data.

The five main factors that CPI providers think are important to attract visitors are the same as the list identified by the CPI users except that the m) product reviews is included, replacing the most important factor identified by the user group; a) accuracy of information/quality. But this factor a) accuracy of information/quality is still considered as an important factor by the CPI providers as the sixth most important factor. The CPI providers feel that product reviews is an important feature that helps users know the performance of products and make informed decisions. However, CPI user group does not agree and they do not consider the product review as an important factor for using the CPI websites (ranked 13th). The factors such as i) various search options, j) supporting files (CADD/3D/BIM), k) product installation video clips, n) finished product photos/presentation files, o) cost saving availability information, p) public forums and q) customer feedback system were rated much more important by the CPI providers than the CPI users. It appears that the CPI provider group thinks that the functions that are not available from non-web based CPI providers such as product manufacturers and paper catalogs are important to attract their visitors than the level to which the actual users think. The CPI user group rated a factor f) comparison with other products much higher than the CPI provider group did. It indicates that this function is the most important function among the functions that are only available at CPI websites. The CPI providers might have neglected the importance of this function as this function is rated very low in its importance but must actively develop and expand this function to satisfy the users.

The CPMs are clients that the CPI providers require to be successful and profitable in business. Hence, the CPMs' expectations for advertising their products on CPI websites should be met to maintain satisfied and continued relationships with the CPI providers. The five major factors that are considered by CPMs when hiring a CPI provider include: t) more visibility, d) regular updates about the products, e) provisions for acquiring additional information, r) users/customers recommendations, g) amount of information. These results suggest that the popularity or name recognition of a CPI website is the major factor of using web-based CPI providers. CPMs consider the CPI providers as one of sources for providing for more visibility of their products for advertisement. Thus, high name recognition of web-based CPI companies for their potential users is the most critical factor.

Figure 3 provides the summary of responses on difficulties faced by the users of CPI websites. The highest ranked difficulty is retrieving necessary information. Most information is related to the specifications, CAD files, and MSDS documents. Although these may seem basic, they are essential information of products. Furthermore, the absence of supporting files can be a hindrance to having proper knowledge of a product. Through analysis of the survey of CPMs, the results showed that manufacturers also prefer CPI providers that can provide supporting files, frequent updates, and online tech support or customer service.

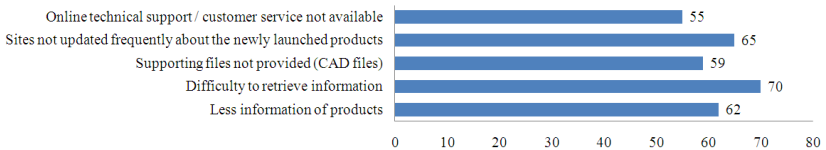


Fig. 3 Difficulties Faced by Users

Strategies to Increases the Number of Visitors

Figure 4 represents the strategies to increase the number of visitors/users of CPI websites. The main strategies that CPI Providers try to implement are i) sale agent benefits for increased contracts with CPMs, and ii) regular introduction of new construction products. It is important to note that the current business model works exactly like a car dealership. The CPI providers believe that the capabilities of each sales agent that they have is critical in increasing their revenue. Thus, the CPI providers feel that they can recruit, attract and retain competent sales agents by providing more salaries or benefits. Most CPI providers have not considered introducing an online ordering function, possibly due to strong resistance of CPMs to having this business relationship yet and consequently, the inability to display cost information of products online.

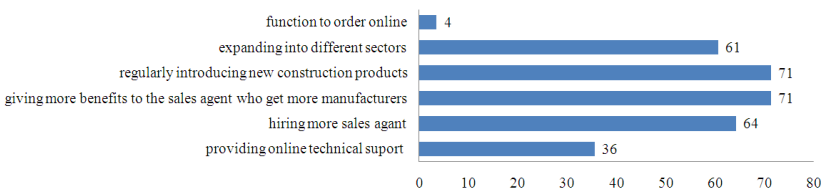


Fig. 5 Strategies to Increase the Number of Visitors/Users

Conclusion

Web-based CPI providers have become very common as a means to access CPI and to advertise construction products since the internet has become widely available. This study identified and discussed a typical business operating model for web based CPI providers. The study also investigated various factors that are critical for successful operation of the construction product information market in the A/E/C industry in the U.S. The collected data from three independent surveys were mainly used for comparing and summarizing different views from three major parties involved in this industry.

From the survey results, it is very apparent that CPI websites are gaining popularity in the A/E/C industry. Manufacturers that traditionally use catalogues and magazines are more dependent on these websites for advertisement of their construction products. CPI users have begun to use CPI websites as a major source of obtaining product information because these sites offer most of the information needed and allow the users to save time. The key competitors for CPI websites were identified to be product manufacturers' websites and popular internet search engines such as Google and Yahoo. Some CPI providers have contractual relations with these internet search engines to have their customers' products be listed first when certain key words are used. This strategic business relationship is suitable considering both are the top methods that users are currently relying on when searching product information.

To successfully maintain and operate a CPI website, the survey identified that the website first must be able to provide accurate product information with frequent updating functions. Second, the product information must be easy to search and access. Comparison function with other products is as equally important as the volume of product information. The other important functions include supporting files and online/tech support. More visibility of the websites and economical fee structure would also be important factors to retain and attract CPMs as customers.

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BIM for Integration of Automated Real-Time Project Control Systems

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Abstract

Various real-time field data acquisition systems have been developed aiming to automate control of construction projects. Some of those have demonstrated potential for automating project control to a certain extent and most of the systems support a specific function of project control. It is envisioned that successful integration of the systems would create new innovations and opportunities in managing the architecture/ engineering/construction (AEC) projects. In an attempt to facilitate integration among real-time systems, this study explored the feasibility of using building information model as a base of integration. In this study, a large volume of literature was reviewed to understand the state of the art real-time project control systems and building information modeling (BIM). Upon the understanding, this study identified a list of conditions or requirements for successful integration. The findings presented in this paper are expected to provide guidelines that need to be taken into consideration when developing automated real-time systems and building information models.

Key Words:

Building Information Modeling; Real-Time Systems; Project Control; Integration

Introduction

Since the opportunities of computer-aided design and construction were ambitiously prospected in the late 1980s (Howard et al. 1989), a dramatic change has happened to the practices that are implemented to manage the AEC projects. The advancement in information technology, such as computing, sensing, tracking, and communication, allowed invention of remarkable tools for managing projects. In particular, automated real-time project control systems and BIM have brought meaningful evolution to the management of AEC projects.

Filed management is one of the areas that have greatly benefited by the enabling technologies. Traditionally, project control on site required a lot of effort to monitor ongoing operations and to collect field data from the operations. Most of the control activities were performed manually, so that on-site control was time consuming and error prone. Seeking for a solution to the problem, the AEC industry has pursued automated project control for decades. As a result, various automated real-time filed data acquisition systems have been developed. Some of those demonstrated potential for automating project control to a certain extent. Depending on the intended purpose, most of those systems support a specific function of project control, for example, progress monitoring, quality control, and safety control.

BIM has brought a new paradigm of project management into the industry by promoting functional and organizational integration for project management (The buildingSMARTalliance™ 2009). Such integration has been esteemed as a significant breakthrough where the AEC industry has been criticized for lack of integration and high fragmentation in the process of project delivery (Howard et al. 1989). Through many cases of implementation, the technology has been tested and proved to be an effective method and tool for managing construction projects (Eastman et al. 2008). The technology, however, has been implemented primarily as a design tool. It has not been widely and actively used for filed management and process control. When its implementation is extended to construction phase, much effort is needed to maintain building models up to date, which is one of the reasons for such a low application as a control tool (Hajian and Becerik-Gerber 2009).

It is envisioned that successful integration of real-time systems can provide the AEC industry with new opportunities in many aspects of project management. Project control on site in particular can be further advanced. Some real-time systems have been integrated individually with building information models. This study investigated the following questions: what roles can BIM play for integrating individual real-time systems and what conditions or requirements should be satisfied to facilitate such integration? A thorough literature review was conducted in an attempt to find answers to the questions. The following section briefly describes the state of the art automated real-time control systems and BIM technology. However, it was not intended to replicate the benefits of and the technical details of the technologies in this paper, because those are already well documented by many previous studies.

The state of the art Real-Time Project Control Systems and BIM

Real-time project control systems

A large volume of literature has been produced in the area of automated real-time systems for project control. As literature shows, the purpose of existing systems varies and each system implements a variety of technologies depending on its primary purpose. Nevertheless, the core of most existing real-time systems in general is a function for automatic field data acquisition. It is worthwhile to note that, while most real-time control systems directly serve a specific function for project control, data or

information collected by the systems can be used for a variety of purposes. For example, a system developed by Golparvar-Fard et al. (2009) can assist with automatic update of building information model while its primary purpose is to monitor progress. The existing systems can be categorized into two groups from a broad perspective. One group, Group-A, is concerned with monitoring and control of processes and operations on-site during construction while the other group, Group-B, is interested in automating tasks or functions that are conducted to operate or monitor systems in the built environment (Fig. 1).

As illustrated in Fig. 1, Group-A can be divided further into two sub-groups: A-1 and A-2. Systems in A-1 are intended to monitor ongoing field operations constantly. The systems primarily focus on tracking moving objects (Bohn and Teizer 2009; Fullerton et al. 2009; Carbonari et al. 2009) and localizing materials (Wang et al. 2006). Meanwhile, A-2 includes systems that support tasks performed to manage construction operations, such as progress monitoring, with a certain length of interval time (Golparvar-Fard et al. 2009; Roh et al. 2009). Some systems in this category also support document transaction and change management. Group-B also consists of two sub-groups: B-1 and B-2. The primary focus of the systems in B-1 is centered in monitoring the health of infrastructure systems, for instance, monitoring the health of building structures (Zhu et al. 2009). Meanwhile, B-2 includes systems for monitoring and controlling service systems, such as HVAC, security control, and fire-hazard prevention system, which have existed for a relatively long time.

As well-known, in order to collect field data either automatically or semi-automatically, the systems implement various information technologies and computing techniques—to name a few, radio frequency identification (RFID), global positioning system (GPS), ultra wide band (UWB), embedded sensors, 3D LASER scanner, Flash LADAR, high-resolution video camera, digital photogrammetry, and Wi-Fi wireless communication (Hwang 2003; Bohn and Teizer 2009). One notable limitation of such technologies is that it is difficult to implement the technologies to track and monitor processes and environment associated with interior work performed in a confined area. The condition becomes even worse when there are many objects and obstacles in the area. Thereby, more real-time systems to date has targeted on monitoring exterior work, such as excavation, structure erection, and building enclosure installation.

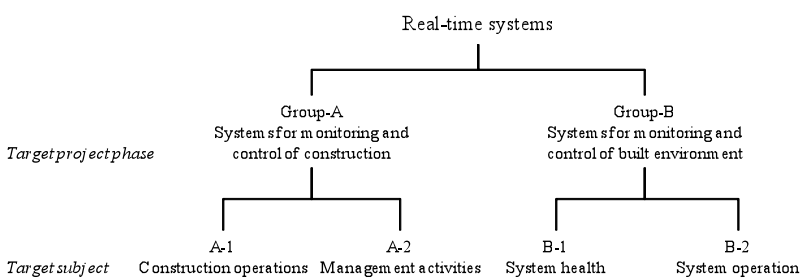


Fig. 1 Classification of real-time systems for AEC projects

Building Information Modeling

While BIM is defined in many ways, a general definition is "a modeling technology and associated set of processes to produce, communicate, and analyze building models (Eastman et al. 2008)." BIM has triggered a paradigm change in project management from the design phase to facility management (The buildingSMARTalliance™ 2009). Accordingly, BIM has been implemented for various purposes. With respect to design, it is widely used for design development and design coordination (Leite et al. 2009). Concerning design coordination, BIM is being more actively used in detecting clash among major mechanical, electrical, and plumbing duct and pipe (MEP) components as well as between architectural/structural components and MEP components. While BIM is primarily implemented for design-related processes, it is used in construction and operation/management to a certain extent. Such implementation includes quantity take-off, scheduling (4D), construction simulation, and work sequence coordination. Concerning energy saving, it is also used for energy simulation (Sumpf et al. 2009) aiming to find an optimal design of a building which can maximize energy efficiency.

Integration of BIM and Real-Time Project Control Systems

Integration of real-time systems with BIM has been under tremendous interest in the AEC discipline. Nevertheless, such integration has been limitedly pursued in certain areas of project control, such as safety, progress monitoring, resource management, and quality measurement. Additionally, among these areas, relatively more active integration has been attempted in progress monitoring and supply chain management. When it comes to technical method for integration, a frequently applied approach is to superimpose digital as-built images on 3D BIM model. This approach is often used for monitoring progress (Golparvar-Fard et al. 2009) and planning path of equipment for coordinating the motions of equipment such as cranes for building construction (Kang and Miranda 2004). In this approach, spatial data of BIM, more specifically boundary data of a building, mainly is used as a reference. Integration of BIM and real-time systems for supply chain management has been centered in tracking and handling materials from manufacturing to delivery to and installation on site (Chin et al. 2008). Existing methods in this category apply various resource tracking technologies such as RFID and GPS. Overall, the integration between real-time systems and BIM remains very low to date and, furthermore, the integration among real-time systems is even lower.

Expected Benefits of the Integration

It has been prospected that successful integration of BIM and real-time systems can create new opportunities in many areas of project control (Hajian and Becerik-Gerber 2009). The following delineates prospects in a few areas that are expected to benefit the greatest synergy effect from successful integration of automatic real-time systems using BIM.

Automatic update of building information models

Being integrated with building information models, real-time field data acquisition systems can increase the degree of automation in updating building information models. Furthermore, updates can be made more frequently, regularly, and accurately. This will remove or, at least, reduce burden of updating building information models up to date along the work progress. Currently, available systems are not able to update the models in real-time. Removing such a critical hurdle will consequently expedite the application of BIM in the AEC industry. All of the afore-mentioned advancements will eventually contribute to accomplishing more proactive and reliable project control in managing the AEC projects.

Advanced data and knowledge management

The advancement in automatic field data acquisition systems will enable more accurate collection of data and knowledge about processes and operations on site. Such critical information assets can be collectively stored and effectively managed within a building information model. Using ontological representation of BIM, data and knowledge can be linked with associated building components and objects. This will allow effective storing, maintenance, and reuse of data and knowledge.

Field management

The afore-mentioned improvement in data and knowledge management will enhance field management in many aspects (Wang and Boukamp 2009). Some exemplary aspects include quality inspection, identification of work hazards and safety requirements, and communications and coordination among project participants. Using wireless communication, the contextual data about processes and objects can be cross-checked in real-time between actual context and that in the building information model.

Robotics

Integration of BIM and real-time systems will make the application of robots in construction more feasible and efficient than ever before. It is expected that robots can use more systematically augmented status information stored in building information model to reason the status of objects under operations. Robots also can utilize current environmental conditions at working areas by communicating with real-time systems. In addition, robot-detected spatial data may be mapped with building information model in real-time to find exact locations.

Conditions and Requirements for the Integration

Successful integration of enabling real-time systems can further enhance project control of AEC projects. The following discusses conditions or requirements to be satisfied or, at least, to be improved for successful integration of real-time systems by means of BIM. The conditions or requirements could be identified by combining and interpreting findings from many previous studies.

Technical Aspects

An effective method for reorganizing BIM components is needed where components are organized differently by designers and planners (Eastman 2008). For example, designers tend to represent a composite partition wall, which consists of metal studs, gypsum boards, insulation, electrical wires, painting, as a single entity. From the perspectives of planners, such an organization presents limitations to project control where the constituents normally belong to different scope of work in contract and built by different trades. In particular, it is difficult to develop schedules and to conduct progress monitoring for management of field operations at a required level of detail. Lack of such a flexible reorganization method currently presents a critical hurdle to facilitating the use of BIM for project control beyond design. Overall, flexible methods for abstraction and representation of building components are needed to enable effective linking between field data and associated components.

As more advanced sensors are implemented for the purpose of controlling construction operations, more building elements as well as resources used are recognized based on sensor data, such as location and other contextual data. Considering such fast growing implementation of sensors, two problems need to be addressed. First, representation of sensor metadata should be supported more effectively by BIM whereas existing standards for BIM like Industry Foundation Classes (IFC) are not fully ready for it (Liu and Akinci 2009). Second, a method for planning sensor deployment on site is necessary to optimize number of sensors, position of sensor, and networking among sensors, taking into consideration the linking between sensors and building components in a building information model.

Excellent mobile environment is essential. As well-known, many decisions relevant to control are supposed to be made promptly on site. This often requires immediate access to relevant data. For instance, an inspector may need specifications and drawing for quality inspection. In a situation like this, mobile computing and wireless communication is essential to acquire needed information in real-time.

It is not difficult to expect the proliferation of data in a building information model when a model is integrated with various real-time field data acquisition systems. "Soon, nearly every piece of information that an owner needs about a facility throughout its life can be made available electronically," prospected the buildingSMARTalliance™ (2009). "The industry, however, does not yet have the standards and infrastructures in place to capture, organize, distribute, and mine that information." Thus, a well-structured ontological representation of data is needed to make user interaction easy with such large and complex data model on site, particularly considering mobile computing environment (Reinhardt et al. 2004). While technical improvement is essential to the successful integration, the significance of non-technical factors should not be forgotten. Nitithamyong and Skibniewski (2004) argued that, despite significant impact of many non-technical barriers on the success of technology implementation, the barriers are often ignored.

Non-Technical Aspects

It may sound redundant that the implementation of BIM is a prerequisite condition for the integration of real-time systems for project control by means of BIM. It, however, is not a meaningless statement in reality. The long-lasting structural problem of the AEC industry—organizational barrier caused by horizontal fragmentation—incurs legal concerns in terms of liability which hinder the use of BIM in the AEC projects (Eastman 2008; Dossick et al. 2009). In this context, it is critical to have a consensus among project participants with regard to implementation of BIM. In particular, owner's role is important where owner determines a project delivery method. A recent report (Brown 2009) shows how influential owner's position is when it comes to implementation of BIM in the AEC projects: "Wisconsin's Division of State Facilities (DSF) issued the new guidelines and standards require architects and engineers to use BIM authoring software in all phases of design, to maintain and update the model during construction, and to submit the model to the owner at the end of the project."

The implementation of BIM also needs to be extended to construction to take a full advantage of the integration. But, the current practices facilitate the implementation of BIM only up to the early stage of construction project (Meadati 2009). Particularly, in a design/bid/build project, the issue of cost compensation plays a critical barrier where contractors need to spend a considerable amount of extra money to develop and maintain building information models.

Last, but not least, education and training need to be fostered with BIM and real-time systems. As noted by Taylor et al. (2009), BIM can be an effective means of integrating the AEC disciplines in educational institutions. A recent survey result (Peterson and Fischer 2009) provides a good indicator to determine whether or not the AEC industry is really ready to adapt BIM and real-time systems to manage construction projects. According to the survey, 55-75 percent of construction professionals do not use software tools beyond Microsoft Office. The same survey also reports an astounding response—a general builder preferred manual data collection method because it is a "good way to train field (engineers) how buildings are built."

Conclusions

Systematic aggregation of real-time systems can be achieved by using BIM as a bridge for integration. Despite the expected benefits of such integration, there are some critical problems that should be overcome to facilitate the integration. This study identified the problems by analyzing a large volume of literature. The problems exist across both technical and non-technical aspects with regard to development and implementation of automated real-time systems as well as building information models. It is expected that researchers and system developers can use the conditions or requirements presented in this paper as guidelines, as they develop real-time systems and building information models.

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DEFINING HIGH-LEVEL PROJECT CONTROL DATA FOR VISUAL INFORMATION SYSTEMS

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ABSTRACT

Over the course of a typical construction project, project managers constantly monitor progress and resolve problems. However, it may be not easy to track and identify performance problems when a construction project generates a great volume and variety of ever-changing data during the construction phase. Traditionally, in order to identify performance problems, project managers walk job sites and meet or call several individuals. Since the advent of web-based tools, project managers have been able to obtain information by logging on to a project's web site. However, early efforts at using computers to manage construction projects came up short with technology that was awkward or costly. Today, thanks to advancements in information technology, web-based tools are capable of displaying information in easy-to-read graphics, assembled from data pulled from multiple sources in real time. This paper explores what data should be collected for web-based systems to provide project managers with threshold level information regarding actual project status so that they can focus on the "big picture." This exploration is based on literature review and interviews with fifteen project managers from construction firms in the Puget Sound area. The information presented in this paper may serve as the foundation for the development of visual information systems to support the work of construction project managers.

INTRODUCTION

The primary challenge of project managers is to deliver facilities within a given time frame and budget while satisfying project objectives. Over the course of a typical project, project managers constantly direct and monitor the progress of construction activities and resolve any discrepancies between as-planned and as-built progress. However, it may not be easy all the times to track and identify performance problems during construction when a construction project generates a great volume and variety of ever-changing data. Due to the volume of data, key issues of schedule, productivity, and quality may be overlooked, thereby resulting in the failure of judicious handling of important situations.

Project success is highly dependent on the responsiveness and agility of project managers in managing such discrepancies. Therefore, up-to-date and accurate project data must be transformed into meaningful information for project managers to gain insights into the actual status of a project and make more informed decisions in dynamic and complex environments.

Most research on project data has focused on how to collect, integrate, and consolidate voluminous data into inter-organizational database systems (Hanlon and Sanvido 1995, Kang and Paulson 1997, 2000, Caldas et al. 2002, Chang and Tsai 2003). However, the massiveness and complexity of these database systems may result in confusion and "analysis paralysis" where project managers may have to invest their valuable time looking for relevant information to aid decision-making.

More recently, there have been a few research efforts focusing on the visualization of project data in the construction management domain (Songer et al. 2004, Korde et al. 2005, Russell et al. 2009). Despite such efforts, the construction management community still faces the problem of how to digest large amounts of data and discover the underlying meanings hidden within the data sets. The lack of adequate visual representation within the construction industry causes project managers to struggle with voluminous data (Song et al. 2005), which may cause costly errors or lead to project delays.

Visual information systems; where project control data is organized into an informative form, presented coherently, and communicated visually; may help project managers better analyze projects, identify problems in performance, and take corrective actions. Therefore, to assist project managers in monitoring the progress of construction activities and gaining insights into actual project performance, we propose the development of interactive visual information systems as a model of visual analytics in the construction management domain. The fundamental challenge to address is how to develop effective systems to assist project managers in decision-making. In order to overcome this challenge, several critical questions must be addressed:

- What data should be collected to generate high level information about actual project performance?
- What issues should be considered before designing appropriate visualization schemes?
- How to manage large amounts of data and visually represent their intrinsic meaning?
- How to design visual information systems to enable users to easily comprehend the complex inter-dependencies and discover the underlying meanings?
- How to develop interactive visual information systems to assists the user in data mining and knowledge discovery?
- How to assess the effectiveness of visual information systems?

To develop effective visual information systems, the initial focus should be on the first question. Thus, this paper explores what data should be collected to provide project managers with threshold level information regarding actual project status so that they can focus on the "big picture."

PROJECT MONITORING AND CONTROL

No construction project can be performed exactly as planned due to uncertainty regarding productivity, design errors, conflicts and omissions, change orders, labor strikes, material delivery delays, vandalism, and bad weather among other factors. Consequently, accurate and timely project monitoring is a prerequisite for project management. Construction projects must be continuously monitored by comparing actual progress to the baseline plan. Project monitoring enables project managers to evaluate actual performance and resolve any discrepancies from planned performance in the dynamic nature of construction projects.

Constantly assessing the actual status of a project and identifying performance variances as early as possible is essential to successful project control. Once performance variances are detected, it is necessary to identify their causes and key drivers. This allows project managers to take appropriate actions in a timely manner, if necessary. Project control begins with the process of identifying current or possible problems based on monitored or projected performance during the implementation of the baseline plan. By doing so, project managers can analyze causes of problems and take corrective actions to adjust the project to meet its requirements (Gould and Joyce 2002).

From the viewpoint of project control, it is useful to forecast future variances between actual progress and the baseline plan in advance of facing real performance problems through periodic assessments of project performance. Most forecasts of project performance predict the conditions at the end of the project, such as forecasted completion dates and cost at completion, based on current and known conditions. For example, based on current production rates and the amount of work remaining, the forecasted completion date can be projected. In addition, it can be useful to evaluate "what if" scenarios according to possible corrective actions prior to final decision-making.

The main objective of project monitoring and control is to identify the discrepancies between actual and planned performance and put the project back on the desired track as early as possible (Bradiru and Pulat 1994). A typical project monitoring and control process can be described as information streams and information processes because it includes a series of steps which requires the input of information during the entire construction phase of a project and generate information project managers need (Meredith and Mantel 1995).

Performance Measurement

Each construction project may exhibit a different view of project monitoring and control based on the project's goals and success criteria. For example, some projects may consider 'keeping the completion date' as the most important objective despite manageable cost overruns, while others may put emphasis on high quality work despite minor delays. The important dimensions of project monitoring and control are specifically defined on performance metrics describing the client's requirements and their value (Lewis 1995).

Performance metrics are typically defined before a project starts to facilitate the project monitoring and control process including collecting, analyzing, and comparing actual project data to planned data. Project managers should define quantifiable performance metrics in preparation for project monitoring and control.

Those performance metrics must reflect the critical success factors as well as project objectives. Due to the importance of performance metrics, a considerable amount of research has been done within the subject of performance measurement. Ward et al. (1991) argue that project performance in construction had been traditionally evaluated by the client's requirements in terms of cost, time, and quality. Egan (1998) emphasizes the importance of specific project targets for the improvement of project performance and the role of performance measurement based on those targets. Consequently, Egan (1998) suggests time, cost, quality, safety, productivity, and scope of work as key performance indicators. In addition, Korde et al. (2005) describe that important factors in evaluating construction performance have been categorized into productivity, time, cost, scope, quality, safety, and others.

Performance problems can be identified by comparing actual progress to the baseline plan, which specifies targets for performance measurement such as the amount of work, budget, and duration. Those targets should be the measurable quantities that readily fit the performance measurement. Sine performance measurement can be done only after some tasks have been completed, some consider them to be ineffective to timely manage projects. However, if project managers do not measure what they have done, it is difficult for them to justify additional resources to improve performance. Furthermore, measuring completed work is important because the performance trend of past work could be an indicator of potential problems, allowing project managers to put the project back on the desired course by making adjustments for upcoming tasks.

Performance Variances

Performance variance can be determined by the deviation of a variable from its target. In this context, performance better than the target is also considered a variance, just as performance worse than the target is considered a variance. Performance variances can be simply calculated by:

$$\text{Performance Variance} = \text{Target Performance} - \text{Actual Performance}$$

Performance variances are important inputs especially for the project control process. However, Shtub et al. (1994) argue that the raw performance measures could be deceiving especially for cost performance. For example, a cost variance of $10,000 is significant on a $20,000 activity, but much less important in a multi-million dollar activity. To judge this relative performance, standardized performance indexes are frequently used (Table 1).

Table 1: Example of Performance Indexes

Performance Index	***Formula***
Schedule Performance	Schedule Variance / Planned Duration
Cost Performance	Cost Variance / Budgeted Cost

The scope of this paper is limited to quantitative measures of project performance including time, cost, productivity, and scope of work. Although, safety and quality should also be monitored and controlled, they are somewhat difficult to

measure in a quantitative way. Of course, safety and quality could be measured by the number of incidents/accidents and the number of punch list or rework items, respectively. However, from the project control perspective, this is not a preventive approach. The most useful way to measure both schedule and cost performance is to use Earned Value analysis, which combines scope, schedule, and cost performance in an integrated system.

DEVELOPING VISUAL INFORMATION SYSTEMS

The main objective of visual information systems should be to help project managers monitor actual performance in an intuitive manner and control project progress. In designing and implementing such visual information systems, the user-centered design methodology could be one of the most effective approaches because it continually addresses the usability issues and tests potential users' expectations and goals. For this reason, our research efforts have been initiated with expert interviews to understand project managers more closely, their main tasks, and their work environments. Such understanding can serve as the foundation of the conceptual design for the target visual information systems.

Expert Interviews

Experts have not only insights into aggregated and specific knowledge regarding their domain, but also privileged access to information about decision-making. Literature shows that experts are sensitive to patterns of meaningful information (Bransford et al. 1999). Expert interviews are a useful way of gathering the opinions of people who have specialized knowledge regarding particular subjects within an industry sector (Nasir et al. 2003).

For our study, experts were defined as individuals who are project managers or senior project managers in construction companies. All such individuals should have at least 10 years of experience in the construction industry to be considered experts. Experts were selected based on their experience and knowledge as determined by peer opinions and review of credentials. We contacted fifteen experts who are project managers or senior project managers in construction companies in the Puget Sound area. In-person expert interviews were conducted as individual meetings, one at a time.

The purpose of these interviews was to understand what information should be incorporated into visual information systems, focusing on the threshold level of project monitoring and control.

The interviews included some fundamental questions that cover the most important topics in terms of project monitoring and control. After introducing the research objectives, experts were asked several questions to elicit comments in the following areas:

- Major concerns when managing a construction project
- Data that should be collected for project monitoring and control
- Procedures for collecting and analyzing such data

Findings from Expert Interviews

Project managers have the overall responsibility for construction operations including the management of project information flow within their own team as well as the primary point of contact for the owner, the architect, and subcontractors. Their tasks are related to achieving project objectives and goals with the main consideration of schedule and cost. Most interviewees commonly stated, "My role is to make sure everyone gets their assignments and reports properly and make sure everything is going on as planned."

Through the interviews, we found that the information necessary for different levels of construction management in a hierarchical communication structure can vary, especially in the degree of detail. In this context, high-level project control data can be defined as the data prepared for the review of senior project managers or executives at a summary level.

One of the interviewees stated, "Certain things we need to track on a regular basis are the production to schedule and cost to verify staying on schedule and within budget. Probably, there are the two key things, schedule and cost, we are tracking." Regarding this statement, another interviewee said, "if you make your schedule and make your budget properly, no one gets hurt and the quality is what you expect. Then, everything works properly." In addition, many interviewees specifically mentioned, "Schedule is probably the most important piece to monitor. If you have your budget aligned properly, the schedule is what's important. It keeps things running." "Schedule is the key to really everything, the key to milestones, and the key to progress and expectations. Everything can be tied to the schedule. So, I call the superintendent every day, once a day or twice a day, to check where we are on the schedule." "Probably schedule information is the most critical for typical construction projects because we are in short duration and the owner is very interested in getting it done on time. Cost information is probably the second most important because part of my job is to keep within the budget."

When any performance problems or unexpected issues arise during construction, project managers have meetings or correspondence with other team members to identify their impacts on schedule and budget. An interviewee said, "Construction is a people-oriented business. It's all about people around you." He also said, "Meeting the schedule is probably the biggest challenge because there are so many inputs or factors to adjust the schedule. When a subcontractor misses its deadline, it affects our deadline." One of the interviewees stated, "In such case, I communicate and interact with all of the trade people and team through meetings, phone calls, or e-mails to ask where the job is?, what's behind?, what's coming up?, what are the milestones coming up?, and what's the corresponding cost?"

According to the interviewees, to better monitor and control a project with unplanned interruptions, the major concerns at a summary level should be:

- Prioritizing construction activities and allocating resources
- Monitoring time on project and managing project schedules
- Projecting job costs
- Reducing costs by avoiding wasting resources
- Communicating with the owner, project team, and subcontractors
- Indicating upcoming deliveries and milestones

Therefore, the key data to be collected for project monitoring and control should be related to both schedule and cost concerns. Almost all of the interviewees indicated that the most valuable and important information is monitoring the schedule. They also indicated that it is important to have a constant flow of cost information.

Based on the interviews, we conclude that effective visual information system should provide project managers with data to answer the following questions:

- What is the current status of the project regarding schedule and cost?
- Are there any potential problems or unplanned issues that need to be solved now?
- When will the project be completed?
- Where did we spend our money?
- How much will it cost to complete the project?
- What are the causes for cost or schedule overruns?
- Who is in charge of dealing with the overruns?
- If the overruns could be solved, what would be the impacts on schedule and budget?

Table 2: High-Level Project Control Data for Visual Information Systems

Information	*Item*	*Description*
Basic	Activity	Description of Activities
	Responsibility	List of Entities Assigned to the Activities
	Schedule Criticality	Critical or Non-Critical Path Activities
	Duration Times	Actual vs. Planned Completion Dates
	Float	Amount of Float
	Proportional Cost	Proportional Cost to Overall Project (including direct and indirect costs)
	Resource Usage and Rate	Description of Resources
Actual Performance	% Complete	Amount of Work Accomplished and Remaining Work
	Schedule Performance Index	Value of Schedule Performance
	Cost Performance Index	Value of Cost Performance
	Schedule Variance	Schedule Deviations between Actual and Planned Duration
	Cost Variance	Cost Deviations between Budget and Actual Cost
	Productivity	Actual vs. Planned Labor and Equipment Productivity
Forecasted Performance	Cost Projection	Estimate at Completion
	Forecasted Duration	Forecasted Total Duration

Our interviews revealed that project control data are collected and analyzed from a variety of sources including phone calls, in-person meetings, and written documents (e-mails, typed letters, daily reports, meeting minutes, labor reports, job

cost reports, and weekly or monthly progress reports). The variety of sources and formats make keeping track of the information a challenge. Indeed, as expressed by one of our interviewees, "One of the things that I would like to see in the future is a software or system to track all the important information including schedule, cost, productivity, quality, and scope of work on the same form or in some similar formats."

The result of our interviews and literature review efforts has been summarized in Table 2. For developers of visual information systems, the following considerations should be integrated into the conceptual design of their systems:

- All information necessary for project monitoring and control should be presented in a single view as much as possible to provide the "big picture" of a project.
- Activities should be displayed in time-scaled and the logical sequences of activities need to be presented.
- The current status, trends, and forecasted status of project performance need to be presented simultaneously to provide trend analysis capability and predictive potential.
- The information should be sorted by activities or work packages to easily identify problems.
- The main focus should be placed on on-going activities because they are controllable.

CONCLUSION

Information visualization can assists construction project managers in many ways, but especially in monitoring and controlling the progress of projects. However, before developing interactive visualization systems in the construction management domain, we need to explore what data should be collected to provide project managers with high-level information regarding actual project status. The objective of our research effort is to assist project managers in gaining insights into actual construction projects through visual information systems and this paper presents some of our findings regarding the kind of data that project managers valued. The objective of visualization systems should be to deliver and share relevant information with all project participants. The technology is certainly available, but such systems will not be effective unless they truly satisfy the needs of project managers.

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Towards a Cyber-Physical Systems Approach to Construction

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Abstract:
There have been several isolated attempts to automate aspects of the construction project delivery process. These have only been marginally successful and it is increasingly being recognized that significant improvements can only be made through an integrated approach that involves the synergistic integration of information technologies into the project delivery process. A cyber-physical systems approach is expected to reduce the tremendous losses that are directly attributable to the inefficiencies associated with the lack of effective integration. This paper describes a specific effort that seeks to facilitate real-time consistency checking between virtual models and the physical construction. It argues for the effective integration of computational resources (such as wireless sensors, virtual prototyping, real-time tracking and data fusion) with the design and construction process, and outlines how bi-directional consistency can be maintained between the virtual models (which are often ignored once the physical construction commences) and the physical facility. The opportunity offered by the adoption of a cyber-physical systems approach to make the construction process more intelligent and sustainable is discussed and the key benefits highlighted.

1. Introduction

Cyber-physical systems (CPS) are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core (Lee, 2009). Presently, a precursor generation of CPS, referred to as embedded systems, has been applied to several industry sectors such as transportation, critical infrastructure, healthcare, defense systems and tele-physical operation and consumer electronics. These embedded systems are information technologies and collaborative communication systems such as wireless sensors, visualization tools, real-time tracking and data fusion tools, whose emphasis is more on computational elements than on the integration between computational and physical elements. Furthermore, unlike the traditional embedded systems, a CPS is designed as a network of interacting elements instead of as standalone devices.

The construction project delivery process is grossly inefficient and in dire need of a paradigm shift that involves, amongst other things, an increased and more targeted investment in cyber-infrastructure. Developments in computational and visualization tools in the design and construction process enable a synergistic integration of computational tools and physical resources in a challenging industrial context. Greater control can be exerted over the project delivery process through appropriate integration of automated systems and emerging information and communication technologies (ICT) in the physical construction process. This cyber-physical systems approach is expected to result in a transformation of the process for the delivery of constructed facilities. The result would be a major reduction in the huge losses (estimated at over $16 billion per year by NIST) that are directly attributable to the inefficiencies associated with the current lack of interoperability (Gallagher et al., 2004). The adoption of a cyber-physical systems approach offers a tremendous opportunity to make the construction process more intelligent and sustainable.

This paper presents an approach to integrating virtual models and physical construction for real time consistency monitoring and control. It reviews and identifies limitations of previous approaches to monitor construction processes. The enabling technologies for the integration are highlighted. It also identifies the need for cyber-physical systems to improve the construction project delivery process, key features and the potential benefits of adopting this approach.

2. Trends in Virtual Prototyping and Physical Construction Monitoring

2.1 Virtual Prototyping

Virtual prototyping provides a realization of an intended design or product to illustrate the characteristics of the product or design to users before actual construction (Gopinath, 2004). Virtual prototyping evolved in response to the requirement for designers and others involved in product development to have a better feel for the end product at the earliest possible opportunity without the expense of building a physical prototype or making the product itself. This is increasingly seen as necessary within the construction industry as it extends the idea of 4D CAD (the integration of 3D geometry to schedule information) by integrating more features (simulation engine, analysis tools and decision support systems), for simulating the real construction process (Li, 2006).

Another aspect virtual prototyping is Building Information Models (BIM), which has the capacity to store embedded information that can be analyzed and utilized throughout the lifecycle of a facility. The construction industry is highly fragmented, involving various key players (Motammedi and Hammad, 2009). Application of cyber physical systems in the construction industry will therefore require efficient information sharing and exchange between the various players. BIM is emerging as having the capacity to create, share, exchange and manage the information throughout the lifecycle between all the stakeholders (Motammedi and Hammad, 2009). Numerous research efforts have identified Virtual Prototyping as having considerable potential for enhancing the construction project delivery process.

Sarshar and Christiansson (2004) described the application of VP in The Divercity research project. They investigated the role of VP in enhancing productivity and effectiveness of construction projects. They discovered that VP can assist in client briefing, constructability and design reviews, enhance communication and co-ordination between project teams. Chau et al. (2004) presented a 4D visualization model which is aimed at helping construction managers plan daily site activities. The 4D visualization model comprises of the activity schedule, associated allocation of resources and layout of facilities on the construction site. They identified 4D model as having strong potential in construction planning and management processes.

Li et al. (2006) described a framework and process for the application of 3D and 4D CAD for virtual prototyping to support project teams on construction planning. With a 3D/4D CAD system, building components from a graphical interface can be related to construction activities. The 4D CAD systems can be used for construction analysis and communication of design to the team.

2.2 Physical Construction Monitoring

Numerous sensing technologies ranging from wireless sensing technologies, tracking systems, and other instrumentation have been adopted for monitoring the physical construction.

Wireless sensor technology offers increased flexibility in terms of placement, reduced cost of installation and maintenance compared with wired sensors; this makes it suitable for adoption in the construction industry. The strength of sensors is that they can form networks such as ZigBee networks, and cooperate according to various models and architectures, capable of processing, sensing, computing and communication throughout the distributed mesh networks. The nature of sensing can vary from embedded sensing such as RFID that assesses some material characteristics of a product, to spatial sensing and imaging technologies that assess both the quality of products being constructed and the safety of processes being utilized during construction (Akinci and Anumba, 2008). In cyber-physical systems, wireless sensors serve as a real time data collection, storage and transmission system. Each sensor captures and communicates sensing information to other sensors, thus forming a wireless sensor network. These wireless sensor networks can be used to acquire and update information stored in the virtual prototype.

Song et al. (2007) developed a ‘Material Tracker’ composed of RFID and ZigBee technology which can identify the data of materials such as bulk or bundle which is loading through RFID reader. ‘Material Tracker’ also has the potential to

check the flow and location of materials in real time using ZigBee technology. From the field test carried out, they discovered that it is possible to track material location within a planned range through the movement of material tracker due to the short coverage range of RFID. On a large construction site, it will be difficult to manually move the material tracker. Xuesong et al. (2008) explored the technical feasibility of applying wireless sensing technologies for resource tracking on building construction sites. They explored various wireless sensing technologies and identified the ZigBee-based wireless sensor network as being the most promising for tracking construction resources.

2.3 Integrated Virtual and Physical Construction

3D laser scanners can analyze construction sites to collect data which is used to develop three dimensional digital models while Photogrammetry is a remote sensing technology in which geometric properties of objects are determined from photographic images. El-Omari and Moselhi (2008) presented a method, which integrates 3D scanning and photogrammetry to support progress measurement and project control. The application of the proposed method was demonstrated using a building under construction. 3D laser scanner scans the construction site from different sides; the method is proven to be time consuming and results in a delay in decision making.

Golparvar-Fard et al. (2009) proposed a method for visualization of performance metrics for progress deviations through superimposition of 4D as the as-planned model into time-lapse photography and videotaping of the as-built progress data collection. The progress information can also be visualized through augmenting the as-built photograph with the as-planned data. Data are collected from as-built and as-planned environments and merged to form a 4D as-planned simulation and time-lapsed photographs. The as-planned model is superimposed on the site photographs. This superimposed image enables discrepancy to be detected, quantified and cost values extracted. This information is appended to the known as-planned and as-built information and allows the budget spent to be properly assessed and the cost discrepancies to be understood but the photograph approach are unsuitable under bad weather conditions.

4D CAD has been applied to the preconstruction phase of projects but is rarely used in the construction phase because of a lack of efficient methods to capture as-built schedule information and to represent the information with 4D CAD to support effective decision making in a timely manner (Chin et al., 2005). RFID tags attached to steel components can be used to collect logistics and as built progress information; this status information can be input to project management information system and 4D CAD, which will reflect the current status of a project in 3D CAD models. Chin et al. (2005) developed RFID+4D CAD, which is an integrated information system that offers the opportunity of managing construction projects automatically. RFID+4D manages progress data from manufacturing to erection at the construction site based on the status of each member. Progress data for each member are collected using RFID readers and then synchronized to RFID+4D PMS (Progress Management System). This approach offers the opportunity to view progress data but does not allow control of the construction process.

2.4 Limitations of Previous Research

While previous studies have demonstrated the potential for significant improvements to the project delivery process based on better modeling of a proposed facility and tracking of construction components and resources, there is still much that needs to be done. Some of these include:

- There are limited or no effective mechanisms for ensuring bi-directional coordination between the virtual prototype and the physical construction. For example, when a key component or sub-assembly is constructed in the physical environment, there is no means of automatically updating the virtual model to reflect this. Conversely, if the design or erection sequence of a set of steel members is altered in the virtual model, there is no real time communication of this change to construction personnel on site.
- There is a lost opportunity to 'instrument' the construction process and to monitor its progress by being aware of when certain key components or sub-assemblies have been installed or built.
- There is limited scope for the use of sensors and other embedded instrumentation to control the construction activities and/or the resulting facility.

3. Need for Cyber-Physical Systems in Construction

Cyber-physical systems refer to the effective integration of, and coordination between, computational and physical systems. The concept of cyber-physical systems emerged from the need for increased adaptability, autonomy, efficiency, functionality, reliability, safety, and usability of various systems (NSF, 2008). 'Research advances in cyber-physical systems promise to transform the world with systems that respond more quickly (e.g., autonomous collision avoidance), are more precise (e.g., robotic surgery and nano-tolerance manufacturing), work in dangerous or inaccessible environments (e.g., autonomous systems for search and rescue, firefighting, and exploration), provide large-scale, distributed coordination (e.g., automated traffic control), are highly efficient (e.g., zero-net energy buildings), augment human capabilities, and enhance societal wellbeing (e.g., assistive technologies and ubiquitous healthcare monitoring and delivery)' (NSF, 2008).

The adoption of the cyber-physical systems approach in the development of buildings and civil infrastructure systems offers opportunities for enhancing construction project delivery process. The construction industry's perennial problems of relatively poor productivity when compared with other industry sectors, the lack of certainty (in terms of outturn cost, quality or delivery date), inadequate client satisfaction (it is estimated that more than 50% of construction clients are dissatisfied with the project delivery process), and the inefficiencies inherent in the use of outmoded, largely manual processes, make it an ideal candidate for a step change (Kamara et al., 2000). The opportunities offered by existing and emerging computational tools provide the enablers that can deliver the required paradigm shift. Point solutions and sub-optimal deployment of discrete tools have only resulted in marginal improvements. A cyber-physical systems approach will enable a more holistic investigation of how the construction of buildings and civil infrastructure systems can be re-engineered to enable greater process control, improved predictability of outcomes, and more intelligent, sustainable facilities. Moreover,

successful implementation of a cyber-physical systems approach will allow rapid identification of potential construction problems, definition and evaluation of alternate solutions or "mid-course" corrections, ability to communicate effectively to the construction team, and quantitative risk assessment and mitigation.

4. Towards a Cyber-Physical Systems Approach

4.1 Overview

It has been suggested that the most appropriate path to the realization of cyber-physical systems in construction lies in the adoption of a 'system of systems' approach (Bulbul et al., 2009). Systems integration has been identified as one of key approaches to help the construction industry to improve productivity and efficiency (Shen et al., 2008). Research to date has identified wireless sensing and virtual prototyping technologies as having the capacity to enhance the construction delivery process: Building Information Models have the potential to enhance creation, sharing, exchanging and management of building information throughout the lifecycle of a project (Motammedi and Hammad, 2009). On the other hand, wireless sensors can collect data and store a wide range of real time information from physical systems. Several research projects have explored the use of bar codes, RFID and other tracking technologies (Jaselskis & El-Misalami, 2003; Domdouzis, 2007) to track the movement of materials and personnel on the construction site. Others have investigated the use of wireless sensors within the context of intelligent buildings, usually to monitor environmental issues such as indoor air quality, temperature and humidity control, and heating, lighting and ventilation (Clements-Croome, 2004). However, no studies have been undertaken on instrumenting both the construction process and the constructed facility in an integrated way such that the sensors and tags enable short term progress and quality monitoring during the construction work, as well as medium and longer term monitoring and active control of the performance of the facility. Shen et al. (2008) identified the need for an integrated approach to support decision making processes in construction sites for real time project management (including dynamic scheduling) and during the operation and maintenance of built facilities for intelligent real time facility management. Thus, this integration will enable construction engineers and facility managers to make the right decisions in a timely manner so as to improve productivity and efficiency.

4.2 Key Features of the Cyber-Physical Systems Approach

The integrated systems approach (see Figure 1) can be divided into three main features, each of which involves the sharing and exchange of information:

- *Development of a virtual model of the proposed facility*: The virtual model of the building facility needs to be developed such that information can be embedded in various components of the model. This information may include material properties, installation methods and all relevant data relevant to the construction process.
- *Mechanisms for tagging and tracking physical components and subassemblies such that their placement in the facility can be monitored*: This could be achieved through the use of wireless sensor networks and other instrumentation that can

record the fact of their placement as well as their relative position to other key components.

- *System Interaction between the virtual model and physical construction*: This involves integrating the Virtual model with the corresponding physical components such that changes in the construction can be automatically communicated and reflected in the virtual model. Changes to the virtual model should also be transmitted to the affected components as appropriate. It is critical in this regard to establish effective protocols for this bidirectional coordination. Wireless sensor networks can be used for this and may be supplemented by other instrumentation; IP cameras and laser scanning.

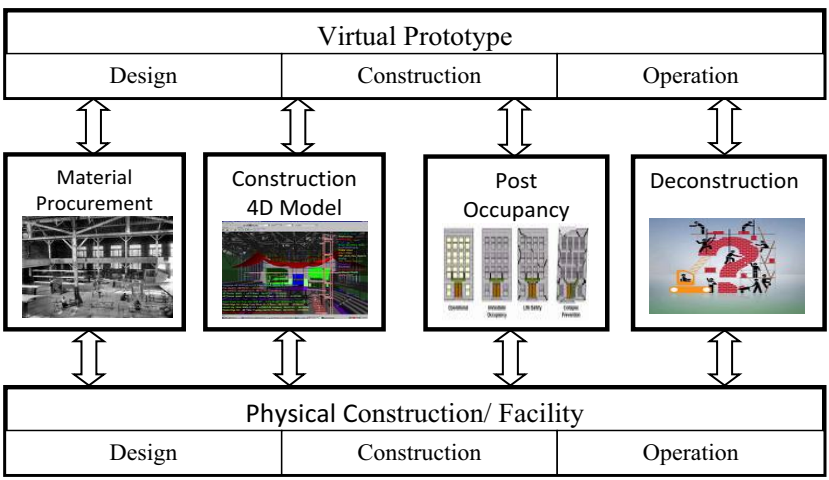


Figure 1: An Integrated Systems Approach

4.3 Potential Approach to Integration

A key aspect of the cyber-physical systems approach involves the development of an effective mechanism for facilitating real-time coordination between the virtual model and the physical construction, such that there is ongoing and evolving intelligence about the facility being built and the associated construction processes (Figure 2). The proposed approach will involve:

- Designing the positioning of the most appropriate sensor types and other instrumentation that will enable real-time data collection and aggregation;
- A plan for laboratory-scale experiments to explore bi-directional coordination between the virtual model and a small physical prototype. This will involve placing sensors on key physical components, tracking the status (placement, removal, construction sequence, etc.) of the components in the physical prototype and developing mechanisms for reflecting changes simultaneously in both the virtual model and the sensed data in the physical prototype.

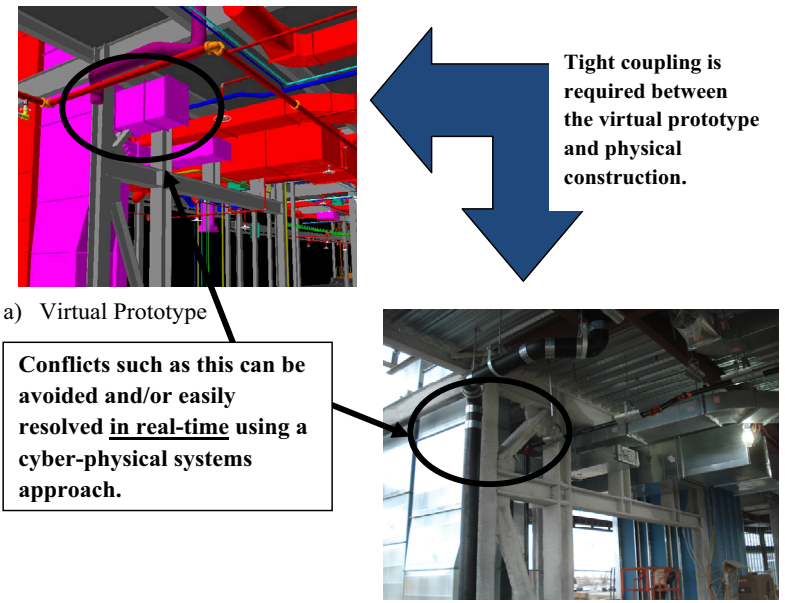


Figure 2: Tight Coupling between Virtual Model and Physical Prototype

- Exploring the most efficient data fusion algorithms for collecting and structuring the sensed data from the virtual model so that it can be used for a variety of short, medium and long term purposes – logistics, quality, safety/security monitoring. A key aspect of task is the formulation of effective rules for synchronization of the virtual and physical prototypes;
- Once effective laboratory scale systems have been proven, further validation will be undertaken on full-scale construction projects on the Penn State campus and elsewhere;
- Identification and resolution of any problems (e.g. interference) from the integrated use of different types of instrumentation on a physical construction;
- Formulation of guidelines for the adoption of cyber-physical systems approach for ensuring consistency and quality of the physical construction.

4.4 Potential benefits of Cyber-Physical Systems Approach

The integration of the virtual model of a facility and its physical construction will provide the following benefits:

- Enhanced computational support to project teams, particularly in their capacity to understand what is occurring at every stage of a project and make real-time interventions;
- Improved certainty and precision in the outcome of projects;

- Clearer understanding of project scope - this will enable better flow of instructions from the design team to the contractors and operators;
- Reduction of construction risks because the activities and processes on the construction site can be more closely monitored and controlled;
- Effective communication and coordination between the design and construction teams;
- Greater opportunities to optimize and meet the construction schedule, and achieve desired quality of work;
- Effective communication of progress information and representation of as-built and as-planned progress discrepancies are key components of successful project management and will allow corrective decisions to be made in a timely manner;
- Greater scope to embed intelligence in the construction process and to harness the potential of emerging computational tools to engender a step-change in the delivery of building and civil infrastructure projects;
- Improved safety on the construction site;
- Construction project team members can retrieve information from, and upload information to, the building information model for consistency checking;
- Access to real-time information about progress of work will reduce uncertainty during construction and thus greatly influence the project outcome and schedule.

5. Conclusions

This paper has proposed a cyber-physical systems approach to construction. This approach aims at integrating virtual models and the physical construction in such a way as to ensure bidirectional flow of information. This information can be used to control the construction activities, thereby reducing uncertainties that lead to unpredictable project outcomes. Building information models of a building facility can be developed and used to store information about the physical building components. Wireless sensors are attached to the physical component to allow the construction and operation teams capture data about materials to be utilized on the construction site and for project performance. The sensors are expected to remain within the facility during its lifecycle and can be used for inspection and maintenance purposes after the construction.

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Use of As-Built Building Information Modeling

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Abstract
With the proliferation of building information modeling (BIM) in architectural design, there will be a rapidly increasing need to create accurate as-built BIM data for existing buildings. Having an accurate as-built model of the existing structure allows owners to visualize and analyze proposed retrofit solutions and ensures that the retrofit meets the owner's requirements and provides the best value. The increased awareness of building energy consumption, green gas emissions, and LEED™ (Leadership in Energy and Environmental Design) also calls for new as-built documents based on BIM. This paper describes a approach for developing as-built BIM coupled with various data acquisition tools. Existing as-built technologies, such as 3D laser scanning, are reviewed and future uses for as-built BIM are suggested. The two case studies presented in this paper are part of an ongoing research project involving a local governmental agency building with significant renovation needs. The first describes a new method of acquiring building energy-related data: BIM paired with a sensor network. The second describes a method of creating as-built BIM using imported 2D plans. Finally, current challenges of as-built BIM technology are addressed to improve the future deployment of the proposed approach for as-built BIM.

Introduction

BIM is one of the most significant innovations in the architecture, engineering, and construction (AEC) and facility management (FM) industry. It has been recognized as a promising tool to become the vehicle of interoperability, integration, and collaboration. The major benefit of BIM is an intelligent, 3D, virtual building model that can be constructed digitally by containing all aspects of building information—

such as 3D geometries; costs; maintenance schedules; materials; structural data; and mechanical, electrical, and plumbing (MEP) systems—into an intelligent format. It can be used to develop optimized building solutions with reduced risk and increased value before committing to a design proposal.

One of the current challenges for the AEC industry is to increase the sustainability of existing buildings that have a significant impact on our natural environment, economy, health, and productivity. Many buildings are undergoing a major sustainability retrofit to reduce energy consumption and the carbon footprint. Commercial and residential buildings account for 72% of electricity consumption, 39% of energy use, and 38% of CO2 emissions (USGBC 2008). Reducing energy use in existing buildings is a high priority for local, state, and national governments. For commercial buildings in the United States of America, 36% of energy consumption is attributed to space heating, 21% for lighting, and 8% for cooling.

The problems cited above are being addressed with energy-efficient retrofit and the adoption of the sustainable guidelines, such as LEED and Green Globes™, by federal, state, and local authorities. There is also an obvious need, primarily driven by owners wanting to maximize the use of their existing buildings and assets, to confirm LEED or Green Globes standards to meet energy efficiency requirements. For example, one of the most famous buildings in the world, the Empire State Building, is undergoing an energy-efficient retrofit and will apply for LEED-EB Gold certification (Content 2009).

Two-dimensional as-built documents currently serve as a graphical communication platform for facility managers. However, that format lacks ability to deliver project data such as cost, specifications, schedules, warranties, or submittals. There is an emergent need for more comprehensive as-built BIMs that describe existing conditions such as existing energy consumption, indoor air quality, and water consumption, as well as solid and hazardous waste production.

Facility management processes, both before and after a retrofit, can be significantly improved through the use of an as-built BIM that can integrate energy-related data via sensors and associated data collection methods. As more information is accumulated in BIM, a higher level of design expertise can be contributed, as required, for sustainable design solutions. As-built BIM also can be used for studying various aspects of building performance.

Objectives

The purpose of this paper is to report the current industry practices regarding the use of as-built BIM and present case studies that demonstrates the process of linking various data sources with as-built BIM and creating as-built BIM using conventional 2D documents.

Developing As-Built BIM

3D Imaging and Laser Scanning

In a study of 3D laser scanning, Xiao, Zhan, and Pang (2007) point out that the use of terrestrial laser scanners for architectural surveying is a promising technique for producing 3D models for as-built documentation and research purposes. Three dimensional imaging and laser scanning technology was used for acquiring the 3D building spatial data which assisted the General Services Administration (GSA) in implementing historical documentation, facility condition assessment, construction as-built, and BIM projects (GSA 2009). The accuracy achieved through this process was well within the tolerances needed for subsequent repairs, maintenance, and/or renovation. A recent development employing the Trimble Total Station allows loading captured 3D spatial data directly into a BIM. The Trimble application can draw a realistic comparison between 3D models and real field situations (http://www.buildingsmartalliance.org/forum/topic.php?id=22). However, this may not be a cost effective solution due to the excessive cost of the equipment and the skilled labor required to operate the Trimble (Goedert and Meadati 2008). The GSA also notes that "important factors affecting the decision include project requirements, project schedule, and cost. For jobs involving simple geometries and readily accessible work sites, 3D imaging may not be the best choice."

Converting from 2D Drawings

The development of 2D as-built drawings through field survey is a time consuming process and, oftentimes, not accurate. BIM, supported by a centralized database, allows as-built models to be modified during construction to record geometrical variations in building components. However, upgrading to BIM from a 2D drafting system is more than simply making a change in CAD software. Rather, BIM is a completely different method of communicating building design information. To accommodate the transition, it is likely that there will be a significant enhancement of the import capabilities of BIM software (Eastman, et al. 2008). This will aid in creating an accurate as-built BIM without requiring 3D imaging.

As architectural designers and facility managers transition to BIM, the need to create as-built BIM for existing buildings is increasing rapidly. It is evident that architects will eliminate the use of 2D as-built once they fully implement BIM in the design phase. As facility managers realize the benefits of a BIM in their day-to-day work, they will want to create 3D models of existing facilities. During the transition, design firms that are quick to adopt BIM will still need to work with firms that are using 2D drafting, but they will want to be able to do the majority of their own work using BIM. Even though designers use BIM, they may be required to provide 2D contract documents to contractors due to the contractual relationships. These situations oftentimes require general contractors to recreate BIMs by tracing geometries from the 2D drawings provided (Bredesen 2009).

The Jackson, Mississippi, courthouse was used as a BIM pilot project by the GSA (Eastman, et al. 2008). The courthouse had an extended design phase, and the decision to switch to BIM was made in the middle of that process. Design began in 2002 using 2D CAD. The BIM pilot began in 2006; construction began in 2008. Because of the late implementation, a hybrid 2D- and 3D-BIM approach was used. The BIM was created from the existing 2D plans. Standard details from the 2D plans were used and several consultants continued to use 2D CAD. This project showed that it may be feasible to switch to a BIM-based design in the middle of the design process and that it is possible to integrate BIM and 2D CAD work. One of the uses of the 3D model for this project produced a virtual review of the proposed design of the courtrooms; building full mock-ups was not required. The authors of this case study expect "virtual review of spatial and environmental parameters to increase as virtual modeling becomes more prevalent."

The Camino Medical Group medical office building presents another case study that shows the coordination possible in implementing BIM while some designers are using 2D CAD (Eastman, et al. 2008). For this project, any team members using 2D design either had to convert their design to 3D or hire a consultant to do so. While this added some cost to the project, the reduction in the overall project duration paid off the initial investment.

The Sydney Opera House was recently presented in a case study showing BIM as a facility management tool. A group of designers created an as-built BIM of the Sydney Opera House using Bentley Architecture, Structure, and MEP (Cooperative Research Centre for Construction Innovation 2008). Due to the complexity of the surfaces, 3D laser scanning was employed to model the acoustic paneling in the auditorium. Using the digital model, Sydney Opera House was able to analyze design proposals and run various building simulations to compare improved solutions (Cooperative Research Centre for Construction Innovation 2008). This case study showed that accurate as-built BIMs can be created for complex structures. The Sydney Opera House BIM was useful for facility management and provided visualization for management of the infrastructure, assets, space, and furniture; tracking for scheduled and unscheduled maintenance activities; and lifecycle project information.

Future Uses for As-Built BIM

Existing Building Energy Simulations

Existing BIM programs, paired with simulation programs, are already capable of calculating energy consumption and predicting building performance for new buildings. However, this is not currently possible for the existing buildings with significant renovation needs due to complicated existing baseline conditions. Sylvester et al (2002) reported that simulation results are often comprised by uncertainty, statistics, and vague assumptions regarding the actual condition of existing buildings. This is unfortunate because there is a significant chance of misunderstanding that affects owner decisions on building energy performance.

One of the most significant opportunities offered by as-built BIM is the ability to collect real-time energy-related data. As-built BIM will be used as a central data repository and integrate diverse energy-related data sources such as utility bills, walk-in surveys, interviews, data loggers, and spot measurements. Dynamic (i.e., real-time) data related to energy performance will include energy and water consumption, temperature, CO2 emission, occupancy, and humidity. It also should be able to capture static data about the size and location of the HVAC equipment, building materials, geometries, and envelope performance (i.e., u-value of the windows). The system will also pass the data to various building energy simulation programs—eQuest, EnergyPlus, or IES <VE>—in order to achieve higher levels of energy savings. The capability to link BIM to various energy analysis programs will provide many opportunities to create more cost-effective retrofitting strategies from earlier design stages (Figure 1).

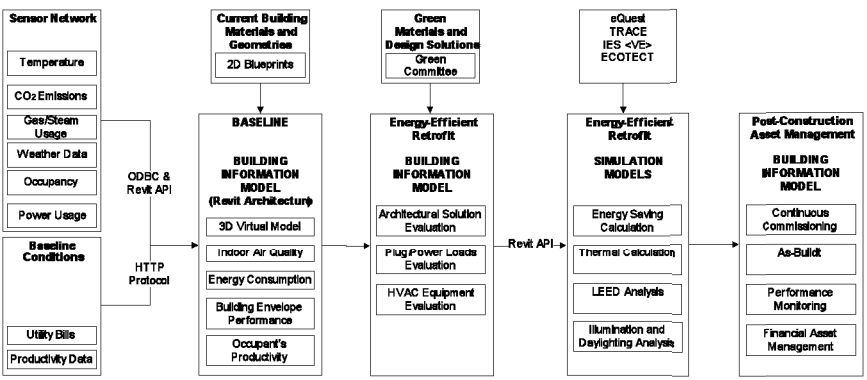


Figure 1: Central Database for BIM linked with Sensor Network

Facility Management for Existing Buildings

Over 40% of building owners currently outsource BIM implementation and 90% of those owners expect to continue or increase outsourcing to improve their facility management practices (Young et al 2008). Case studies such as the Sydney Opera House and Jackson courthouse show that an accurate as-built BIM can be useful for managing facilities and analyzing potential building projects. As tools that use BIM for facilities management expand, owners will be able to use an as-built BIM to maximize the use of their existing facilities, analyze retrofit solutions, and track maintenance. BIM can serve as a real-time monitoring system that continuously provides real-time energy data and actual operating conditions. These capabilities are not possible using traditional CAD tools. Traditional CAD tools require a separate energy analysis performed at the end of the design process, thus reducing the opportunities for modifications that could improve the building's energy performance. There is also a possibility of integrating with the existing building monitoring systems,

such as Metasys™ from Johnson Controls, Inc. Information related with commissioning, tenants, maintenance, or equipment warranty can be integrated with BIM through a building maintenance and asset management system such as Maximo™.

Historical Preservation

A case study by Penttilä et al (2007) reported using BIM for historical building renovation projects. They point out that the design phase of a BIM-based retrofit project should be started early to take full advantage of the expertise, resources, and possibility of optimizing design solutions from the beginning. They also predict the new concept of a BIM that acts as the container for all building inventory, survey, and measurement data. Historic buildings need more extensive surveys and accurate data collection about buildings considering retrofit.

LEED-EB Analysis

The LEED for Existing Buildings (LEED-EB) rating system awards certification for buildings demonstrating enhanced environmental performance in energy consumption, green gas emissions, water consumption, and solid and hazardous waste management. LEED-EB provides a comprehensive guideline for implementing systematic sustainability programs for existing buildings.

As-Built BIM Case Studies

Case Study 1: Implementing Data Import/Export from BIM

This case study demonstrated how BIM can acquire building performance data from data collection tools such as sensors and other facility control modules. This study utilized a commercially-available BIM design tool, Revit Architecture™ from Autodesk, Inc. A sample building was virtually constructed in 3D platform. Then, the model was extended as a baseline database management system (DBMS) via RDBLink, an open database connectivity (ODBC) protocol which is provided in 2009 Revit application programming interface (API). RDBLink is capable of pushing a variety of property changes that are made in the DBMS back to their corresponding elements in Revit. In addition, the RDBLink application can create a new Revit Family based on added records in the DBMS. Figure 2 shows that ODBC links the external DBMS database and Revit's database system.

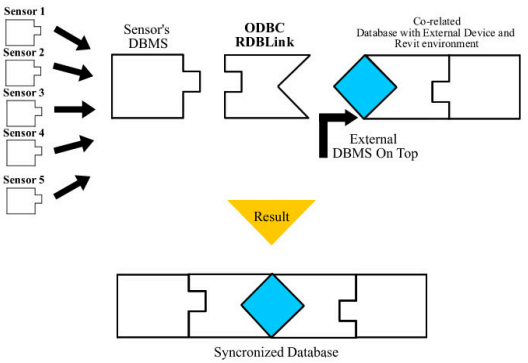
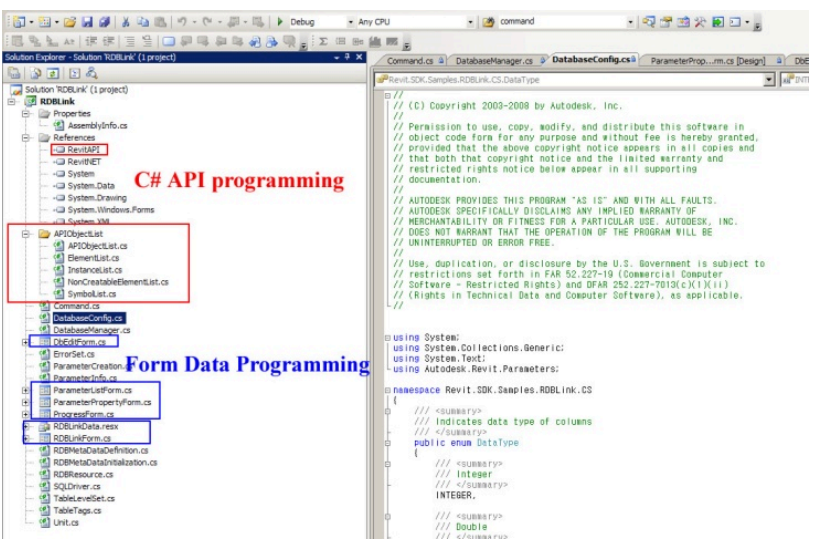


Figure 2: Synchronized Database using RDBLink

Necessary parameters for the energy-related analysis were manipulated in Revit and accessed directly from the DBMS. A prototype system was developed using .NET programming languages, including Visual Basic and C#. Visual Studio.NET was chosen as the development platform to establish the internet-based application via ODBC protocol (Figure 3).



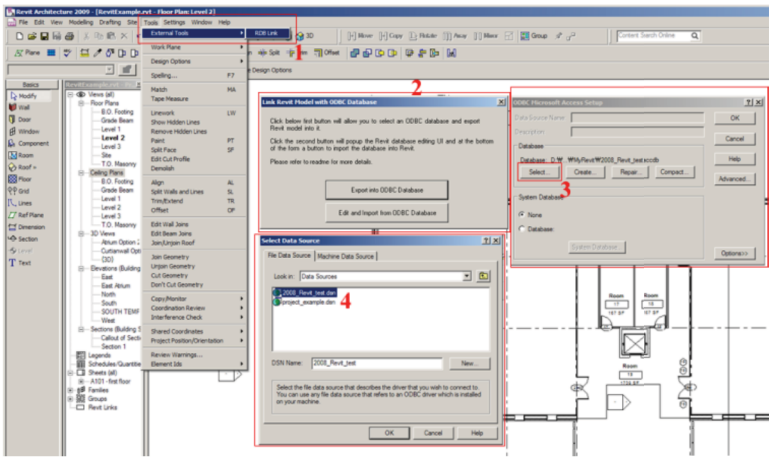


Figure 3: Visual Studio.Net Programming Environment

Case Study 2: Creating an As-Built BIM from 2D drawings

This case study demonstrated how the designers can develop an as-built BIM from 2D drawings. The building used for this case study was a medical office building in Arlington, Texas. The architectural and structural design for the project was done by Excel Engineering in Fond du Lac, Wisconsin. The project, completed in July, 2008, included construction of a new medical facility with physician office, laboratory, and support spaces.

When modeling the plan views of the building, the AutoCAD files were used as a direct reference in Revit. The 2D files were imported directly into Revit and used as a background for trace over. This process simulates the steps that would be required to create an as-built BIM of a building when the original CAD drawings are available. For this study, only the architectural and structural components of the building were included in the model. Currently, these are the two most likely parts of a building to be modeled using BIM according to the BIM SmartMarket Report (Young et al. 2008). The software used to create the BIM for this study was Revit Architecture and Structure.

The import allowed the Pick Lines feature to be used to place walls in Revit and ensured accurate placement while creating the architectural components of the model. Having the imported files as a reference was especially useful when creating the structural framing plans. Including the reference directly in the drawing allowed the beams and joists to be placed quickly and accurately. A portable document format (PDF) version of the site plan was also copied into the model and scaled up to create an approximate model of the site for visualization purposes. The architectural components of the model were created first. The first step created the building shell

and a rough out of the interior. Gridlines were the first elements placed in the model. The required level heights were also set prior to making the model. This helped to ensure dimensional accuracy as the model was created. Before beginning to create the model in place, customized wall assemblies were created in Revit. Then, the building enclosure was modeled.

After completing the majority of the architectural model, the structural modeling was begun. The first step added the foundation walls and footings and placed the columns. Next the framing was added for the second floor and roof. One of the most time consuming parts of the process was ensuring that all the roof framing elements had the proper sloping. Once those were correct, the columns were adjusted to show the correct beam-column connections. Then, the roof was added. This was done last so it could match the roof framing that was already modeled. The final step in modeling was to create the detail components of the exterior of the building. Families were made for the fascia on the clerestory roof and the coping for the walls. The entry canopy and cables were modeled using masses in Revit. Once the building model was complete, a basic copy of the site was added for visualization purposes. Once the model was completed, the final step was to validate the accuracy of the model. This was first done by dimensioning the model and confirming that the model dimensions matched the original plan. Sections of the model were compared to the sections provided in the original plans (Figure 4).

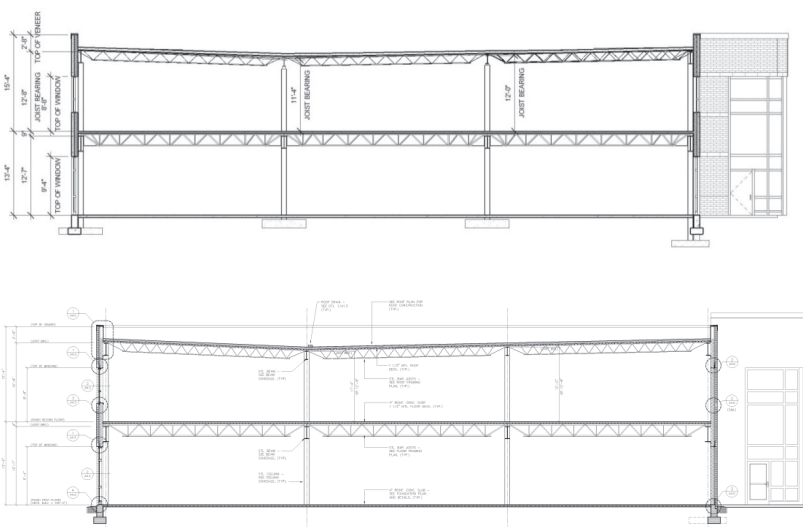


Figure 4: 2D CAD and BIM Sections

Conclusion

Two case studies discussed in this paper were part of an ongoing research project involving a local governmental agency building with significant renovation needs. The next development of the project will include capturing existing building conditions using 3D laser scanning. The approach discussed in this paper serves as an initial step toward implementing as-built BIM for energy-efficient retrofit projects. The as-built BIMs developed in these case studies identify a number of advantages, including linking capabilities with .NET programming environments, enhanced interoperability, web-enabled communication, and accurate and fast model construction. The most challenging part of creating as-built BIM is accurately creating the detail-oriented building components (decorative column crowns and the like) in the architectural model. This was the most time consuming job and had no clear relevance on building energy performance. Most of the building components needed to be created accurately to confirm the future use of the model for building energy analysis. The author noted several important standards required to successfully merge the 2D and 3D BIM efforts. These included using a common naming system, automatic user input, a common reference point, and compatible file formats. There are still many enhancements that can be made to BIM software. Further research will be undertaken to validate the proposed approach to develop as-built BIM for building monitoring and maintenance.

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A NOVEL APPROACH TO MEASURING GROUND MOVEMENTS ASSOCIATED WITH TRENCHLESS CONSTRUCTION TECHNIQUES

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Abstract:

This paper discusses the application of photogrammetric methods to monitor ground movements during trenchless construction projects. Ground movements are a concern as they can cause damage to buried utilities and surface structures. Photogrammetry is a remote sensing technique in which the geometric properties of objects and surfaces can be determined from photographic images. This technique allows for accurate three-dimensional measurements of specific points on the ground surface. Measurements are determined utilizing two or more photographs taken from different positions at specific time intervals. Photographs from specific time intervals are complied using photogrammetry software to determine the position of surface points in three-dimensional space. This paper provides an overview of the photogrammetric method, its application to trenchless projects, and results and analysis of data gathered from calibration and repeatability of measurement studies.

INTRODUCTION

Ground movements associated with trenchless construction operations can cause significant damage to existing buried and surface infrastructure. This may be the result of soil displacement, slurry or drilling fluid pressurization, over excavation, or settlement. The type of ground movement that occurs is related to the trenchless method utilized, soil conditions, and the contractor's methodology or actions during the construction operation (Bennett and Ariaratnam 2008). Subsurface soil movements may damage buried utilities, foundations, structures, and depending on the depth of cover, may manifest in surface movements. Surface movements, either

settlement or heave, can damage pavements, sidewalks, and on grade foundations (Lueke and Ariaratnam 2005).

The advantages of trenchless construction are numerous, and have resulted in rapid adoption of these techniques by municipalities and contractors over the past decade, especially for urban utility installation, rehabilitation and renovation. It is in this urban setting that ground movements are especially critical as there are frequently other utilities and infrastructure in the vicinity of a trenchless project. While some types and magnitude of ground movement may be expected with an operation or particular project, it is frequently the unexpected movement events that cause the most concern for utility owners and municipalities. Often these unexpected ground movements can cause catastrophic failures resulting in severe economic and social consequences. Figure 1 illustrates surface heave from a horizontal directional drilling operation that resulted in lifting of an electrical transformer box. As a result of such incidents, some municipalities are now requiring surface ground profile monitoring above trenchless projects as specified in construction contracts.



Figure 1. Heaving of an Electrical Transformer Box

Measurement of surface movements on a construction site has historically been conducted by conventional survey with rod and level, or total station units. Today this may also be accomplished by global positioning systems for topographic survey. They require direct access to the points to be surveyed, do not allow for simultaneous measurements of multiple points at a specific time interval, and require trained personnel to gather measurements and interpret the results. In some cases, it is not possible to access the points being surveyed or stop the construction process to obtain measurements to record a specific time interval or ground movement event.

This research focuses on the measurement and monitoring of surface ground movements utilizing photogrammetry to provide quality control on trenchless construction projects. A framework for applying this method to an installation of a 1,377 mm (54 inch) steel casing beneath a busy urban street and rail crossing is presented, along with a study to determine the repeatability of the measurement process. Compared to conventional survey techniques, photogrammetry does not require physical access to the surface or targets being monitored, but rather only requires pictures of the site using off-the-shelf cameras that can be taken by anyone familiar with the operation of a digital camera; and can provide measurements at a higher accuracy than conventional survey techniques.

OVERVIEW OF PHOTOGRAMMETRY

Photogrammetry is a remote sensing technique in which the geometric properties of objects and surfaces can be determined from photographic images (Mikhail et al. 2001). It essentially allows measurements to be made from photographs. The method used in this research is more appropriately termed stereophotogrammetry, and it is capable of estimating the location of points on objects and surfaces in three dimensions through analysis of two or more photos taken from different positions of the target area.

The photogrammetric process is based on line of sight and analysis of the geometry of the scene or subject. Utilizing a series or set of photos of the subject area, common points of interest, or targets, are identified in each photograph. A line of sight, or ray, is created between each target and the camera for each photograph. Though the triangulation of these rays for each unique target from each photograph, one can solve for the position of the camera and points relative to each other in three-dimensional space. With knowing at least one dimension in the subject scene, typically the distance between two targets, the solution can be scaled. The solution creates a virtual model of the scene, that allows for accurate measurements to be made of the position of each target.

APPLICATION OF PHOTOGRAMMETRY

This research utilized a software package called PhotoModeler developed by EOS Systems Inc. to conduct the photogrammetric analysis. PhotoModeler photogrammetry software provides image-based modeling, for accurate measurement and three-dimensional models for a variety of applications and industry sectors including accident reconstruction, archaeology and anthropology, architecture and preservation, forensics, and plant and mechanical engineering. This software is commercially available and requires minimal training to utilize.

This research utilized a Canon EOS Rebel XSi digital SLR camera with a 12.2-megapixel CMOS Sensor, equipped with an EF-S 18-55mm f/3.5-5.6 IS lens. In

order for the photogrammetry algorithm to solve for the position of the camera and target points, the cameras utilized in the taking of the pictures must be calibrated. More precisely, the geometry of the camera lens must be determined. In order to do this, PhotoModeler has a camera calibration module.

To calibrate the camera a series of twelve pictures are taken of a calibration grid. Within the grid are four uniquely coded targets near the corners of pattern that can be identified by the software. These four coded targets allow the software to automatically orient the pictures to each other. Four pictures are taken of the calibration grid with the camera in landscape position, four more with the camera rotated 90 degrees (portrait), and the final four with the camera rotated another 180 degrees (inverse portrait). Each set of four pictures is taken at 90 degrees to each other and perpendicular to the sides of the square pattern formed by the calibration grid. Photomodeler analyzes these 12 pictures to determine the parameters of the camera and lens. This is a vital process, as these parameters form the basis for the solution by triangulation.

During the calibration process – as when the cameras are utilized in the field – all parameters on the camera must be kept constant. This includes zoom setting and focal length. Thus for a particular application the calibration process should be taken under similar conditions as one would expect in the field. As a result, the cameras used in this research were calibrated at both an 18 and 55 mm focal length. In the field this allows for both telephoto and wide-angle pictures to be taken depending on what access is available to the photographer on site.

MONITORING OF AN AUGERED CROSSING

An augured crossing in the City of Glendale, AZ was selected as the inaugural project to monitor ground movements utilizing the photogrammetric measurement process. The project required the installation of a 1,372 mm (54 inch) steel casing pipe beneath Grand Avenue, a rail line, and a block wall fence (Figure 2). The installation is approximately 125 m in length, and designed with approximately 5 m of cover beneath the Grand Avenue and 7 m of cover beneath the rail line. The city and rail road company are very concerned with any ground movements that may occur during the installation process, and have outlined specific means to monitor ground movements as part of the construction contract. In the construction specifications for this project, the City requires the contractor to install settlement points consisting of a 150 mm diameter concrete pile to a depth of 1,200 mm into which a leveling hub is set. Elevations of the hub are taken at regular time intervals to monitor the settlement or have that may occur.

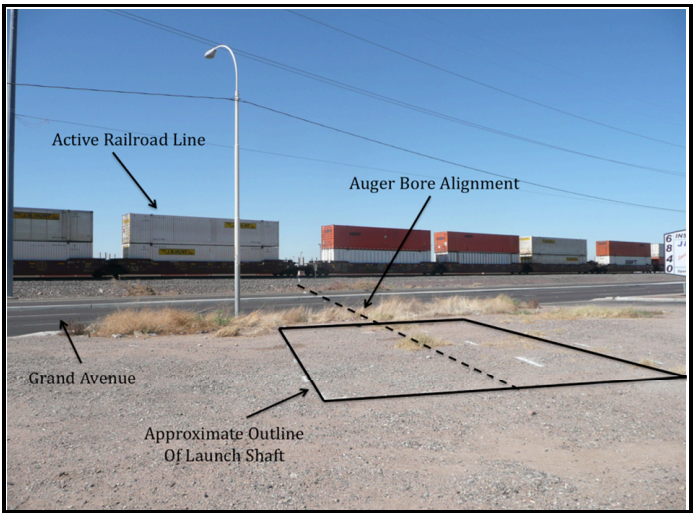


Figure 2. Layout of Augured Crossing in Glendale, AZ

To meet the contract specifications, the contractor proposed utilizing photogrammetry to monitor the ground surface for settlement or heave in three locations above the centerline of the installation. These locations are in the median of Grand Ave, and on either side of the railroad berm outside the zone of the track ballast. By monitoring the ground surface on either side of the rail line with the shallower depth of cover, it is anticipated that the contractor will get advanced warning of potential ground movement that may affect the rail line and then adjust their installation practices accordingly. While the City of Glendale found the concept of utilizing photogrammetry to monitor the installation intriguing, they wanted to maintain their existing monitoring specifications utilizing conventional rod and level techniques. This provided an opportunity to directly compare the photogrammetric method of monitoring ground movements to that of the more traditional surveying techniques.

To monitor the ground movements above the crossing, two rows of targets (10 in each row) will be installed perpendicular to the centerline of the installation, covering a total width of 2.74 m (9 ft). Targets will be spaced 30.48 cm (12 inches) apart. The proposed layout of the targets is illustrated in Figure 3. In this configuration, the settlement trough or surface heave profile can be measured and monitored during the course of the installation. Simply by taking a set of four pictures of the target area, the Photomodeler software can process the set and determine the position of each target in three dimensions. By including a control point (point that will not move during the installation process) as part of the targets, the relative movement of targets to one another can be monitored and determined with each consecutive set of pictures taken. Picture sets can be taken as required, and target positions determined within minutes. Using this methodology, and an off-the-shelf digital camera, ground

movements can be monitored on any project without the need for conventional survey equipment or crews.

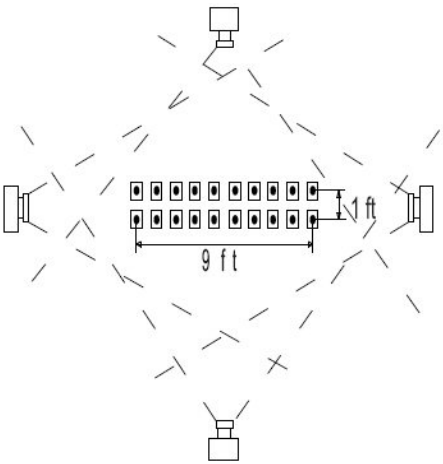


Figure 3. Target Layout for Augured Crossing Monitoring

REPEATABILITY OF MEASUREMENTS

In preparation to measure the augured crossing, a full-scale field test was setup in the same configuration as outlined in Figure 3, in a parking lot at Arizona State University. A total of ten picture sets were taken, half with an 18 mm focal length and half with a 55 mm focal length lens setting. The purpose of using two different focal lengths was to determine the accuracy of measurements at different distances to the monitoring targets. The 18 mm focal length (wide angle) allowed for the camera to be much closer to the targets, while the 55 mm focal length (telephoto) allowed the camera to be a much greater distance away from the targets, while in both cases still recording all targets in the picture frame. It is hypothesized in some applications, and during some operations on site, that having the camera in close proximity to the targets may not always be possible – thus the telephoto pictures would be necessary.

As illustrated in Figure 3, each set of photos consisted of four pictures taken at various locations around the targets. Each photo taken had to be composed in such a manner as to capture all targets within the photo frame. The optimal configuration of photos in a set are each being about 90 degrees to the target stations. However, in each set taken to determine the repeatability of the measurements the position of the cameras were randomly determined, with varying angles separating the line of site for each photo. This was done again to test the process in situations where optimal camera positions on a construction site could not be achieved.

Table 1 and 2 summarize the results of the measurement study for cameras set at 18 and 55 mm focal lengths, respectively. In each table, the average measurement of each target was provided. This is the average of five measurements or photo set analysis. The standard deviation and the average variance, the difference from the measured point to the average, are calculated. In all instances, this variance is within one standard deviation from the average indicating a good statistical correlation. These preliminary results indicate that the measurement process using photogrammetry and PhotoModeler software provides repeatable measurements.

In reviewing the average variance, or tightness of the measurements, it can be seen that for the 55 mm focal length pictures the average difference is about 3.0 mm in the X, 0.4 mm in the Y, and 0.2 mm in the Z axis; while for the 18 mm focal length the average is about 6.0 mm in the X, 1.0 mm in the Y, and 1.0 mm in the Z axis. As expected, the 18 mm focal length produced results that were not quite as good as the 55 mm focal length due to the resolution of the photographs taken. The 18 mm has a wider field of view; therefore each pixel in the photo covers a wider area making identification of the center of the target slightly more imprecise.

In a point-to-point comparison of the difference between the modeled location of the targets between the 18 and 55 mm focal length models. In general, the difference between the modeled points is less than 1.6 mm – this is the average difference between each of the 5 sets of photos taken.

Table 1. Statistics for Repeatability Measurements at 18 mm Focal Length

	Average Measurement			Stdev			Ave Variance		
Pt ID	X (cm)	Y (cm)	Z (cm)	X (cm)	Y (cm)	Z (cm)	X (cm)	Y (cm)	Z (cm)
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	-0.760	30.481	0.000	0.837	0.006	0.000	0.598	0.004	0.000
3	29.555	30.251	-0.100	0.532	0.066	0.159	0.375	0.049	0.098
4	30.267	-0.171	-0.256	0.340	0.034	0.064	0.238	0.021	0.050
5	60.721	-1.077	-0.143	0.588	0.057	0.071	0.415	0.044	0.052
6	59.841	30.188	0.019	0.448	0.096	0.077	0.324	0.064	0.064
7	90.509	30.230	-0.053	0.360	0.120	0.096	0.284	0.090	0.066
8	90.536	-0.847	-0.205	0.626	0.096	0.198	0.434	0.081	0.148
9	121.444	-0.205	-0.632	0.698	0.112	0.089	0.475	0.080	0.058
10	120.176	30.311	0.269	0.318	0.091	0.063	0.270	0.077	0.052
11	150.914	30.160	-0.174	0.402	0.154	0.088	0.316	0.114	0.067
12	151.526	-0.413	-1.062	0.634	0.139	0.069	0.473	0.092	0.052
13	182.042	0.354	-1.008	0.481	0.108	0.079	0.347	0.075	0.054
14	181.299	29.981	-0.263	0.525	0.087	0.142	0.404	0.065	0.111
15	211.823	29.896	-0.168	0.676	0.080	0.214	0.511	0.060	0.173
16	212.850	0.125	-0.813	0.363	0.141	0.094	0.266	0.090	0.066
17	243.051	0.120	-0.529	0.384	0.137	0.146	0.296	0.113	0.105
18	241.980	30.049	-0.164	0.992	0.074	0.232	0.725	0.060	0.172
19	272.004	29.954	0.591	1.269	0.055	0.267	0.906	0.046	0.192
20	272.889	0.000	0.000	0.689	0.000	0.000	0.546	0.000	0.000

Table 2. Statistics for Repeatability Measurements at 55 mm Focal Length

	Average Measurement			Stdev			Ave Variance from Stdev		
Pt ID	X (cm)	Y (cm)	Z (cm)	X (cm)	Y (cm)	Z (cm)	X (cm)	Y (cm)	Z (cm)
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	-0.958	30.484	0.000	0.209	0.006	0.000	0.159	0.005	0.000
3	29.470	30.241	-0.105	0.259	0.050	0.031	0.225	0.040	0.021
4	30.366	-0.224	-0.179	0.070	0.033	0.014	0.047	0.026	0.012
5	60.941	-1.100	-0.100	0.188	0.051	0.021	0.128	0.036	0.018
6	59.948	30.152	-0.055	0.287	0.079	0.037	0.244	0.066	0.029
7	90.644	30.158	-0.135	0.370	0.074	0.044	0.294	0.064	0.032
8	90.826	-0.961	-0.271	0.279	0.068	0.034	0.192	0.050	0.027
9	121.764	-0.239	-0.625	0.343	0.069	0.039	0.236	0.046	0.028
10	120.358	30.223	0.120	0.447	0.083	0.046	0.339	0.064	0.031
11	151.033	30.085	-0.296	0.514	0.069	0.060	0.372	0.052	0.039
12	151.850	-0.470	-1.007	0.413	0.054	0.036	0.289	0.037	0.027
13	182.279	0.277	-1.030	0.494	0.036	0.039	0.344	0.026	0.028
14	181.346	29.866	-0.420	0.559	0.104	0.046	0.388	0.076	0.031
15	211.798	29.794	-0.388	0.631	0.048	0.060	0.434	0.033	0.040
16	212.937	0.107	-0.869	0.526	0.041	0.021	0.363	0.029	0.014
17	243.007	0.083	-0.615	0.558	0.039	0.039	0.382	0.027	0.028
18	241.799	30.030	-0.355	0.659	0.039	0.059	0.456	0.029	0.041
19	271.709	29.970	0.415	0.690	0.035	0.048	0.478	0.024	0.033
20	272.695	0.000	0.000	0.611	0.000	0.000	0.415	0.000	0.000

CONCLUSIONS

Based on these preliminary results, it would appear that utilizing photogrammetry to monitor ground movements on a scale suitable for a large diameter augured crossing is feasible. The quality and repeatability of these initial results prove the feasibility of this technique, and its accuracy will be confirmed in the near future when compared to conventional survey techniques on the City of Glendale, AZ project.

The benefits of using photogrammetric techniques for the monitoring of trenchless projects include: the speed of measurement and analysis; not having to directly access the monitoring area to measure the targets while the project is underway; and the ability to use off-the-shelf consumer grade digital cameras and software with minimal training. While the accuracy of the system still needs to be confirmed, the repeatability of measurements, and the comparison the simulated field measurements are favorable.

These techniques can be applied to various trenchless construction methods where monitoring of the ground surface for movements as part of a quality control process is required. This analysis focuses on a large diameter installation, with a large potential area of influence estimated to be approximately 2.74 m in width. It is anticipated that this technique will be applicable to horizontal directional drilling, pipe bursting, pipe ramming, impact mole, tunneling, microtunneling, and guided boring methods of

construction. The authors are planning additional field monitoring projects for the various trenchless methods.

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A Stochastic Method for Condition Rating of Concrete Bridges

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Abstract

Bridge condition rating is used to make important decisions regarding needs assessment and budget allocation. This study analyzes the use of the fuzzy logic approach to overcome uncertainty problems associated with the bridge condition assessment process. The analysis reveals a number of practical difficulties associated with the application of the fuzzy mathematics to develop an overall bridge condition rating. An alternative probabilistic methodology to rate the bridge elements taking into account the uncertainty issue is developed. The Analytic Hierarchy Process is adopted to evaluate the structural importance of the various bridge elements. A technique is proposed to aggregate the condition rating and the structural importance of the bridge elements into an overall bridge condition rating. The developed methodology uses the detailed visual inspection results to perform bridge condition rating and blends perfectly with the popular Markov chain approach to model deterioration.

Keywords: Bridge, concrete, inspection, condition assessment, Monte Carlo, fuzzy, probabilistic.

Introduction

It has been evident that highway agencies have to deal with an increasing number of deficient bridges which require intervention in the years to come. Maintenance, repair and replacement (MR&R) of deteriorating bridges are among the most expensive items for these agencies. Such a high cost commitment needs rationale justification through a systematic method to assess the current condition and forecasting future

condition of existing bridges. In doing so, current conditions are defined using a condition assessment methodology while future conditions are predicted using a deterioration model. It is essential for the condition assessment and the deterioration model to be consistent in defining conditions of bridge structures for yielding reliable condition assessment.

Sasmal et al. (2006) reported that the existing literature contains extensive studies to develop condition assessment methodologies for existing bridge structures. However, these methodologies are either too simplistic (Qian 1992; Liang et al. 2001) or very complex (Kawamura and Miyamoto 2003). The simplistic methodologies do not reflect the accurate condition of the structures and the complex methodologies require considerable computation time and effort to solve the problem. Sasmal et al. (2006) developed a fuzzy based condition rating methodology for existing concrete bridges using membership functions for structural importance reported by (Melhem and Aturaliya 1996). These membership functions were originally constructed through a survey of a number of bridge engineers and inspectors in Indiana and its neighboring states (Tee et al. 1988).

The membership functions developed by (Tee et al. 1988) for the bridge elements structural importance were constructed to be general and were not bridge specific. This generalization is not supported by the stochastic nature of the deterioration process since several factors control the behaviour of the deteriorated bridge elements. Each bridge is a unique case and should be analyzed through inspection to define the structural importance of its various elements. In this research, the Analytic Hierarchy Process is proposed to evaluate the structural importance factors of the various bridge elements. The process is applied to each bridge individually to develop the structural importance factors specific to the bridge under consideration.

Fuzzy Logic for Bridge Condition Assessment

Fuzzy logic was introduced to model uncertainty of natural language by Zadeh (1965) where a logic was developed to handle the definition of partial truth which is the true value between completely true and completely false. The concept of fuzzy set is an extension of the conventional set theory. A fuzzy set, R, is defined as a set of pairs (t, $\mu R(t)$), where t is an object or an element in the universe of discourse, and $\mu R(t)$ is the degree of membership associated with the element t. If t is a continuous variable, the degree of membership can be defined by a membership function.

Tee et al. (1988) proposed a fuzzy mathematical approach to account for subjectivity, imprecision and personal bias associated with bridge inspection and condition rating process. They presented algorithms for fuzzy weighted average (FWA) computation and since then many of the proposed methodologies to perform bridge condition rating have adopted this approach (Sasmal et al. 2006, Yadav and Barai 2004).
A weighted average technique is normally used to combine pieces of information with unequal weights. The FWA extends the traditional weighted average technique by applying it on fuzzy quantities. The FWA is given by the following equation.

$$FWA = \frac{\sum_{i}^{n} W_i R_i}{\sum_{i}^{n} W_i}$$

where W_i denotes the fuzzy importance factor of the i^{th} element and R_i denotes the fuzzy condition ratting of the same element. Fuzzy addition, fuzzy multiplication, and fuzzy division, proposed by the extension principle (Zadeh 1965), are used to perform the mathematical operations and the resultant average is the FWA.

The FWA computation algorithm for bridge condition consists of the following steps:
1) Develop the membership functions for both the element condition rating and the structural importance of the various elements. The membership function for the element condition rating is a mathematical representation of the natural language rating expressions used by inspectors such as Good, Fair or Poor.

2) Translate the inspector rating variables and the structural importance of the various bridge elements to fuzzy sets by using membership functions developed in step 1.

3) Combine the fuzzy condition ratings and their structural importance using Equation 3 to obtain a fuzzy set representing the entire system.

4) Map the resultant fuzzy set obtained in the previous step to one of the natural language rating expressions. The bridge overall natural language rating is the variable that has the shortest distance from the resultant fuzzy set.
The initial effort of this research targeted the use of the FWA approach to develop a bridge condition rating methodology. However, while analyzing the approach, a number of practical difficulties have been encountered. These difficulties can affect the robustness and reliability of any condition assessment methodology that uses the FWA approach.

The major drawback of using FWA approach is that the resultant fuzzy set might not be convex. The convexity indicates that the membership function has only one distinct peak. Enforcing convexity facilitates the task of finding a natural language expression to describe a computed fuzzy set. As a result, an adjustment has to be made to the resultant fuzzy set to achieve its convexity by replacing multiple peaks with a single peak. Another adjustment that is often made to the resultant fuzzy set is the normalization. The normalization ensures that at least one element in the set has a degree of membership equal to one.

There is no apparent mathematical rationale supporting the use of convexity and normalization operations on the fuzzy set (Tee et al., 1988). However, empirical tests have shown that enforcing convexity and normalization produced a more reliable and accurate final translated results (Mullarky and Fenves 1985).

There are no standard guidelines or procedures to enforce these two constraints and the process is left for judgment. This might not be suitable for atomizing the condition rating process for a network of large number of bridges.

One more problem associated with the FWA technique is the final mapping between the resultant fuzzy set and the rating variables. The shortest distance approach is normally used to map the resultant fuzzy set of the entire system back to a rating variable. The natural language with a membership function that has the shortest distance from the resultant fuzzy set is the one used for the overall bridge condition rating. This approach does not take into account how much shorter the distance between one rating variable and another. In certain cases, the distances between the fuzzy set and the membership function of two rating variables are the same or close to each other. It is not clear in such cases as to which rating variable will be used in order to rate the bridge conditions.

Alternatively, probabilistic analysis using the Monte Carlo simulation technique would be favorable in avoiding these issues. The following section discusses applying probabilistic analysis to develop bridge element condition rating.

Stochastic Bridge Condition Rating Using Simulation

An effective way to deal with uncertainties is through simulation which can provide more accurate estimates using a large number of "what if" scenarios. The Monte Carlo simulation is a stochastic technique that randomly generates values for uncertain variables over and over to simulate a model. This technique can be used to evaluate a bridge element condition index (*BECI)*. The index is estimated using the following equation:

$$BECI = (\text{current element value}/\text{initial element value}) \times 100$$

A range is defined to represent the remaining element value in Excellent, Good, Fair and Poor condition states and a probability distribution can be assigned for each range to represent the variable frequency. For each iteration, the simulation selects random values from the defined ranges and calculates the *BECI*. After running several iterations, the simulation will develop the distribution for the *BECI*. Pessimistic, optimistic, and most likely remaining element values for each condition state are defined in Table 1. Triangular probability distributions are used to define the distribution of each variable within each interval.

Table 1: Remaining value of the bridge deck at the four condition states

Condition State	Pessimistic	Most likely	Optimistic
Excellent	0.81	0.90	0.95
Good	0.576	0.70	0.80
Fair	0.31	0.45	0.575
Poor	0.075	0.15	0.30

Kawamura et al. (2003) identified values of a condition index to represent the different condition states. Similar values of the condition index are used to represent Poor, Fair, Good and Excellent, respectively as presented in Table 2.

Table 2: Values of condition index for the four condition states

Condition State	Condition Index
Excellent	87.6–100
Good	62.6–87.5
Fair	37.6–62.5
Poor	0-37.5

Crystal Ball software is used to run Monte Carlo simulation and to identify the probability associated with each condition state. Many simulations can be run to evaluate the *BECI*. Each simulation uses random values from the range of values defined in Table 1 for each condition state. The purpose of each simulation is to evaluate the *BECI*. The frequencies of having the *BECI* in the range of Excellent, Good, Fair and Poor condition states are estimated. For example, if the simulation runs for 1000 iterations and for 700 iterations the *BECI* is estimated to be between 62.6 and 87.5, then the probability of the element to be in Good condition state is 70 %.

An example to demonstrate the concept is presented in Table 3. The bridge element condition index is estimated using Monte Carlo simulation. Five thousand iterations were performed to evaluate the probability associated with each condition state. The result of the simulation is shown in Figure 1. The $BECI_{Deck}$ ranges from 57.92 to 71.52 with a mean value equal to 64.65.

Table 3: Bridge elements inspection results

Element	**Total Quantity (m^2)**	**Excellent (m^2)**	**Good (m^2)**	**Fair (m^2)**	**Poor (m^2)**
Deck	1000	500	100	200	200
Beams				300	300
Abutments	100		50	50	
Piers	100		50	50	
Barrier	200		120	80	

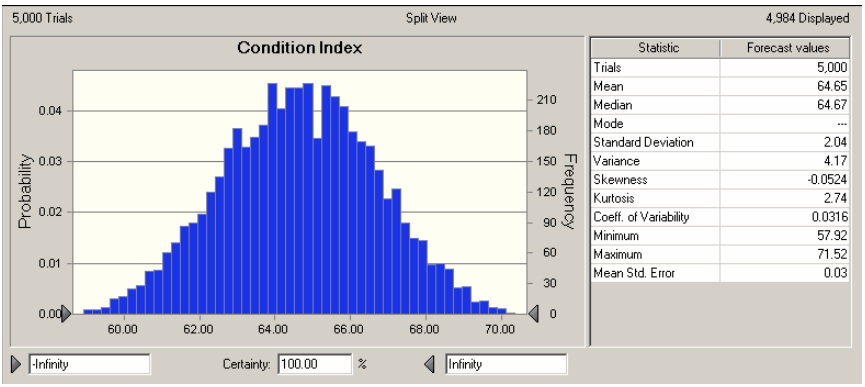


Figure 1: Simulation result for the *BECI*

The probability of the bridge deck to be in a Fair condition state with a BDCI ranges between 37.6 to 62.50 is 15.01% and the probability of the bridge deck to be in Good condition state with BDCI ranges between 62.50 to 87.50 is 84.99% as shown in Figure 2. The final condition vector which holds the probability of the bridge deck to be in Poor, Fair, Good and Excellent condition, respectively, is as follows: [0 15.01% 84.99% 0].

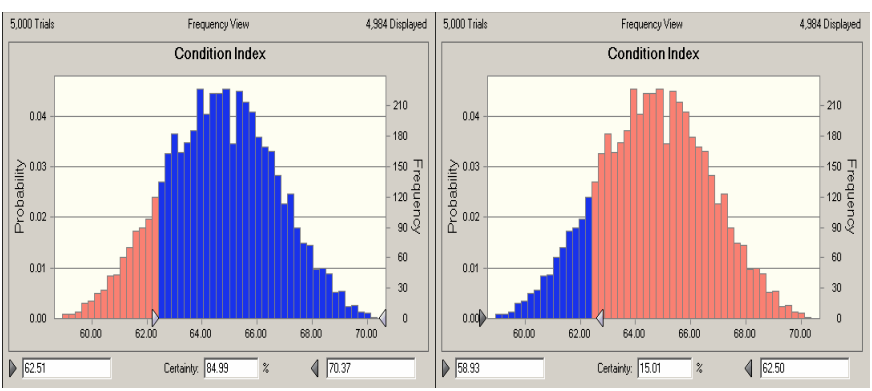


Figure 2: Probability of $BECI_{Deck}$ to be in Good and Fair condition states

Following the methodology presented above, the condition vector for the different bridge elements can be developed. The condition vectors for the bridge elements are presented in Table 4.

Table 4: Bridge elements condition vector

Element	Condition Vector [Poor Fair Good Excellent]
Deck	[0% 15.01% 84.99% 0%]
Beams	[96.77% 3.23% 0% 0%]
Abutments	[0% 94.49% 5.51% 0%]
Piers	[0% 94.49% 5.51% 0%]
Barrier	[0% 80.75% 19.25% 0%]

Structural Importance Factors for Bridge Elements

There is no precise definition of the structural importance of the different bridge elements in literature. Tee et al. (1988) referred to the structural importance as the structural role of the element. This research defines the structural importance of bridge element as the degree the element contributes to the overall structural integrity and safety of the bridge.

The Analytic Hierarchy Process (AHP) is used to extract the expert judgment and to evaluate the structural importance of the different bridge elements. The AHP is a general theory of measurements developed by Thomas Saaty (1980). Two fundamental steps are required to use the AHP methodology. First step is the task of simplifying the problem where the complex system is broken into a hierarchy structure. Second step is the task of performing pairwise comparisons to measure the relative impact of different elements in the hierarchy and to establish relations within the structure. A fundamental scale of absolute values for representing the strength of judgments has been developed and validated (Saaty 1980). In this approach the decision maker expresses his/her opinion about the value of one single pairwise comparison at a time. Usually, the decision maker has to choose an answer among discrete choices. Table 5 presents the scale of relative importance.

Table 5: Scale of relative importance

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

For the purpose of evaluating the structural importance of the bridge elements, a two level hierarchy structure is developed as presented in Figure 3. The bridge inspector and expert are required to compare each two elements with respect to the overall bridge structural criticality and to specify the intensity of the relative importance. If an element jeopardize the bridge safety and integrity while another one has limited effect on safety and integrity then the first one has absolute importance over the second one. The bridge elements are compared in pairs and the intensities of the relative importance are specified.

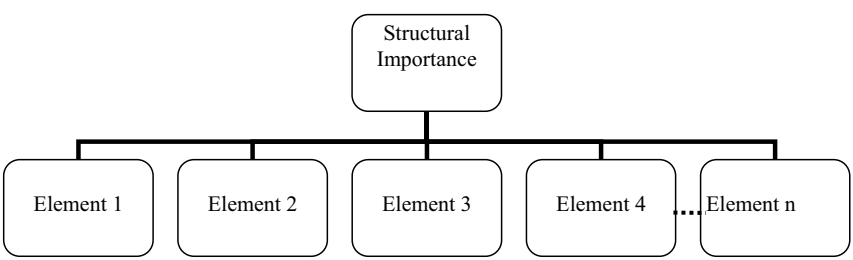


Figure 3: Hierarch structure for the elements' structural importance

Defects and extent of distress of the various elements determine their structural importance. The detailed visual inspection should capture these defects and evaluate the extent of distress of the various elements. The effect of these defects and distress on the structural performance of the elements should be analyzed and included in the judgment.

The results of the pairwise comparison are laid in a reciprocal matrix of comparison as shown in Table 6. In this matrix, a_{ij} is the relative structural importance of element i with respect to j. This matrix is reciprocal once it satisfies the following two conditions: $a_{ij} = 1/a_{ji}$ and $a_{ii} = 1$ for all i and j.

Table 6: Pairwise comparison for elements structural importance

	Element 1	Element 2	Element 3	Element 4	……	Element n	Structural Importance
Element 1	1	a_{12}	a_{13}	a_{14}	……	a_{1n}	S_1
Element 2	a_{21}	1	a_{23}	a_{24}	……	a_{2n}	S_2
Element 3	a_{31}	a_{32}	1	a_{34}	……	a_{3n}	S_3
Element 4	a_{41}	a_{42}	a_{43}	1	……	a_{4n}	S_4
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
Element n	a_{n1}	a_{n2}	a_{n3}	a_{n4}	…	1	S_n

The structural importance of the various elements is developed as a vector of priorities which is a normalized eigenvector and estimated in two steps. First is to normalize the developed matrix of comparison by computing the sum of each column, and then dividing each element in each column by the sum of that column. Second is to compute the average of each row which represents the priority weight of the corresponding element. First row corresponds to the first element and second row corresponds to the second element and so on. The structural importance factors are presented in Table 7.

Table 7: Pairwise comparison of elements structural importance

	Deck	Beams	Abutments	Piers	Barrier	Structural Importance
Deck	1	1/7	1	3	2	0.127
Beams	7	1	7	9	7	0.630
Abutments	1	1/7	1	3	1	0.110
Piers	1/3	1/9	1/3	1	1	0.056
Barrier	1/2	1/7	1	1	1	0.076

An important feature of the AHP methodology is the ability to check for consistency in judgments. Abu Dabous et al. 2007 presents the details of the consistency check in the AHP.

Summary and Conclusions

The fuzzy logic approach to rate bridge conditions was evaluated and its practical difficulties were discussed. Alternatively, a probabilistic methodology to perform

bridge condition rating was developed. Element level bridge condition index based on the remaining value of the deteriorating quantities was also developed. The Monte Carlo simulation technique was used to evaluate the probabilities of the bridge deck being in one of the four condition states namely, Excellent, Good, Fair and Poor. The AHP was adopted to evaluate the structural importance of the bridge elements. A technique to aggregate the condition ratings and the structural importance of the bridge elements into an overall bridge condition rating was proposed. The proposed methodology evaluates the structural importance of the bridge elements in a robust manner. Once the methodology is implemented, it enables the decision maker to retrieve bridges or elements that require intervention from a bridge network.

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Analysis of Injury and Fatal Crashes in Highway Construction Zones

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ABSTRACT:

This paper presents a comprehensive data analysis of recent highway construction zone crashes in the state of Illinois to provide a better understanding of the characteristics of these crashes in order to identify effective safety measures to improve construction zone layouts. The two main research objectives of this data analysis are to (1) analyze the frequency and severity of work zone crashes; and (2) investigate probable causes and contributing factors of these work zone crashes. To accomplish these objectives, two main research tasks were performed that focused on: (a) gathering the most recent and comprehensive set of data and reports on highway construction zone crashes in Illinois; and (b) studying the correlation among all construction zone crash variables that are available in the gathered data to investigate probable causes and contributing factors of this type of highway crashes.

INTRODUCTION

Work zone crashes are defined as crashes that occur in the terrain of a work zone whether it is a construction, maintenance, or utility work zone (MUTCD 2003). Work zone safety and mobility continues to be a major concern for the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO) as well as most state Departments of Transportation (DOTs). The current highway construction and maintenance work zone crash data indicates that there is an average of 745 fatalities and 40,700 severe injuries per year (Zech et al. 2005). Figure 1 illustrates the total number of fatalities per year in highway construction and maintenance zones during a 13-year period from 1995 to 2007 (FARS 2008).

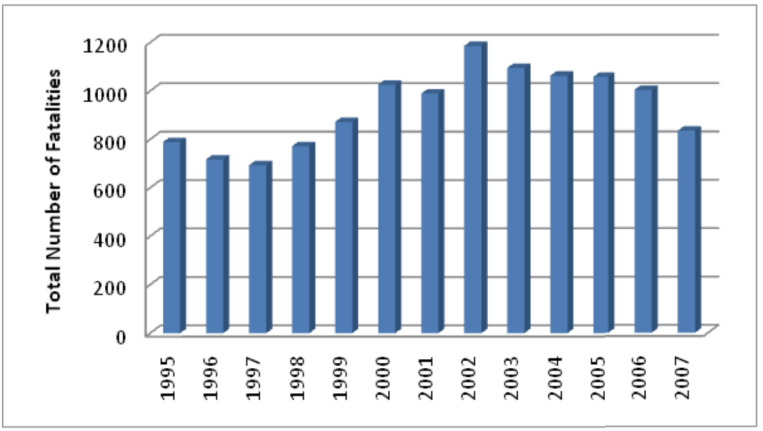


Figure 1: Total number of fatalities in construction/maintenance zones per year (1995-2007) (FARS 2008).

A number of research studies have been conducted to investigate and improve work zone safety in various states (Daniel et al. 2000; Raub et al. 2001; Garber and Zhao 2002; Bai and Li 2006; and Harb et al. 2008). Daniel et al. (2000) examined the difference between fatal crashes within work zones and fatal crashes in non-work zone locations in the State of Georgia to identify the manner of collision, location, and construction activity associated with fatal crashes in work zones. Raub et al. (2001) studied work zone crashes in the State of Illinois between 1994 and 1995. The analysis examined similarities and differences between work zone and non-work zone crashes for these twp years. Garber and Zhao (2002) investigated the characteristics of work zone crashes that occurred in the State of Virginia from 1996 through 1999 based on police crash reports and re-categorized crashes according to work zone layout. Bai and Li (2006) analyzed fatal crashes that occurred in the State of Kansas between 1992 and 2004 to identify basic characteristics. Harb et al. (2008) in a recent study focused on the analysis of work zone crashes in the State of Florida for years 2002, 2003, and 2004 to evaluate basic features of freeway single-vehicle and two-vehicle crashes in work zones. Despite the significance and contributions of these studies, work zone safety remains a critical and pressing concern nationwide since most of these studies investigated work zone crashes characteristics aside from work zone parameters that may affect the injury severity of work zone crashes.

There is a pressing need to investigate and indentify various work zone parameters that correlate with the injury severity of work zone crashes in order to improve safety in and around construction and maintenance work zones. To address this research need, a comprehensive data analysis of recent highway construction zone crashes in the State of Illinois (2003 ~ 2007) is presented in this paper to provide a better understanding of the characteristics of these crashes in order to identify effective safety measures to improve construction zone layouts. The objectives of this paper are to (1) analyze the frequency and severity of work zone crashes; and (2) investigate probable causes and contributing factors of these work zone crashes. To

accomplish these objectives, two main tasks were performed that focused on: (a) gathering and fusing the most recent and comprehensive set of data and reports on highway construction zone crashes in Illinois; and (b) studying the correlation among all construction zone crash variables that are available in the gathered data to investigate probable causes and contributing factors of this type of highway crashes.

CRASH DATA COLLECTION AND FUSION

The first task in this analysis focuses on gathering available data and reports on work zone crashes in Illinois from all available resources to build a comprehensive dataset. This was accomplished by collecting the latest available data on work zone crashes in Illinois from all available resources, including: (1) the National Highway Traffic Safety Administration (NHTSA); and (2) the Highway Safety Information System (HSIS).

NHTSA crash data files for the state of Illinois contains data on approximately 400,000 accidents per year structured in three main files: (1) crash file; (2) vehicle file; and (3) person file (NHTSA 2007). A single crash case may occupy multiple rows in the person file depending on the number of persons involved in a crash. HSIS crash data contains only a subset of the aforementioned NHTSA crash data records as it includes between 105,000 and 205,000 crashes per year (www.hsisinfo.org). The main reason that the HSIS data was collected and analyzed in this study is the additional road and traffic data that it provides that are not available in the aforementioned NHTSA data files (Council and Mohamedshah 2009). The crash dataset provided by HSIS for the State of Illinois has, in addition to the aforementioned three NHTSA files, a fourth file (Roadlog file) that contains additional data on the road and traffic such as number of lanes, lane width, median type and width, Annual Average Daily Traffic (AADT), commercial volume, and speed limit.

The work zone crash dataset that was used in this study included 1,729 records that represent recorded injury and fatal work zone crashes in the State of Illinois during a 5 year period from January 1, 2003 to December 31, 2007. This work zone crash dataset was created and organized in four main steps. The first step involved extracting work zone crash records from all the available records and combining them in a single spread sheet. The second step involved extracting work zone injury and fatal crash records excluding property damage only (PDO) work zone crashes. The third step involved joining crash files and roadlog files using both “Cntyrte: County Route” and “milepost” in crash files and matched with “cnty_rte: County Route” and “begmp: Beginning milepost” in roadlog files. This link resulted in a dataset that included records of 1,729 work zone injury and fatal crashes with data on 30 different variables. The fourth step was to reorganize the observations of 26 variables among a total of 30 variables into sub-categories to better quantify the correlations among variables. For example: the contributing cause variable encloses 31 observations that were regrouped in 6 subcategories. Another example: 6 sub-categories were developed to represent the AADT of each road in which a work zone crash occurred instead of using the actual number. The list of the 30 crash variables is shown in Table 1.

Table 1: Work zone crash variables

Major Category	Variable
1- Time Data	1- Accident Year
	2- Acc Hour
2- Crash Data	3- Severity
	4- Injury Severity
	5- Total Killed
	6- Total Injured
	7- Type of Collision
	8- Number of Vehicles
3- Contributing Causes	9- Cause 1
	10- Cause 2
	11- Traffic Control Type
	12- Traffic Control Condition
4- Road Data	13- Road Classification
	14- Class of Trafficway
	15- Route Prefix
	16- One way Indicator
	17- Intersection Relevance
	18- Type of Construction
	19- Number of Lanes
	20- Surface Type
	21- Road Surface Condition
	22- Median Type
	23- Median Width
5- Traffic Data	24- AADT
	25- Multiple Daily Volume
	26- Commercial Volume
	27- Million Vehicle Mile Travel
	28- Speed Limit
6- Environment	29- Light
	30 Weather

CORRELATION ANALYSIS OF WORK ZONE CRASH VARIABLES

Tests for independence were performed to identify the association and potential correlation among the aforementioned crash variables. Two statistical tests for independence were used in this study: Pearson chi-square and likelihood-ratio chi-square (Bai and Li 2006; SAS Institute Inc. 2006). Regardless of the different advantages of these two independence tests, they were both adopted in this study to assure the maximized accuracy when identifying all possible correlations. A dependent relationship was determined if and only if both tests supported it (i.e., p-value < 0.05). Each crash variable was tested against all other variables. The p-values for both statistical tests were calculated to test whether a null hypothesis could be accepted or not, and at a significance level of 5%, if p-value is larger than or equal to 0.05, the null hypothesis H0 is considered and the two factors are not correlated. If the p-value is less than 0.05, the alternative hypothesis H1 is considered and the two factors are correlated.

Correlation Results

All possible correlations among the work zone variables were evaluated using the aforementioned two correlation tests and a correlation matrix has been developed showing all possible correlations. This paper presents an example set of the identified correlations between the injury severity variable and five other variables as shown in Table 2. These correlations are discussed in more details in the following sections including their crash frequency percentages.

Table 2: Identified correlated variables of the severity of injuries in work zone crashes

Correlated Crash Factors		Pearson Chi-Square		Likelihood Ratio Chi-Square	
		P-Value	Related	P-Value	Related
1- Injury Severity	Type of Collision	<0.0001	YES	<0.0001	YES
2- Injury Severity	Contributing Cause	<0.0001	YES	<0.0001	YES
3- Injury Severity	Surface Type	0.0057	YES	0.0295	YES
4- Injury Severity	Median Type	0.039	YES	0.0324	YES
5- Injury Severity	Speed	0.052	YES	0.04	YES

Injury Severity and Type of Collision

The results of the correlation analysis show that the severity of work zone injuries is correlated with the type of collision as different collision types tended to cause different degrees of injury severity, as shown in Figure 2. The results show that the majority of rear-end crashes had only complaints with no visible injury while the majority of other collision types such as angle and fixed object crashes produced visible injuries rather than complaints of pain.

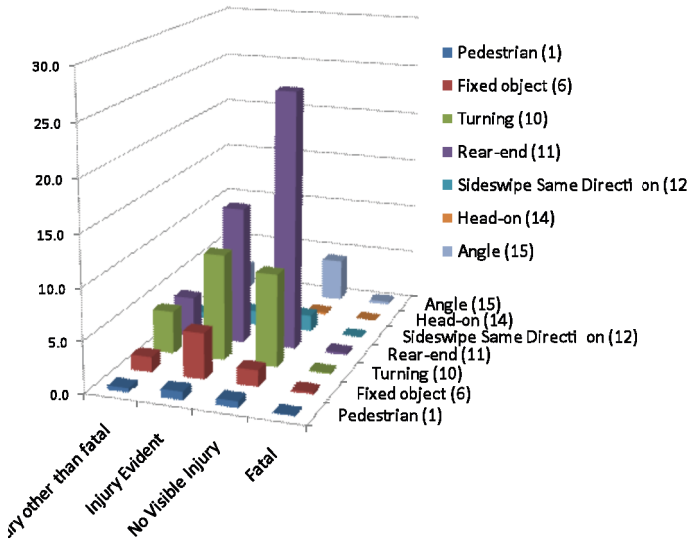


Figure 2: Crash frequency percentages by injury severity and type of collision

Injury Severity and Contributing Cause

A detailed analysis of this correlation indicates that speed was the dominant contributing cause of fatal crashes while improper driving was the leading cause of injury crashes, as shown in Figure 3. The results also show that the top three causes of injury crashes are improper driving, speed and work zone environment.

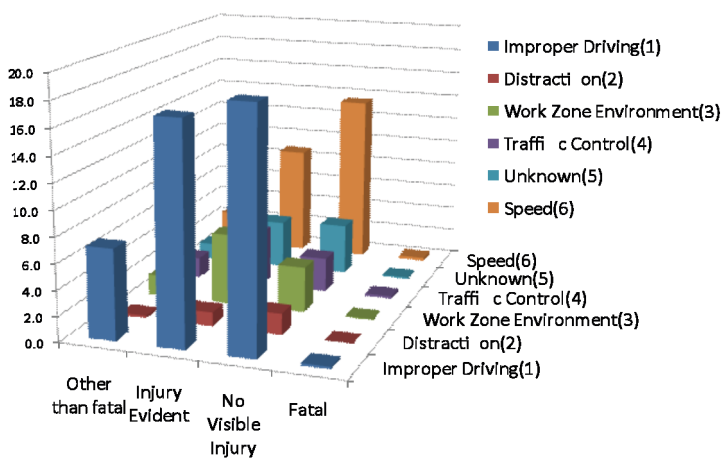


Figure 3: Crash frequency percentages by injury severity and contributing cause

Injury Severity and Surface Type

The results of the correlation analysis show that the severity of work zone injuries is correlated with the surface type of the road. A detailed analysis of this correlation indicates that more than 40% of the reported evident injury crashes occurred on Portland Cement Concrete (PCC) roadways with unknown reinforcement (type 600) as shown in Figure 4.

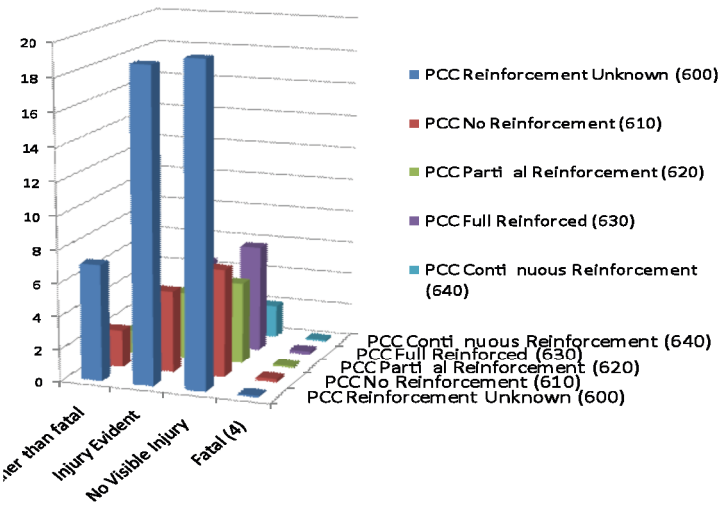


Figure 4: Crash frequency percentages by injury severity and surface type

Injury Severity and Median Type

The results of the correlation analysis show that the severity of work zone injuries is correlated with the type of median in the road. A detailed analysis of this correlation indicates that more than 37% of fatal crashes occurred in roadways that had no medians while no fatal crashes occurred in roads with rumble strips and painted medians, as shown in Figure 5. The results also show that more than 50% of injury crashes occurred on roadways that had no medians or curbed medians.

Injury Severity and Speed Limit

The results of the correlation analysis show that the severity of work zone injuries is correlated with the speed limit of the road. An in-depth analysis of this correlation indicates that more than 50% of fatal work zone crashes occurred in roads that have a speed limit of 50 mph or higher, as shown in Figure 6. In roads with a speed limit of 65 mph, more than 70% of work zone crashes had evident injuries while that percentage dropped to 57% in roads with lower speed limits. This confirms that injuries sustained in work zone crashes are more severe in roads that have higher speed limits.

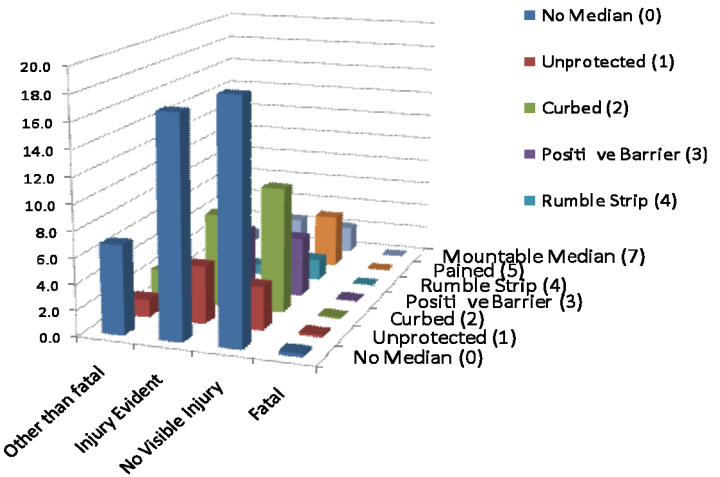


Figure 5: Crash frequency percentages by injury severity and median type

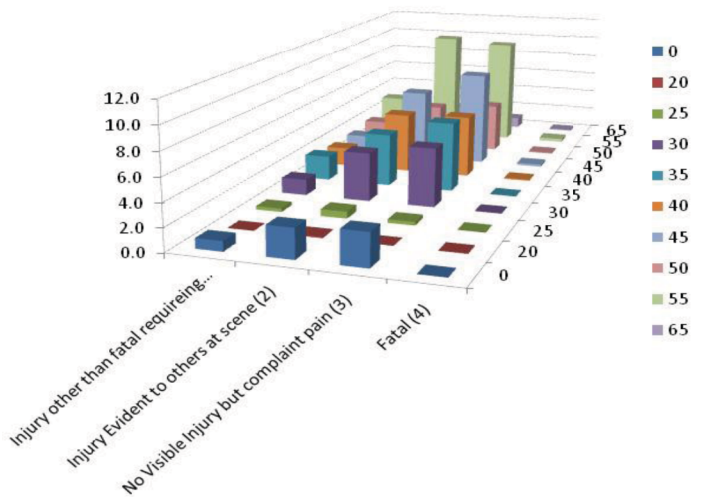


Figure 6: Crash frequency percentages by injury severity and speed limit

SUMMARY AND CONCLUSION

This paper presented a comprehensive data analysis of 1,729 highway construction zone fatal and serious injury crashes in the state of Illinois during a 5 year period (2003~2007). The main research objectives of this data analysis were to: (1) analyze the frequency of work zone crashes corresponding to various crash variables; and (2)

investigate probable causes and contributing factors of these work zone crashes. Thirty variables representing (1) crash data; (2) vehicle data; (3) driver data; and (4) roadway and traffic data were studied. The methodology of data collection and fusion was presented in more details. The $\chi 2$ statistic at a significance level of 0.05 revealed more than 120 possible correlations. Five correlations pairs between the injury severity variable and five other variables were analyzed in more details and crash frequency percentages were developed. The main findings of this analysis include:

(1) The severity of work zone crashes was found to be correlated with and affected by the type of collision, the drivers' actions that caused the crash, the type of road surface, the type of median and the speed limits of the road.
(2) The majority of rear-end crashes had only complaints with no visible injury while the majority of other collision types such as angle and fixed object crashes produced visible injuries rather than merely complaints.
(3) More than 40% of the reported work zone crashes that caused evident injuries occurred on PCC roadways with unknown reinforcement.
(4) More than 37% of fatal crashes occurred in roadways that had no medians while no fatal crashes occurred in roads with rumble strips and painted medians.
(5) The correlation results show that more than 50% of injury crashes occurred on roadways that had no medians or curbed medians.
(6) More than 50% of fatal work zone crashes occurred in roads that have a speed limit of 50 mph or higher.

ACKNOWLEDGEMENT

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Community-Driven And Reliability-Based Budget Allocation For Water Networks

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ABSTRACT

City managers and elected officials in many municipalities are frequently faced with the challenge to cater for public expectations on one hand and to comply with technical/engineering requirements on the other. This paper presents a four phased level of service driven reliability based methodology for allocation of budget to water mains. This methodology comprises of: (1) development of an Analytical Hierarchy model of LoS; (2) a sub-network criticality model to account for certain quantitative and qualitative characteristics of a given sub-network (3) a sub-network reliability assessment model and 4) a budget allocation model. Combination of the above contradicting requirements, i.e. level of service and network reliability, is expected to assist decision makers in quantifying the required condition improvement to meet service goals and to make more informed decisions on interventions and relayed priorities. To show the robustness of the developed models, a hypothetical case study is developed and analyzed.

***Keywords*:** Asset Management, Budget Allocation, Level of Service, Reliability, Sub-Network

INTRODUCTION

The Canadian Federation of Municipalities (InfraGuide 2004), defines asset management as: "The combination of management, financial, economic, engineering, operational and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner". Best practices for municipal asset management require municipalities/communities to clearly define and state their respective goals that reflect their expectations (e.g. levels of service). Establishment of level of service should be a fact-based, rational, transparent, reproducible and systematic process that not only assists in planning, but also in tracking and monitoring assets' performance against those initially set by the communities. Developing levels of service is essential to the rationalization of asset management decision making processes. In a way, levels of service define the terms of reference, set by the community either directly, through public consultation, or indirectly via elected officials, for the quality of services rendered by the municipality (Moselhi 2005). Levels of service are composite indicators, which may vary from one community to another, and account for the social, environmental and economic goals of the community as well as for its budget constraints. Establishment and achievement of levels of service are therefore important for sustainable development, which has been defined as "meeting the needs of the present generation without compromising the ability of future generations to meet their own needs" (InfraGuide 2003). Generally, the risk associated with assets is directly related to the condition and probability of failure of the assets whereas the targets for asset condition and risk tolerance are related to the levels of service to be delivered to the public by the authority (InfraGuide 2006). Depending on the age and condition, the potential for infrastructure failure or reduction in level of service can increase. This risk arises from the deterioration of assets. Knowing the representative condition and the historic deterioration and failure/ break rates of the various groups of assets is therefore, a prerequisite of asset management decision making. An asset management plan must ensure that current users pay a fair share for the service so future users do not have to pay a higher cost for the same level of service. It is therefore rational to suggest that an efficient asset management plan, while maintaining an adequate level of service should also minimize level of risk, which may be measured and expressed in terms of system reliability. Level of service can, therefore, be considered as an integral part of sustainable municipal asset management which has an upward link with sustainable asset management plan and a downward link with asset condition assessment and network reliability. The objective of this paper is to develop a community driven and network reliability based methodology for sustainable management of water distribution networks.

PROPOSED METHODOLOGY

The data requirement for the proposed methodology can be grouped into two categories. First is the segment related information where data relating to asset identification and performance is required. Ranges of values of performance measures corresponding to each level of service and the failure threshold values of

each indicator are to be set. Second is the network related information which involves population size, sub-network tax base, level of complaining by local residence and the type of sub-network. Further details can be found in InfraGuide (2002a). Additional information on benchmarking can be found in AWWA (1996), AWWA-RF (1996) and Keehley et al (1997). The proposed methodology consists of four integrated models the detailed description of which is given below:

Model 1: Level of Service (LoS) Model

This model accounts for community goals and expectations. The Analytical Hierarchy Process is used for quantification and measurement of Network Level of Service accounting for a set of tactical and operational level indicators and performance measures of water distribution networks. A hypothetical example is designed to illustrate the working of model 1 and is presented in Table 1.

Table 1. Ranges and thresholds of performance measure for different LoS

Performance Indicator	Pefromance Measure	Range of Performance Measure for Different Levels of Service (LoS)					Service Thresholds
		LoS 1	LoS 2	LoS 3	LoS 4	LoS 5	
Physical Condition	Annual Break Rate (Breaks/km/Yr) *	0 - 0 (1.0 - 1.0)	1 - 1 (0.75 - 0.75)	2 - 2 (0.5 - 0.5)	3 - 3 (0.25 - 0.25)	4 - 4 (0 - 0)	4 (0.0)
	No of Leaks (No/km) *	0.0 - 0.5 (1.0 - 0.75)	0.51 - 0.75 (0.74 - 0.63)	0.76 - 1.25 (0.625 - 0.38)	1.26 -1.75 (0.375 - 0.125)	1.76 - 2.0 (0.12 - 0.0)	2.0 (0.0)
	Leakage Volume (cum/hr) *	0.0 - 0.1 (1.0 - 0.80)	0.11 - 0.2 (0.79 - 0.60)	0.21 - 0.3 (0.59 - 0.40)	0.31 - 0.4 (0.39 - 0.20)	0.41 - 0.50 0.19 - 0.0)	0.5 (0.0)
Operational Condition	Fire Flow (C-Factor)	150 - 101 (1.0 - 0.62)	100 - 81 (0.61 - 0.47)	80 - 61 (0.46 - 0.31)	60 - 41 (0.30 - 0.16)	40 - 21 (0.15 - 0.0)	21 (0.0)
	Loss in Internal Water Pressure at peak demand (psi) *	0-5 (1.0 - 0.8)	6-10 (0.79 - 0.60)	11-15 (0.59 - 0.4)	16-20 (0.39 - 0.2)	21-25 (0.19 - 0.0)	25 (0.0)
	Frequency of Interruption (No/Yr) *	0-3 (1.0 - 0.83)	4-6 (0.82 - 0.67)	7-10 (0.66 - 0.44)	11-14 (0.43 - 0.22)	15-18 (0.21 - 0.0)	18 (0.0)
Water Quality	Lead Concentration (% of threshold) *	0-10 (1.0 - 0.9)	11-25 (0.89 - 0.75)	26-45 (0.74- -0.55)	46-70 (0.54 - 0. 30)	71-100 (0.29 - 0.0)	100 (0.0)
	Iron Concentration (% of Threshold) *	0-10 (1.0 - 0.9)	11-25 (0.89 - 0.75)	26-45 (0.74- -0.55)	46-70 (0.54 - 0. 30)	71-100 (0.29 - 0.0)	100 (0.0)
	Sepaeration from Sewer (m)	2.25-2.01 (1.0 - 0.81)	2.00-1.76 (0.8 - 0.61)	1.75-1.51 (0.6 - 0.41)	1.5-1.26 (0.4 - 0.21)	1.25-1.0 (0.2 - 0.0)	1.0 (0.0)

*-- The normalized values are subtracted from 1 to change the order so that increase in normalized value results in increase in LoS

The performance measures used in the hypothetical example, along with respective failure thresholds and ranges corresponding to different LoS are presented in Table1. Using the Water Main Service Percentile (WMSP) model developed earlier (Khan, Moselhi and Zayed, 2009) reproduced below, the service percentiles for the studied network can be determined. It should be noted that 'WMSP' described in Eq.(1), upon grouping leads to cluster level of service. In this study level of service has been

clustered in five categories from 1 to 5, with 1 representing the best possible scenario and 5 representing the least acceptable.

Water main service percentile = WMSP = $\sum_{i=1}^{n} \sum_{j=1}^{m} (Wij) * (PMij)$ ……..……...(1)

where: Wij = weight of sub-factor 'i' in factor 'j', PMij= value of performance measure 'i' in performance indicator 'j'
The overall network level of service (NLoS) quantified from segment level of service is worked as follows:

NLoS (%) = $\sum$ LoS_i x L_i / $\sum L_i$ .....(2)

where: LoS_i = Level of service of the segment *'i'*(%), L_i = Length of the segment *'i'* in meters

To facilitate data processing with reliability measures as will be described later, Network Level Un-Serviceability (NLoUS) is introduced and is given as:

NLoUS= 1- NLoS ……. (3)

Network Level of Un-Serviceability to be used for budget allocation of the case study, is calculated based on hypothetical data (Table 1). It should be noted that for criticality and reliability models data collected directly from the City of Moncton, New Brunswick is used.

Model 2: Weighted Score Sub-network Criticality Model

This model accounts for the following qualitative and quantitative factors:

1. Level of complain by local residence

A significant number of complaints by local residences indicate that the specific sub-network has reached a critical state. Residence complaints are divided into two types; either due to low quantity or due to low quality of water. A scale of 1 to 5 is suitable for this purpose. A score of 1 represents no complaints by residences implying excellent performance of the network whereas 5 signifies the opposite i.e. the highest level of complain.

2. Type of the sub-network

A sub-network can be classified as residential, commercial, industrial or recreational. The type of sub-network signifies the nature and the extent of the impact that may occur in the case of failure to provide the expected level of service. Stated alternatively, the consequences of failure of a network having a hospital will be far more serious than the consequences of failure of a sub-network having parking

facilities. A scale from 1 to 5 is suitable for this purpose with 1 being the most critical and 5 as the least.

1. Number of local residence

The density of population serviced by a sub-network is a principal factor is establishing the demand. The higher the population density the higher is the demand and the more critical is the sub network

2. Tax return

The desired levels of service have specific costs associated with them. If the tax payers are not willing to accept the costs, then the levels of service are to be reduced to the point where costs are acceptable. This means service levels are adjusted. This is an iterative process that means returning to the Delphi panel until levels of service and willingness to pay are aligned. The revenue collected from the community to provide services forms the tax base. The bigger the tax base the more critical is the network.

Budget allocation for sub-networks can be performed by weighting the criteria of all sub-networks, as shown in the Tables 2 and 3. The process of allocating budget to a sub-network involves the determination of the criticality weight of the sub-network. The user has the freedom to decide upon the weights of importance of the population number (Wlc), tax rate (Wtx), level of complaint by local residents (Wloc) and sub-network type (Wt) based on the specific situation of the sub network. By multiplying sub-network criticality factors (population number tax return, level of complaint, and type of sub-network) by their weights, the criticality of sub-networks can be determined. For details readers may refer to Salman et al. (2009).

Table 2. Budget allocation criteria

Sub Network No.	Sub Network Factors		
	Unreliability(%)	Unserviceability(%)	Criticality(%)
	Wq	Wus	Wcr
1	Q_1	US_1	CR_1
2	Q_2	US_2	CR_2
....	....	....	....
.....	.....	.....	.....
n	Q_n	Usn	CR_n
Summation	ΣQi	ΣUSi	ΣCRi

Model 3: Reliability Assessment

In this model the reliability based condition assessment of sub networks is determined. First of all, the city network is administratively broken down into zones. These zones are constituted of sub-networks. Each sub-network is further divided

into segments. Each segment may comprise of pipes and accessories. The last level of detail is the component; a component (a pipe or an accessory) represents the smallest entity of the water distribution network. In this study, reliability assessment using reliability theory is performed at component level and then aggregated bottom up in the hierarchal order, to determine the sub network level reliability as described below:

Component Reliability: To calculate the reliability of a component deterministically, the average failure rate (λ) of a component can be calculated first, as shown in Eq. (4):

$$\lambda = \frac{N_{Failure}}{Time} \quad \text{……..……...…(4)}$$

$N_{Failure}$ is the number of failures of pipe during the period considered. For a water main pipe, the average number of failures that have occurred from the time of installation can be calculated, as shown in Eq. (5):

$$\lambda_{Pipe} = \frac{N_{Failure\ /\ Km}}{T_{analyzing} - T_{inst.}} \quad \text{……..…...…....(5)}$$

$T_{analyzing}$ and $T_{inst.}$ are respectively the time of analysis and pipe installation.To calculate the average failure rate (λ) of a hydrant or a valve, Eq. (6) can be utilized:

$$\lambda_{hydrant,valve} = \frac{N_{Failure}}{T_{analyzing} - T_{inst.}} \quad \text{……..……...…...…(6)}$$

After determining the average failure rate of a component, the reliability of the component can be found using Eq. (7), (Billinton and Allan, 1983). Reliability is considered to follow the negative exponential function, which means that reliability decreases exponentially with time because the average failure rate increases with time.

$$R(t) = e^{-\lambda t} \quad \text{……...……...(7)}$$

In this case, average failure rate (λ) means the hazard rate, while failure rate *f(t)* is :

$$f(t) = \frac{-dR(t)}{dt} = \lambda e^{-\lambda t} \quad \text{……...…...……..… (8)}$$

All failure numbers and ages of water network components are collected to determine their reliabilities. Segment reliability ($R_{seg.}$) and sub-network reliability ($R_{sub\text{-}net.}$) are determined after finding their respective component reliabilities.

Segment Reliability: Figure 1 shows a typical segment of a water main network. Following Eq. (5) above the reliability for each component of the segment (pipes, valves and hydrants) was analyzed.

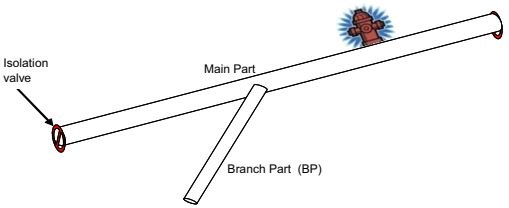


Figure 1. Components of a segment

The reliability of the segment can be calculated as:

$$R_{seg.} = e^{-(\lambda_{Segment}\ t_{Segment})} \quad \text{.....(9)}$$

where

$$\lambda_{Segment} t_{Segment} = \lambda_{Pipe}.t_{Pipe} + \lambda_{B.P}.t_{B.P} + \lambda_{Hydrant} t_{Hydrant} + \lambda_{Valve} t_{Valve} + \lambda_{Others} t_{Others} \text{....(10)}$$

Sub-network Reliability

In modeling reliability of large networks, it has been reported that the Cut-set and Path-set are the most suitable methods (Quimpo, 1996). Sub-network reliability is used to determine failure density function, Q (t), which is used with other factors to determine budget allocation of a sub-network. Failure density function is calculated as follows:

$$Q(t) = \int_0^t \lambda e^{-\lambda t} dt = 1 - e^{-\lambda t} \quad \text{..... (11)}$$

From Eq. (7) and Eq. (8), the relationship between R(t) and Q(t) can be expressed as Eq. (12), where 'R' and 'Q' are respectively the reliability and un-reliability of the given sub-network:

$$Q(t) = 1 - R(t) \quad \text{..... (12)}$$

Model 4: Budget Allocation Model

The criteria used are sub-network reliability, water sub-network level of service and sub-network criticality. Based on the community and agency preferences, weights are assigned to the three criteria respectively in terms of un-serviceability (Wus), sub-network criticality (Wcr) and un-reliability (Wq), as shown in Table 2. Outputs of models 1, 2 and 3 are utilized to determine the relative weight of each sub-network for budget allocation.

Table 3. Budget allocation of a city

Sub Network No.	Sub Network Factors				
	Unreliabilty(%)	Unserviceability(%)	Criticality(%)	Weight(%)	Budget Allocation
	(1)	(2)	(3)	(4) =(1)+(2)+(3)	(4)*TB
1	$(Q_1/\Sigma Qi)*Wq = Q_{11}$	$(US_1/\Sigma US_i)*Wus = US_{12}$	$(CR_1/\Sigma CR_i)*Wcr = CR_{13}$	W_1	$TB * W_1$
2	$(Q_2/\Sigma Qi)*Wq = Q_{21}$	$(US_2/\Sigma US_i)*Wus = US_{22}$	$(CR_2/\Sigma CR_i)*Wcr = CR_{23}$	W_2	$TB * W_2$
...	...	...	...	...	...
...	...	...	...	...	...
n	$(Qn/\Sigma Qi)*Wq = Q_{n1}$	$(US_n/\Sigma US_i)*Wus = US_{n2}$	$(CR_3/\Sigma CR_i)*Wcr = CR_{33}$	W_n	$TB * W_n$

CASE STUDY (CITY OF MONCTON)

The city of Moncton, New Brunswick (Figure 2) has been considered as a case study for the application of the developed method. The population is 126,424 and its area is 141.17 km². The total length of the water mains is 448 km and the average water consumption is 462/capita/day. The data collected for the city can be divided into two parts; the first part concerns the pipes, such as age, material, diameter, length, and number of breaks. The second part is related to the accessories that are attached to these pipes, such as valves and hydrants. However, the age and failure rate of these accessories are not provided and will be assessed to generate scenarios. To apply the methodology described in this proposal, the following steps are followed:

1. The first step is to divide the city into 14 sub-networks. This process is called the Break Down Structure of the City area (BDS). To apply the reliability assessment model, sub-network number one has been chosen using a GIS map (Figure 3). The GIS map shows the water mains, isolation valves and hydrants. The total number of segments is 113. The reliability of other sub-networks has been assumed.
2. Calculate Network Level of Un-Serviceability using Model 1
3. Assign different failure rates to the isolation valves and the hydrants.
4. Assume an amount for the city's available budget. This available budget is specified for rehabilitation only.

In this model, the reliability of each sub-network has been used in conjunction with sub-networks un-serviceability and sub-networks criticality. By normalizing the criteria and the sub-networks, the weight of each network has been found. Based on this weight, the ideal available budget can be obtained. For this case study, it is assumed that there is 16.5 million dollars are specified for the rehabilitation of the

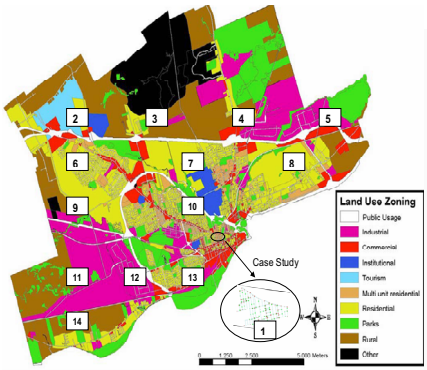


Figure 2. BDS of City of Moncton

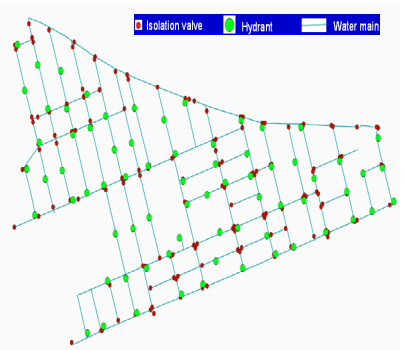


Figure 3. Sub-network 1- Moncton

city of Moncton for the next year. Therefore, 16.5 million dollars will be divided into the 14 sub-networks based on their reliabilities, water consumption, and contingency. The output of this model is the available budget of each sub-network, which is shown Table 4.

Table 4. Expected input and output of the budget allocation model

Sub Network	Un serviceability (1)	Un reliability (2)	Criticality (3)	Sub network Weight (4) = (1)+(2)+(3)	Allocated Budget (5) = (4) * TB
1	0.0638	0.0738	0.0665	0.0680	1,122,220
2	0.0382	0.0482	0.0643	0.0503	829,235
3	0.0704	0.0804	0.0482	0.0663	1,094,555
4	0.0222	0.0322	0.0257	0.0267	440,110
5	0.0463	0.0563	0.0579	0.0535	882,310
6	0.1322	0.1222	0.0740	0.1094	1,805,815
7	0.0406	0.0306	0.1608	0.0773	1,275,285
8	0.0518	0.0418	0.1190	0.0709	1,169,135
9	0.0888	0.0788	0.0643	0.0773	1,275,285
10	0.1258	0.1158	0.0547	0.0987	1,628,990
11	0.1231	0.1031	0.0557	0.0939	1,550,010
12	0.0811	0.0611	0.0354	0.0592	976,525
13	0.0893	0.1093	0.0772	0.0919	1,516,955
14	0.0266	0.0466	0.0965	0.0566	933,350
Total	1.0000	1.0000	1.0000	1.0000	16,499,780

SUMMARY AND CONCLUSION

A methodology has been presented for budget allocation of water distribution networks. The developed methodology is intended to assist public work departments to internally distribute the budget, originally allocated for the water distribution

network, in their respective areas. An example has been analyzed to demonstrate the use of the developed method in allocating the budget assigned internally to water distribution network. The allocation will be for the individual zones, sub-networks and their respective components. The developed methodology accounts for community preferences expressed in defined targeted level of service and on the other hand it accounts for condition of the network expressed in terms of reliability of its components, segments and sub networks. The developed methodology is expected to help municipal engineers in making decisions that account for technical and financial plans of the city.

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Development of an Innovative Free-Swimming Device for Detection of Leaks in Oil and Gas Pipelines

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Abstract:

Line leakage of oil and natural gas systems can result in significant financial and environmental consequences. Often, small leaks lead to ruptures in the pipeline that result in product escaping into the surrounding soil. Oil product can taint water supplies by migrating into aquifers, while natural gas leaks are susceptible to catastrophic explosions. A joint academic-industry research initiative funded by the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) has lead to the development and refinement of a free-swimming device capable of detecting small leaks in oil product and natural gas pipelines. The SmartBall® swims through a pipeline being assessed and produces results at significantly reduced cost to the end user compared to current leak detection methods. GIS based above ground loggers that are GPS synchronized capture low frequency acoustic signatures and digitally log the passage of the SmartBall® through a pipeline. This paper presents the development, laboratory and field validation testing of the SmartBall® for both oil and natural gas applications with discussion of demonstrated case studies.

INTRODUCTION

Early detection of leaks in hazardous materials pipelines is essential to reduce product loss and damage to the environment (Carlson 1993; Zhang 1996). Small leaks, if undetected, can result in elevated clean-up costs and have the potential to grow to more serious failures (Figure 1). On July 30, 2003 a 200mm (8-inch) steel pipeline carry fuel between Tucson and Phoenix, AZ ruptured resulting in over 50,000 gallons of gasoline being spilled. This resulted in contamination to the soil and groundwater.

Fortunately, an adjacent 68 lot housing subdivision was only under construction at the time and thus did not have any residents present. This incident not only resulted in physical damage, but also economic consequences due to elevated prices at gas stations due to limited supply while the line was under repair.

There are a variety of available methods capable of detecting leaks in pipelines, ranging from manual inspection to advanced satellite-based imaging. Typically, most operators opt for a combination of Computational Pipeline Modeling (CPM) and direct observation methodologies including aerial or ground patrols. Permanent monitoring sensors based on acoustic or other technologies are also available; however, these methods can be costly, and none can reliably detect small leaks regardless of their location in the pipeline.



Figure 1. Consequences of a leaking pipeline

Most pipeline operators also employ in-line inspection (ILI) programs using "smart pigs" that detect cracking, wall thinning, and other anomalies (Turner 1991). However, a major of pipelines are typically only inspected at intervals of several years, and all ILI technologies have limits on the minimum cross-sectional area of the defects they can detect. Furthermore, they are unable to differentiate between a deep defect and a leak. Through-wall pinhole leaks resulting from aggressive corrosion mechanisms such as MIC are not typically detected. Also many lines, particularly in the gathering and distribution sectors, are never pigged.

SmartBall® is a new approach that combines the sensitivity of acoustic leak detection with the 100% coverage capability of in-line inspection. The free-swimming device is spherical and smaller than the pipe bore allowing it to roll silently through the line and achieve the highest responsiveness to small leaks. It can be launched and retrieved using conventional pig traps, but its size and shape allow it to be launched by other means and to negotiate obstacles that could otherwise render

a pipeline unpiggable. Figure 2 illustrates the internal components and polyurethane outer shell that can withstand external pressures up to 2,000 psi (138 bars).

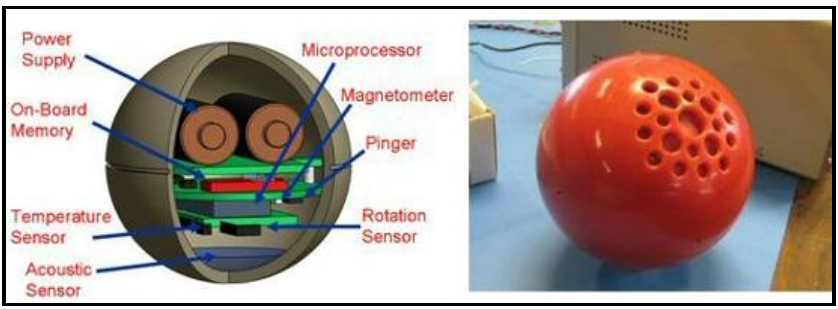


Figure 2. SmartBall internal components (L); Outer shell (R)

TECHNOLOGY DEVELOPMENT BACKGROUND

When pressurized product leaks from a pipe, it creates a distinctive acoustic signal that is transmitted through the product flowing in the pipeline. Acoustic leak detection equipment identifies the resulting sound or vibration (Klein 1993). Such systems have proven to be one of the most effective and reliable means for identifying leaks in pipelines, but fixed sensors have limited range due to the rapid attenuation of sound. A free-swimming, un-tethered acoustic leak detection device avoids this limitation by passing directly by any leak, regardless of its location along the pipeline. By operating inside the pipe, the device is not affected by ground cover or environmental conditions, and there is never any concern that sections of the line could be missed.

Recognizing the value offered by acoustic technology, but also the range limitations for a fixed sensor system, a research and development program was undertaken to develop a free-swimming (non-tethered) acoustic leak detection device. The goal of the program was to develop a technology that would provide operators with the ability to detect leaks at an early stage (i.e. small leaks), to determine the location with sufficient precision to allow remedial work to be performed without additional surveying. It had also to be available at an affordable cost without the need for major changes in the pipelines construction or operation.

The resulting system, named SmartBall®, was initially developed in 2005 for water transmission pipelines because of the magnitude of the leak problems in the water industry and the lack of alternative solutions. However, the SmartBall® principle is equally applicable to oil and gas pipelines, so the research and development program was extended in 2007 to modify the technology for use in the hydrocarbons industry. This led to a two year research project funded by the U.S. DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA) in collaboration with Pure Technologies Limited and Arizona State University.

The SmartBall® device diverges from the traditional cylindrical shape of in-line equipment or "pigs". The spherical shape greatly reduces the noise produced by the device as it passes along the pipe, thus permitting the sensitive acoustic sensor to operate free of external interference. The net result is a tool that is sensitive to very small acoustic events and, therefore, very small leaks.

An additional benefit of the spherical design is that it allows much greater flexibility in the methods of deployment and retrieval compared to a cylindrical tool, and it is able to negotiate a much wider range of bore changes, small radius bends and other obstacles that may exist within the pipe. SmartBall® can run in lines without pig traps, and in a wide range of traditionally unpiggable locations. Both liquids and gas pipelines can be inspected. With the current series of tools, any pipeline size of 100mm (4-inch) diameter or greater is accessible.

The device is inserted into an operational pipeline in the same manner as a smart pig and can monitor many miles of pipeline during a single deployment (Figure 3). The SmartBall's position is logged internally by on-board accelerometers and the ball can also be tracked by GPS synchronized surface sensors in the same way a conventional pig. This combination of tracking systems allows the location of any leaks to be determined within ±1 meter.

The SmartBall® is fully sealed with no electronic components exposed to the pipeline environment. This allows us to achieve high levels of reliability in a wide range of hostile conditions, and ensures that the device is intrinsically safe for use in flammable products such as oil and gas.

Following a run, the data are downloaded to a computer for analysis. This process is relatively fast; subsequently the initial decision on whether a leak exists in the line can often be made before the field crew leaves the inspection site. The SmartBall® log comprises of a continuous, high-fidelity acoustic record of the inspected section over a wide range of frequencies. Leaks are identified by a combination of increased acoustic power and a characteristic frequency spectrum. Subsequent logs may be overlaid to identify changes between inspections, further enhancing sensitivity.

FIELD PROJECT USING SMARTBALL

A 250mm (10-inch) SmartBall® was deployed to inspect a 300mm (12-inch) steel portion of MOL's Oil pipeline from Szajol to Tiszaújváros in Hungary on April 23 and 24, 2009 (Figure 3). Total run length was approximately 126 km. The SmartBall® was inserted and extracted through MOL's existing pig traps. One known simulated leak (Figure 4) was generated along the pipeline as both a test of the SmartBall's® ability to locate leaks and as reference points for calibrating unknown leaks. A second unknown leak was discovered upon running the analysis on the data retrieved from the SmartBall tool. Analysis of the data allowed for an estimation on the location and size of the leak. Leak location was estimated at Sta. 76+458, and the leak rate was estimated at 3 L/min.



Figure 3. SmartBall® setup for field installations



Figure 4. Simulated leak point along the pipeline

During the inspection, the SmartBall® and SmartBall® Receivers (SBRs) collected data to aid in determining an accurate size and location of all leaks detected. Frequency spectrum data were recorded for the two leaks (Figures 5 and 6).

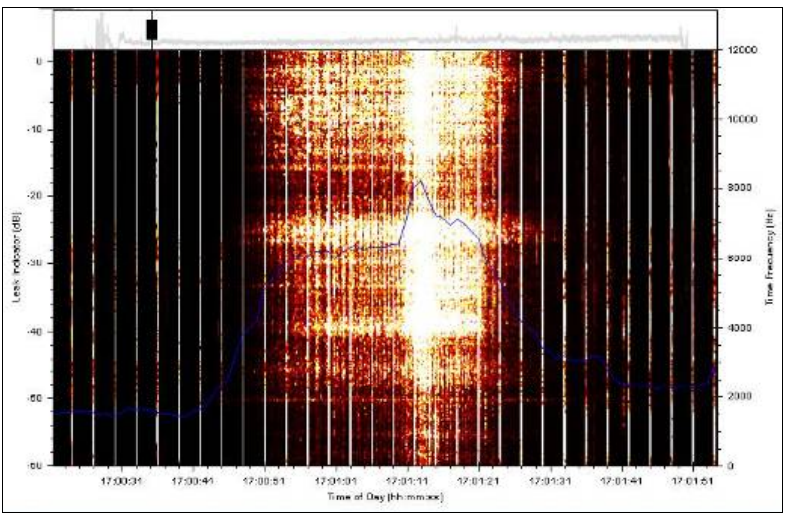


Figure 5. Frequency spectrum recorded at the first simulated leak point

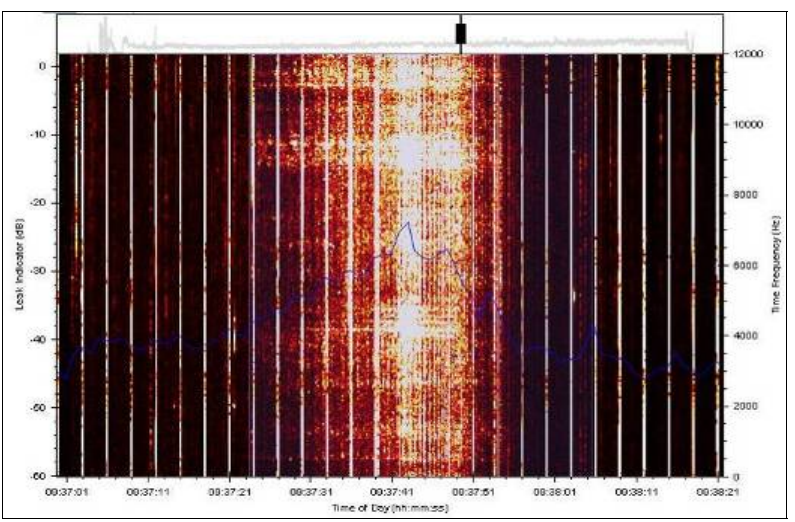


Figure 6. Frequency spectrum at the unknown leak location.

Knowledge of the position of the SmartBall® within a pipeline is critical for locating important features, such as leaks. The methodology used to track the tool involves obtaining a velocity profile using data obtained from the accelerometers and magnetometers on board the SmartBall®. Then, absolute position reference points obtained from the SBRs are applied to time stamped data. Individual SBRs are able to track the ball's progress through the pipeline for up to 150m. The result of the rotation profile and SBR tracking is a position versus time relationship for the entire run of the tool.

To assist in identifying the approximate leak rate of any identified leak, an end-user can compare the leak indication power of a detected leak with that of a known leak rate. Known leak rates and corresponding leak indication power (in dB) are developed by holding the SmartBall® in the launch trap at the start of the survey run. The acoustic analysis of the calibration leaks were compared with the leak rate of each leak detected during the inspection of the MOL pipeline. The leak indication power is the single most important indicator of a leak's presence and size.

Because the simulated leaks are controlled and released through a threaded outlet, the comparison to actual field condition leaks may vary. This is because the acoustic frequency and power indication of any leak will vary with many factors, including pressure, pipe diameter, size and configuration (i.e. pin-hole, rolled gasket, split pipe, etc.). However, a leak calibration curve provides a useful tool in approximating leak rates for identified leaks. The leak calibration curve increases in accuracy as more data points and calibration leaks are added to the curve.

A 3-dimensional accelerometer also aids in locating the position of the SmartBall® tool within the pipeline as well as providing an indication of motion of the ball as it travels through the pipeline (i.e. uniform rotation, slipping/skidding, etc). Figure 7 illustrates a typical accelerometer profile. This enables the user to identify locations where flow was interrupted or the exact time the ball departs and arrives at the pigging facilities.

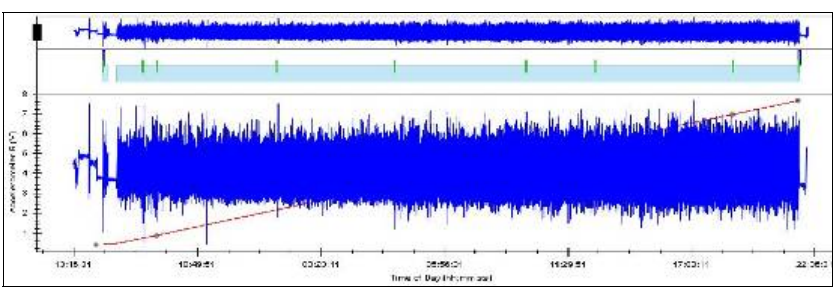


Figure 7. Accelerometer profile

CONCLUSIONS AND RECOMMENDATIONS

SmartBall® was initially developed in 2005 for inspecting leaks in water pipelines. Since its introduction, it has been successfully run in 48 water inspections totaling over 300km. Within those, more than 120 leaks have been detected. Introduction to the oil and gas industry has been more recent with research and development efforts currently on-going between Arizona State University and Pure Technologies Limited. Limited field testing has been undertaken using SmartBall® for assessing leaks in oil product pipelines. Modifications to the device and further testing should result in a fully commercial version of this device.

Further technological developments are planned. Refinement of the SmartBall® for use in gas pipelines is currently underway. The requirement is to modify the outer shell material to reduce rolling noise, and simultaneously to increase the drag to weight ratio to enhance propulsion.

Manufacture of additional sizes of SmartBalls® for oil and gas applications will continue. Beyond 250mm (10-inch) pipelines, overshells with standard 250mm (10-inch) SmartBalls® mounted inside will be used to eliminate the need to create a large inventory of individually sized SmartBalls®.

Additionally, increased internal memory and battery capacity will be added to extend the range of SmartBalls in larger sizes. The upper temperature limit will be increased to allow SmartBall® to operate in an even wider range of pipelines. Typical high temperature applications include the production from the Alberta Oil Sands.

A simplified arrangement for data download that avoids the need to open the ball will be introduced. This will have the additional advantage of reducing the risk of damage to internal components and help ensure that the seals remain intact.

The customer version of the analysis software is in the process of being developed and modified to increase the level of automation and reduce the need for technical expertise from the user

ACKNOWLEDGMENTS

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Analyzing Municipal Blockage Failure Datasets for Sewer Systems

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Abstract:

The objective of this research is to analyze historical records of random non-mechanistic failures in civil infrastructure systems. In this paper, we particularly focus on blockage failures in sewer systems that result from combination of external factors, such as variations in usage loads, construction quality and soil characteristics. The study uses historical blockage failure records maintained by municipalities. However, such datasets often tend to be incomplete and/or not representative of failure patterns. We discuss the application of statistical tests – specifically the Kolmogorov-Smirnov (KS) test and Anderson-Darling (AD) goodness-of-fit test – to estimate (i) if the datasets are complete and representative enough, and (ii) estimate parameters of distributions that appropriately characterize failure event arrival pattern. A dataset consisting of sewer blockage failures for ten years from a small municipality in the State of Michigan was used. The methods discussed in this paper can be used to implement reliability models of other related infrastructure systems as well.

Introduction

The motivation of this research is to provide decision-makers in state and municipal agencies tools to estimate and budget expenditures for sewer line maintenance. Specifically, the focus is on aiding efficient and cost effective decision-making in municipalities with aging sewer systems. Sewer pipes are often inspected using closed circuit television (CCTV) to apprehend blockages before backups occur (Sinha 2004). Instead of depending on inspection methods, our approach uses historical records of blockage failures maintained by municipalities. Analysis of such historical data can significantly enhance the decision-making process involved in prioritizing maintenance decisions. We illustrate the application of this method using sewer line blockage failure data from a small municipality in the State of Michigan.

Background

Literature pertaining to serviceability predictions of sewer infrastructure systems can be classified using the following approaches to service assessment:

(i) By studying mechanistic system failures using hydraulic properties of sewer lines and pumping (Bennis et al. 2003; Ermolin et al. 2002),

(ii) By studying system failures as random events that can be a direct or indirect outcome of mechanistic and non-mechanistic events. The methods used in this approach are:

   a. Use historical failure data from case studies to predict behavior of specific systems. Typically, specific random failure events such as sewage pump failure and sanitary sewer overflows are modeled using historical data (Korving et al. 2006; Sumer et al. 2007).

   b. Assume the Markov property to develop general models that assess the condition of infrastructure for modeling pipe condition and deterioration, and optimizing maintenance schedules. (Abraham et al. 1998; Chughtai and Zayed 2008; Micevski et al. 2002; Wirahadikusumah et al. 2001).

The research presented in this paper specifically falls in category (ii.a). It analyzes sewer system failures resulting from blockages using historical failure data for a small municipality.

Stochastic methods are used in assessing failure of infrastructure systems due to discrete events, such as sewer overflows and sewer blockages that are modeled as random events. By definition, a stochastic process $X=\{X(t), t\in T\}$ is a collection of random variables $X(t)$, which denote the state of a process at time t (Ross 1993). When time is measured discretely, $X(t)$ is either true or false based on whether an event occurs or not at the time point t. When time is continuous, the inter-arrival times between failure events are recorded. A continuous stochastic process in which events occur independently of one another with no overlapping arrivals at a constant rate reduces to a Poisson process (Kingman 1993). Then the inter-arrival times are exponentially distributed. In other areas of Civil Engineering, similar approaches have been used in modeling rainfall (Cowpertwait et al. 2007) and analyzing motor vehicle crash frequencies (Ma and Goulias 2007). In such studies, the challenge has been in appropriately estimating parameters that define the processes. Indeed, the attractive memoryless property, unique to the exponential distribution (and its discrete counterpart the geometric distribution) provides significant analytical advantages (Vaughan 2008). While the assumption may be justified in certain cases, often in the absence of validation, it leads to conservative estimates of reliability (Chu and Durango-Cohen 2008).

In reality, failure rates often are not constant. The Weibull and Gamma family of distributions provide alternative better fits in such cases. The exponential distribution is a special case of both these families of distributions. Specifically, a 2-parameter Weibull distribution is a continuous probability distribution with the density function:

$$f(t;\alpha,k)=\frac{k}{\alpha}\left(\frac{t}{\alpha}\right)^{k-1}e^{-(t/\alpha)^k} \qquad t\geq 0$$

and cumulative distribution function:

$$F(t;\alpha,k) = 1 - e^{-(t/\alpha)^k} \qquad t \geq 0$$

where k is the shape parameter, α is the scale parameter. When $k=1$, the Weibull distribution has constant failure rate at any time t and reduces to the exponential distribution. The 3-parameter Weibull introduces an additional location parameter τ on top of two-parameter Weibull to describe a right shift of the distribution. The density function is given by:

$$f(t;\alpha,k) = \frac{k}{\alpha}\left(\frac{t-\tau}{\alpha}\right)^{k-1} e^{-((t-\tau)/\alpha)^k} \qquad t \geq \tau$$

and distribution function is

$$F(t;\alpha,k) = 1 - e^{-((t-\tau)/\alpha)^k} \qquad t \geq \tau$$

Our research efforts in this study is similar to Korving's (2006) work as both aim to evaluate reliabilities of sewer systems through analysis of failure data. Instead of focusing on pump failure data, sewer blockage dataset is the target. This study also supports the use of interactive simulations to support decision making in co-dependent infrastructure systems (Mukherjee et al. 2010).

Methodology

The main challenges in characterizing failure datasets using stochastic models are 1) datasets could be incomplete or not representative, 2) finding suitable distributions to describe the event arrival process. While the Poisson process is often assumed, other distributions might provide better fits and provide deeper insight into the behavior of the system. These challenges were addressed by analyzing a sewer blockage dataset. The municipality under observation is a small town with no major industry located in the vicinity. The predominant use is housing while commercial use only accounts for a small portion. The town consumes about 1.1 million gallons of water per day. There are about 1500 customers, of which 1100 are single-family units (Houghton-City 2009). Sewer event data was obtained from hand written records and manually organized in digital spreadsheets. The dataset covers sewer events collected on all sewer pipelines running through the town. Events recorded were categorized into new construction, maintenance activities, failures and blockage rescues. Sewer blockage event information included occurrence date and location, type of obstruction, and total time required to repair the problem. The entire dataset consisted of records from 1996 to 2006. The study used records from 1996 to 2003, as the records between 2004 and 2006 were ill maintained and incomplete. Most blockage events reflected in the historic data records are related to pipes with sizes smaller than 24 inches in diameter. No repeated blockages were found at one specific location. Data analyses were performed on the inter-arrival times datasets derived from blockage events.

The analysis procedure is described in Figure 1. Raw failure data was evaluated and blockage failures were identified by occurrences of sewage backup events or overflow events. In order to ensure that the dataset provided a representative sample, a two sample Kolmogorov-Smirnov test was done to check if sub-sets of the data were similar to each other – and therefore by extension, if the dataset was a suitable sample for study. This was followed by a goodness of fit analysis using the Anderson-Darling test to select a distribution that suitably

characterized the inter-arrival times. In particular, exponential and Weibull inter-arrival times were compared for the accurate description of failure arrivals.

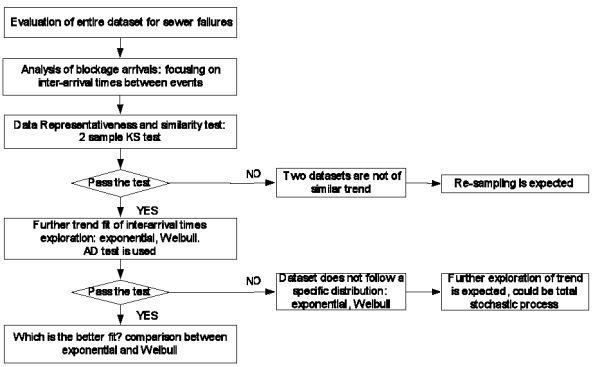


Figure 1: Procedure for blockage arrivals analysis in sewer systems

Inter-event Times Analysis

Theoretically, in a continuous Poisson process, no more than one event occurs at the time interval Δt. However, the dataset contained instances in which more than one blockage failure was recorded per day. Hence, a day could not be used as a suitable time increment. Instead, the smallest unit of time was chosen to be an hour, and events were randomly assigned occurrence times over the 24-hour period within which they were recorded.

The longest inter-arrival time in the dataset was found to be 83 days – significantly longer than all the other records, which were less than 45 days. This instance was considered an outlier, most likely an outcome of incomplete records. Hence, the data point was truncated and tests were done upon the corrected dataset.

Data Representativeness Analysis

Data used in this study covers a time duration from 1996 to 2003, which have relatively complete records of blockage occurrences (henceforth referred to as the *applied dataset*). We believe that this dataset suffices to represent blockage failure patterns for this municipality after 1996. To prove this, two sets of tests were performed. Firstly, inter-arrival times of dataset in this study were tested against all available data to test for representativeness. Secondly, tests to validate consistencies between datasets were performed by comparing the entire dataset to split sub-datasets. Collected blockage events were grouped into 2 split datasets, which were noted as split1 and split2. Split1 covered all samples collected in the first 4 years and split2 included data recorded in the next 4 years. To test if there was a significant difference between these datasets, a two-sample Kolmogorov-Smirnov (KS) test was performed. The null and alternate hypothesis was as follows:

H_0: The two datasets have a common distribution.

H_a: The two datasets do not have a common distribution.

Figure 2(a) below illustrates comparisons between the sub datasets and the applied dataset, plotted on a cumulative fraction basis. Under a given 95% confidence level, the null hypothesis cannot be rejected (p=0.8004). Figures 2(b)-(d) display comparisons between samples from data split1, data split2 and applied dataset. The hypothesis of a common distribution can be accepted for data split1 and data split2. Similar conclusions can be made regarding the split datasets and applied dataset as illustrated in Figures 2(c) and 2(d). Having confirmed that the dataset has a common distribution the next step was to establish specific distribution trends to characterize blockage arrivals.

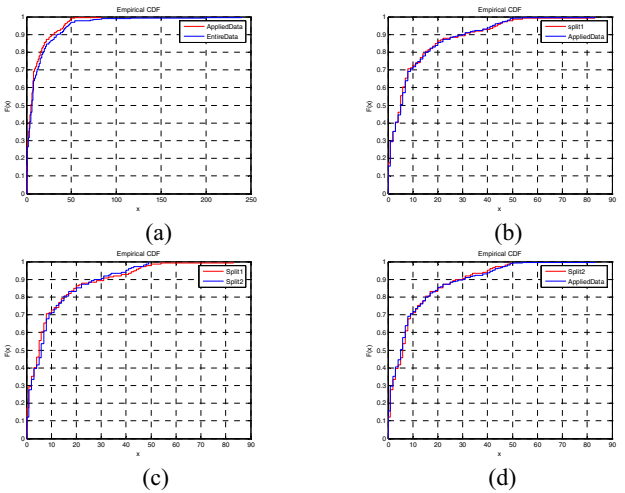


Figure 2: KS-test Comparison Fraction Plot between: (a) Applied dataset and Entire dataset, D=0.0532, P=0.8004; (b) data Split1 and Split2, D=0.0976, P=0.4799; (c) Split1 and Applied dataset, D=0.0503, P=0.9697; (d) Split2 and Applied dataset D=0.0472, P=0.9796.

Distribution Fitting of Inter-event Times

This section describes how the distributions of inter-event times were determined. The Anderson-Darling (AD) goodness-of-fit test was used. This null and alternate hypothesis for this test is as follows:

H_0: The dataset follow a specific distribution,

H_a: The dataset does not follow a specific distribution,

Significance level: 0.05.

Tests were performed upon datasets based on a yearly duration as well as datasets combined per wider time ranges, namely per 2 years, per 4 years and per the entire dataset. Test results were compared and discussed respectively for each timing combination.

Exponential distribution fitting and analysis: Table 1 lists exponential fitting results applied upon categorized datasets. Given a 95% confidence level, the

null hypothesis of an exponential distribution could not be rejected for each annual dataset. When the period was expanded to 2 years or higher, the null hypothesis could be rejected at the given 95% confidence level. There are multiple factors leading to such test failures. Major external weather events, and/or variations in external forces may induce high frequency events may be one reason. To further explore this, a Weibull distribution was applied upon the inter-arrival times datasets.

Table 1: Exponential distribution tests results for all timing combinations (1year, 2 years, 4years and entire dataset)

Year	λ	Failure rate	P value
1996	12.57	0.0796	0.138
1997	8.332	0.1200	0.664
1998	12.04	0.0831	0.052
1999	7.989	0.1252	0.109
2000	10.72	0.0933	0.204
2001	7.831	0.1277	0.245
2002	13.19	0.0758	0.589
2003	9.446	0.1059	0.084
96-97	10.17	0.0983	0.018
97-98	10.16	0.0984	0.011
98-99	9.930	0.1007	0.005
99-00	9.310	0.1074	0.024
00-01	9.147	0.1093	0.041
01-02	10.37	0.0964	0.039
02-03	10.92	0.0916	0.045
96-99	10.39	0.0962	<0.003
00-03	10.19	0.0981	<0.003
96-03	10.28	0.0973	<0.003

Weibull distribution fitting and analysis: Multiple factors contribute to blockage occurrences. As a result, failure arrivals are not completely random, as a Poisson process would imply. Hence, the Weibull distribution was tested for a suitable fit. Table 2 lists Weibull test results, it can be seen that except data sub-sets 2000-2003 and 1996-2003, all others generate *p* values greater than 0.05, which support a Weibull distribution fit for the inter-arrival times. Further examination on the tests reveals that the shape parameters are smaller than *1* for all datasets. This means that compared to an exponential distribution, a higher probability density was noticed for short inter-arrival times. Given that a Weibull distribution reduces to an Exponential distribution when the shape parameter equals to *1*, it can be seen from the shape parameters in Table 2, that the behavior of the dataset can be approximated using a Poisson process over short observation periods. However, when the observation period is extended, various impacts skew this exponential trend. Thus, a Poisson process cannot be validated for the entire observation period. Instead, blockage arrivals are better characterized by Weibull distributed inter-arrival times.

In order to understand why Weibull is a better fit, we further investigated the underlying contexts. Such Weibull inter-event times are mainly caused by more frequent than a 'general random' arrival of blockages during certain times of the year. To illustrate this, figure 3 below depicts total blockage numbers versus each month categorized from the entire data population. High numbers of blockages were noticed from March to May. This can be attributed to increased flow from snowmelt. Another gentler increase was also observed at the end of year, which is believed to be caused by intensive human activity.

Results in Table 2 also reveal that the dataset fails the null hypothesis of a Weibull distribution for dataset 00-03 and the entire dataset respectively. To handle this situation, a 3-parameter Weibull distribution was further applied, where a new location parameter is introduced. It can be seen from Table 2 that all datasets tests have p values greater than 0.05. These additional location parameter adjustments assist to handle the heavy tails accumulated over time, although they do not significantly impact parameters for distribution shift. Analysis of inter-arrival times datasets was also performed by using the Gamma distribution family. Test results were found to be similar to those from Weibull distribution tests, both of which are two- or three- parameter distributions. Weibull distributions provide better fits for datasets covering wide time periods.

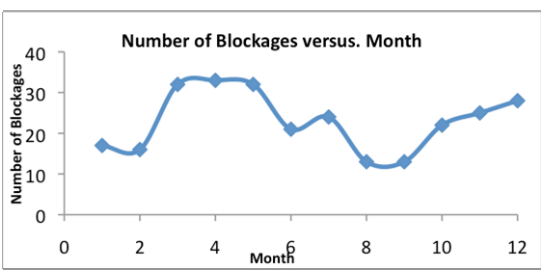


Figure 3: Number of blockages versus month

Table 2: Weibull distribution tests results for all timing combinations

Year	Shape parameter	Scale	P value
1996	0.7990	11.11	>0.25
1997	0.8868	7.490	>0.25
1998	0.8101	10.73	>0.25
1999	0.8180	7.144	>0.25
2000	0.8438	9.800	>0.25
2001	0.8836	7.318	>0.25
2002	0.9435	12.85	>0.25
2003	0.8297	8.487	>0.25
96-97	0.8201	9.096	>0.25
97-98	0.8192	9.085	>0.25
98-99	0.8052	8.795	>0.25

99-00	0.8305	8.418	>0.25
00-01	0.8666	8.468	>0.25
01-02	0.8720	9.645	0.21
02-03	0.8702	10.15	0.231
96-99	0.8042	9.178	>0.25
00-03	0.8612	9.042	0.037
96-03	0.8351	9.308	0.012

Table 3: 3-parameter Weibull tests for datasets

Year	Shape parameter	Scale	Location parameter	P value
96-99	0.7817	8.965	0.05938	>0.50
00-03	0.8343	9.154	0.08414	0.105
96-03	0.8102	9.079	0.07006	0.061

To sum up statistical analyses in this section, Figure 4 depicts all test results upon available inter-arrival times datasets. Specifically, a one parameter exponential distribution fits annual datasets favorably. Standard Weibull (2-parameter) distributions generate better fits for datasets covering 2 years ranges. Similar results are indicated from Gamma distribution test fits. The exponential distribution fit can only be approximated for short observation periods. A Weibull distribution fit or close approximations were also noticed for 4-year datasets and the entire dataset, an additional location parameter assists to produce better fits at this level. Theoretically, an exponential distribution of inter-arrival times implies an underlying Poisson arrival process. However, multiple real life impacts usually skew this exponential trend to a certain extent. Specifically in this study, snowmelt and intensive human activity lead to Weibull inter-arrival times of blockage event sequences.

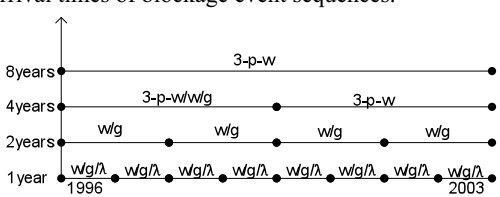


Figure 4: Test results for different time duration combinations (1year, 2years, 4years, 8years)

Note: only successful tests are shown in the chart. w/g/**λ**=all Weibull, Gamma and exponential distributions pass tests, Weibull is the best fit; **w/g=** both Weibull and Gamma distributions fulfills tests, approximate exponential distributions are noticed; 3-p-w=3 parameter Weibull distribution pass AD tests, which are only used on datasets 4years and entire dataset, approximate 2 parameter Weibull is noticed.

Discussion

Three target distributions were tested, namely, the one-parameter exponential distribution, the two- and three-parameter Weibull distribution and the Gamma distribution. Usually, a two- or three- parameter distribution is always more likely to fit a data set as additional parameters provide a more complete description of data

sets characteristics. In this study, the shape parameter in the Weibull distribution provided insight into the nature of blockage failures. In addition, a detailed analysis over sub-data sets and consideration of time trends, illustrated the possible influence of local factors and usage patterns. Trend of inter-arrival times in this study displayed a Weibull distribution with a shape parameter $k < 1$, a close approximation to an exponential distribution ($k = 1$) as shown in Figure 5. This implied a higher density of shorter inter-arrival times, that identified higher frequency of event occurrences due to snowmelt and periods of increased human activities. Data sets used in this study were collected from a sewer system of a small town. For a large sewer infrastructure system, the same method can be extended and used across data subsets classified by usage areas, blockage scenarios, and soil conditions to get a better understanding of underlying system behavior.

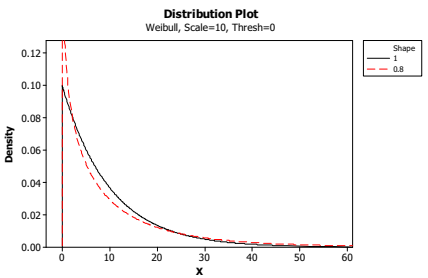


Figure 5: Probability density function for shape parameter k=1 and k=0.8

Conclusion

This paper proposes a methodology to study sewer systems serviceability given a blockage occurrence dataset. Blockage events were found to arrive in a process with Weibull inter-arrival times. Specifically, a Poisson arrival process holds true over short observation periods and an approximate Poisson model can be assumed over longer observation periods. However, a more precise description of Weibull inter-arrival times was noticed resulting from real life impacts that vary regionally. Further applications can be performed by employing properties of a Poisson process and distribution in order to estimate failure rate in order to assist stalk-holders in the decision making process.

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Framework for Web-based Highway Construction Geospatial Data Management

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ABSTRACT

As an on-going project, the main objective of this research is to develop a framework for the functional and widely accessible Geographic Information System tools to track information collected throughout the highway construction and maintenance projects in the state of Nebraska. Microsoft's Bing Maps and Google's Google Earth are both being investigated for possible integration with the Nebraska Pavement Management System. A test system has been built utilizing an increasingly large data pool previously created from the past hot mix asphalt (HMA) projects. Different data types including: physically marked locations, digitally marked locations, density reads, moisture readings, weather information, and temperate segregation were linked together using Google Earth that can be accessible from the field or the office. The developed framework is identified as a feasible solution to supplement the existing Nebraska Department of Roads (NDOR) pavement management system(PMS) with an upgradeable, efficient, and user friendly web-based interface.

Keywords: Hot Mix Asphalt (HMA), geospatial data management, Pavement Management System (PMS), GIS, interoperability

1 INTRODUCTION

There are over 5.7 million miles of roads stretching across the United States (FHWA 2008). These roads are comprised of concrete pavements, hot-mix asphalt pavements, overlays, sections paved recently, sections paved 15 years ago, and the list goes on. It

is crucial that some form of data management system be used to effectively monitor, maintain, and improve the national roads system. Wlaschin, director of the Office of Asset Management for the Federal Highway Administration (FHWA) describes such factors as "an aging national infrastructure, increasing congestion, expanding traffic, and limited funds," as weighing heavily on state and local transportation agencies. Wlaschin goes on to explain that one of the keys to lightening the load on these agencies is through the use of Transportation Asset Management (TAM). TAM is a systematic and strategic approach at maximizing system performance and minimizing life-cycle costs while providing the greatest return on each transportation dollar invested. TAM can almost be seen simply as a system that provides decision makers with efficient tools to most appropriately make informed decisions that are aligned with the maximization of utilizing transportation assets (Washington 2008). Perhaps the most important tool in a TAM system is the concept of a pavement management system (PMS).

Currently, every state uses some form of a pavement management system although it was reported that only five states were using such tools in 1980 (Finn 1997). The evaluations of roadways under these fledgling systems were rudimentary at best. Road tests often simply involved the subjective and monotonous process of visually surveying of the pavement (Finn 1997).

Initial management systems would use databases of collected data to rank and prioritize roadway projects on a "worst first" basis (Finn, 1997). Through the use of their PMS, Washington State was able to investigate pavement repair, overlay and overhead costs for the rehabilitation of hot mix asphalt (HMA) for various pavement conditions and couple that data to evaluate their programming and funding distribution policies. What Washington found was that they were often times rehabilitating a road too soon or too late and in turn either wasting the useful life of the road or roadway maintenance funds. By effectively utilizing a pavement management system, Washington has found the worst first philosophy to be flawed and transitioned into a life-cycle cost philosophy to determine which roads are slated for primary attention (Washington 2008).

Today's pavement management system is quickly being recognized as a vital decision making tool for pavement managers. To be an effective tool, pavement managers are beginning to demand (or expect) their PMS to provide a high level of visualization, be easy to use, and accessible whenever and wherever needed.

Visualization is the key in clearly communicating data and ideas to one another. Whether it is from a simple graph of complex data to complete virtual Building Information Models tied to schedules and estimates; visualization of data promotes understanding. PMSs have historically provided a means of representing data in simple tabular charts and graphs; however pavement managers are now demanding 2D or 3D geometrically mapping tools to sort and explain collected data. A graphical representation of what components make up a Geographic Information System (GIS) is shown below in Figure 1.

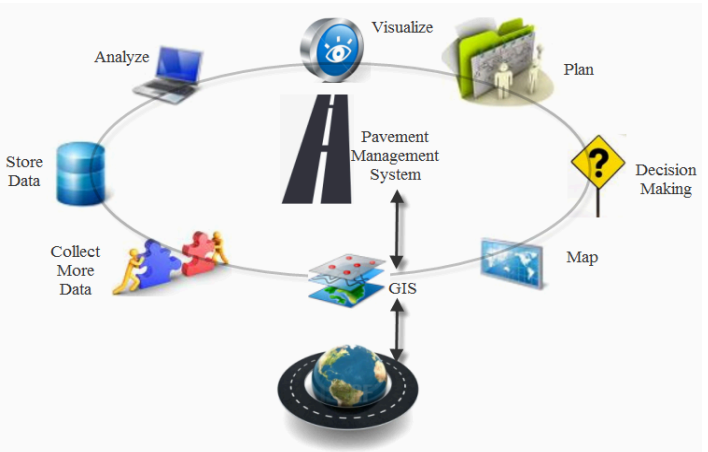


Figure 1 GIS Cycle

Usability has been a problem with PMSs in the past. During the 1980's when PMSs were still coming of age, the civil engineers typically in charge of these systems found it hard to fully trust their results. Basic knowledge of economics, computer programming, statistics, and operations research were required to fully understand how the systems functioned, unfortunately most civil engineers were untrained in these areas. PMSs have proven their usefulness to today's pavement engineers; however usability remains crucial in supporting the user's confidence in the system's outputs. Integrating GIS software allows for a map interface to provide mangers with an overview of an entire roadway network, or focus in on data parameters of a specific stretch of road. Managers are also able to create user specified preferences like color coding or user formatted results all with the click of a mouse (Allen 2007).

Transportation asset management involves the coordination of a number of agencies on a number of levels. It makes little sense for the water company to rip up a stretch of road to make repairs, and then repair that section of road if the gas company will need to do the same thing two months later. This often happens because of a lack of coordination and communication among different agencies. PMSs must be widely accessible and interoperable to all those who have a stake in roadway management. PMS-GIS integration allows users from many organizations, from traffic, and sanitation, to public safety and public works, to quickly identify specific pavement areas of interest for their agency while promoting coordination to mitigate project rework and loss of pavement service life (Saunders 2005; Allen 2007).

2 RESEARCH OBJECTIVE AND APPROACHES

As an on-going project, the primary objective of this investigation is to develop a framework for the practical development of a functional and widely accessible

system to manage and track collected data while representing that data in a highly graphic, and user friendly manner. The approaches to accomplish this objective are as follows: (1) investigate an appropriate geospatial framework in which to implement the proposed data management system, (2) utilize a geospatial program such as Google Earth or Bing Maps application as a means of providing users roadway data in a highly visual, highly accessible, and user-friendly manner, (3) personally validate the effectiveness of the selected geospatial program as a data tracking system in highway applications while testing its interoperability between current and proposed components of the Nebraska Department of Roads(NDOR)'s PMS(NPMS). Figure 2 illustrates these proposed approaches through the current NDOR research projects.

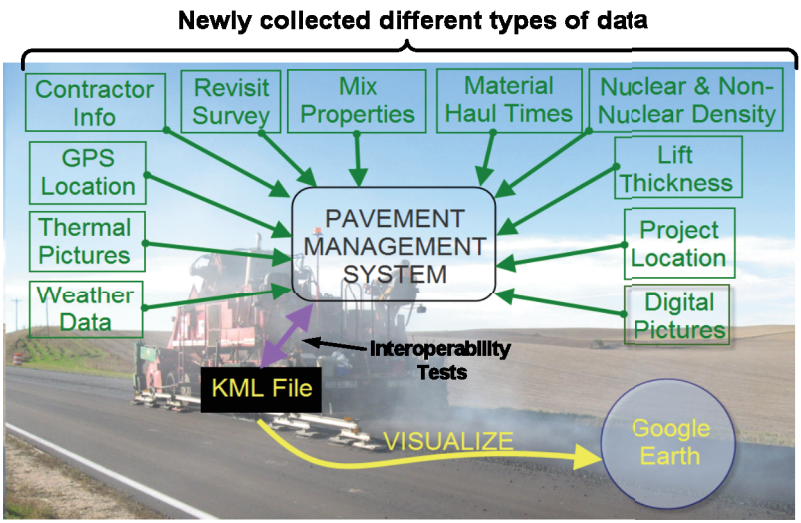


Figure 2 Proposed approaches to develop a framework for a web-based integrated pavement management system

3 IMPROVING THE GEOSPATIAL FRAMEWORK WITHIN THE STATE OF NEBRASKA

Before developing the project specific data management tool, a preliminary investigation was carried out to analyze the State of Nebraska's current geospatial management system and viewing framework. The analysis was completed in order to understand how the State's existing framework might be improved for both internal and external staff.

An overview of proposed framework layout is shown in Figure 3. NDOR's current framework is structured in such a way that one stake holder has complete control of all information that is distributed out to other interested parties. The core of the data

structure is the NPMS which is where all data and analysis take place. Relevant geospatial data pertaining to roadway construction and maintenance is funneled through a Pavement Optimization Program (POP). The POP program is maintained and controlled by internal staff at the NDOR headquarter, where it performs all geospatial data analysis through a number of programs. Furthermore, these analyses are updated once a year and mailed to the appropriate district offices. The district offices also have the capability of using at least three different needs specific software programs to view geospatial data from the State's database, e.g., FHWA GIS. The current NDOR PMS is built upon an intranet connection; meaning that only individuals within the organization have the security to access the needed information.

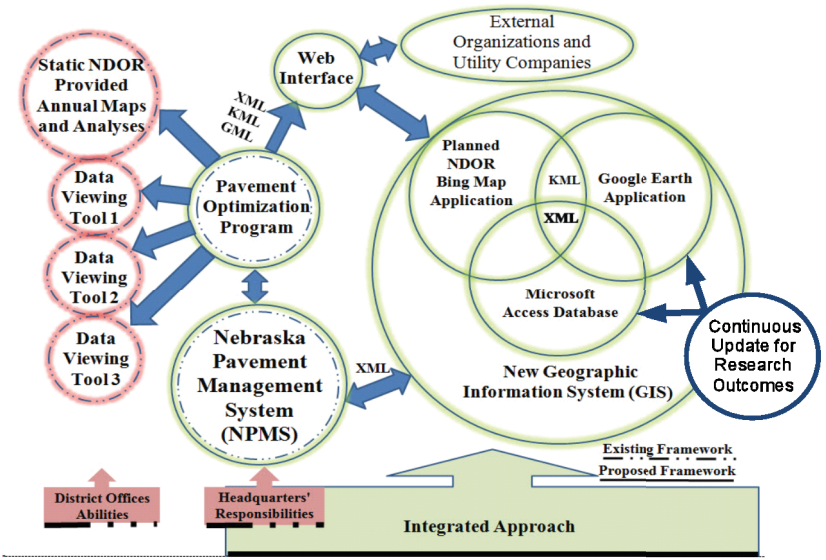


Figure 3 Proposed framework for data Integration (interoperability) with Nebraska's Pavement Management System

The NDOR has recently begun to investigate possible options to upgrade their current system due to its limited data visualization capability and difficult accessibility from the users. As one of the options, the State has begun the surveying of its roadway system with the Pathway, an advanced road profiling system. The profiling system collects information on rutting, cracking, raveling and other pavement flaws, while it continuously records video footages of the road and tags all collected information to an exact location. The level of geospatial detail this new profiling system generates necessitates the need for updated software.

After the data has been collected and uploaded to the State's mainframe, up-to-date information should be able to be viewed year round. The viewer should also be

flexible enough to be easily customizable by its users. It is identified that mainstream geospatial mapping programs like Microsoft's Bing Maps and Google's Google Earth programs are most appropriate as a web-based user interface. It is because these mapping programs have been widely tested, and once implemented come with vast support communities making further development and troubleshooting easier. Additionally, these geospatial programs allow for unique layers to be created that could contain almost any assortment of information. The layers features within these programs will allow the NDOR to combine the different viewer programs currently in use into one simple geospatial platform, and in turn save software maintenance cost and annual licenses fees.

The proprietary nature of the current State framework should also be addressed. Although it is understandable that the State does not wish to share all database information with whoever is interested in looking at it, certain information should be provided to relevant stakeholders. Rather than giving direct access to the organization's intranet, access to specific data layers within the geospatial program should be granted to certain stakeholders via a secured simple internet connection. Allowing outside viewing and contributions to the State's transportation information promotes an increase in the level of coordination that be achieved between organizations. For example, utility and railway companies are able to coordinate when scheduled maintenance or construction can more easily take place.

Also, the proposed framework includes the research information component which is connected to State's PMS as shown in Figure 3. The related academic or industry research outcomes can be continuously updated through one of the introduced geospatial programs above. In this research, research outcomes were continuously updated through Google Earth as a main research progress communication tool between the university research group and the NDOR research group during the entire period of research. Further details will be introduced in Section 3.1.

Data Interoperability

It is important to consider how such web-based geospatial programs will be integrated with the existing and future PMS. The Texas Transportation Institute of Texas A&M University highlighted this issue in their development of a web-based tracking system for flexible pavement. The Institute noted that a system based on the eXtensible Markup Language (XML) schema promoted easy data or file exchange (Krugler et. Al 2006).

The current Google Earth program is built on a Keyhole Markup Language (KML). In turn, the KML language schema is based on XML and was created specifically for the representation of geographic data (Open Geospatial Consortium 2009). To reduce the file size, a KMZ file format is widely used. A KMZ file is simply a zipped KML file. KML files can be converted to XML files and vice versa by opening the KML file in a text file followed by opening and saving that text file in Excel as XML data.

As an initial attempt, the Nebraska Department of Roads (NDOR) has been testing Bing Maps within their organization for its adoption. It is convenient to note that Bing Maps is also capable of reading KML files in much the same way Google Earth is as shown in Figure 3. However, the interoperability between competing programs is always a concern. In an effort to formulate the pavement data management system as well as test the interoperability between the State's new and existing geospatial framework, Google Earth was selected in this study as the program upon which to build the project specific database.

As previously shown in Figure 3, the XML file schema was found to be common between the State's current Pavement Management System(PMS) as well the two geospatial programs and Mircosoft Access used in this study, providing the bridge between the recommended software programs and existing framework components. As an on-going project, several different data types shown in Figure 3 are being tested among Microsoft Access, Bing Maps, and Google Earth to identify the interoperable formats of data structure and data file. It is identified from this study that a KML file (as well as an XML file) working for Google Earth is not always readily working for Bing Maps, or vice versa for certain types of data format such as image data and multimedia data. The current test results of interoperability are not yet at the stage for the further discussion in this paper, thus the detailed test results and recommended data formats will be introduced in near future.

3 GOOGLE EARTH'S APPLICATION ON HIGHWAY PAVING CONSTRUCTION PROJECTS

It became apparent that the research group's undertaking of a project for the Nebraska Department of Roads (NDOR) necessitated a system to efficiently manage the growing pool of collected and analyzed data that had been accumulated up to that point. The research project involved the visitation of several paving sites across the State of Nebraska to investigate the relationship between temperature segregation and material density in hot mix asphalt (HMA)(Cho et al. 2009). Figure 4 shows a site summary of an individual research site in Google Earth after data analysis.

3.1 A Case Study of Google Earth Usefulness as a PMS Tool

In order to perform this investigation, a number of devices were utilized, those devices included: 1) a portable anemometer to record current weather conditions, 2) portable GPS unit to digitally mark areas of interest for later revisit, 3) a thermal imaging camera to locate areas of HMA temperature segregation, 4) a penetrating thermometer to validate the thermal camera, 5) a digital camera to record site conditions and procedures, and 6) nuclear and non-nuclear pavement density devices to measure the compacted density of the material. In addition to the data collected via portable devices, site specific information was noted that included: 1) pavement or mix type, 2) lift thickness, 3) haul time, 4) equipment used, and 5) location. As shown in the proposed framework in Figure 3, Microsoft Access was used to build a database for all collected data and results of analysis and comments.

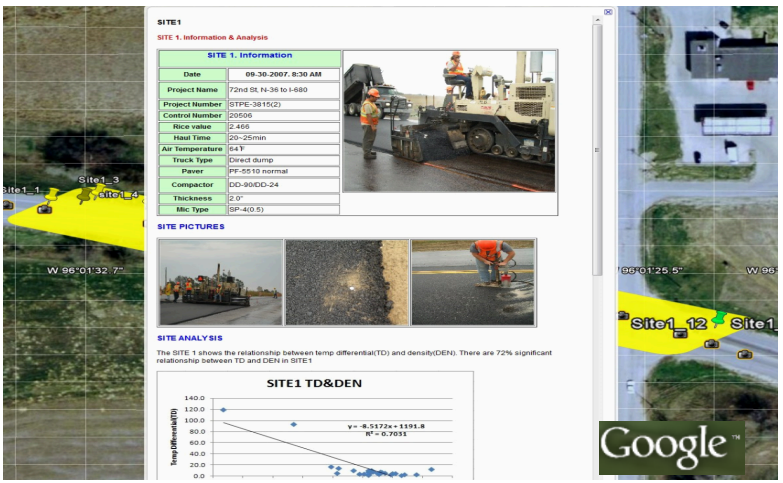


Figure 4 Google Earth Based Visualization of Pavement Data

The system was constructed during the paving offseason, and ready to be utilized at the start of the paving season in Nebraska. That spring all previous sites were revisited in an effort to measure and identify any change in overall pavement quality. Changes in quality were documented in MicroSoft Access and imported into the Google Earth Data Management System that had been created. After all information from the revisit was uploaded, users were able to simply "fly" around within the Google Earth program and select individual sites to focus on, and view relative site specific information (Figure 4). Once a particular site had been selected, users are able to further focus on a site specific data point (Figure 5). For instance, when a flaw was noted at a specific location during site re-visitation users were able to immediately call up that exact location to view germane information that was logged at the time of construction that might explain the pavement's premature failure. Paved road sections were highlighted and high temperature segregation spots were pin-pointed with different color based on the severity of temperature segregation (Figures 4 and 5). Not only virtually marked in the Google Earth database system, the pin points were physically marked at the corresponding locations on the pavement for the purpose of site revisit later (Figure

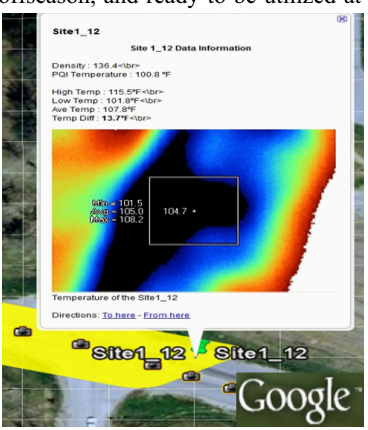


Figure 5 Specific Pavement Data (thermal)

6). These marks were used to locate an exact spot to inspect any premature failure or distress developed around the mark after a couple of freeze and thawing cycles.

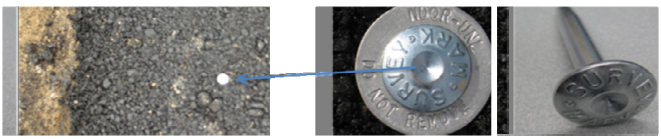


Figure 6 Marking a high temperature segregation point on the pavement

Google Earth used as a part of the NDOR research project enabled the sponsored NDOR research group to have a better understanding of the research outcomes and progresses. It is because the NDOR research project sponsors/managers were able to instantly recall location specific data, typically in a highly visual manner, making decision making more fluent and reliable, which are not available from the current NDOR PMS. Its inclusion made the university research team communicating research conclusions easy to relay to them.

4 CONCLUSIONS AND RECOMMENDATIONS

This paper has introduced web-based geospatial data management system as a cost-effective GIS tool to be integrated with the State of Nebraska's Pavement Management System. After compiling a brief analysis of available literature, as well as current pavement managers' needs regarding pavement management systems, a simple model encapsulating those findings was created and tested through a real life application in HMA pavement construction and maintenance.

A brief study was also conducted on the State's current geospatial framework and how changes might be made to improve it. The research team found that a number of the standalone programs used for specific tasks should be integrated into one consistent platform. Current mainstream geospatial mapping programs like Bing Maps and Google Earth were recommended as capable in fulfilling the State's needs. The investigation also found a need to share up–to-date information with outside organizations including companies and universities in an effort to promote synergistic coordination. The level of sharing could easily be accomplished by making certain layers of NDOR provided data which is viewable on programs like Google Earth via simple web interfaces.

Users of the created management system including the NDOR research sponsors and the authors found its application in tracking pavement information very useful and intuitive. The developed system in this study was highly customizable and portable. Adjustments to the system are continuous as data and procedures are constantly updated from other pavement research projects. The system's use has improved how this research group's transportation research data is collected, analyzed, and shared.

For future study, such geospatial data management systems including Google Earth and Bing Maps need to be further investigated for their interoperability with different data types and data structures commonly used in States' PMS or Transportation Asset Management (TAM) systems to be successfully utilized for State's infrastructure management.

ACKNOWLEDGEMENT
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Infrastructure and Energy OR Energy and Infrastructure: How Energy Demand and Infrastructure Impact Each Other and What Carbon Limits Will Mean for Both

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ABSTRACT

This paper examines how energy and infrastructure impact each other and what that means for carbon limits and peak oil. Throughout history mankind has always had ample sources of energy to rely on. This reliance on energy, particularly through the industrial revolution, allowed mankind to build a modern lifestyle. However, as infrastructure has evolved and become more complex the world has demanded greater supplies of energy. Initially this demand for energy was met with nearby supplies. However, as those supplies have decreased, more energy is needed from further and further away. This has meant that greater and more complex infrastructure has had to be built to supply the energy resources from greater distances. The easy energy resources have also been tapped resulting in a need to expend more energy to unlock the remaining sources of energy. Now, as the world ponders carbon limits and potentially faces peak oil the viability of our existing infrastructure and the energy that supports it is a cause for great concern. Are we taking into account our future energy sources as we build more and more infrastructure? In a world of constrained resources building infrastructure without regard to energy could significantly impact the price we pay for energy as well as the viability of the infrastructure. Infrastructure and energy is an important discussion as it will impact our standard of living and how we plan now for 2050.

INTRODUCTION

The demand for energy around the world has accelerated. With the advent of cheaper energy sources, global demand for energy has doubled every 25 years since 1900, and in 2000, the world demanded 16x more energy than in 1900 (Smith 2009). From houses to transport to commerce mankind has increased its demand for energy significantly by increasing its infrastructure. Prior to the automobile and modern transport, transport was limited, goods were consumed locally and only specialty products would travel great distances. With the advent of the oil and its refined products the demand for autos, ships and airplanes has grown tremendously. With

these in great demand infrastructure had to be build to support them. However, once built the infrastructure makes it easier to consume greater amounts of energy.
One need only look at what happens when we build a highway expansion. The infrastructure allows more people to live further from the city in less expensive and larger housing. As infrastructure expands society demands more energy to use the infrastructure. The need for more energy increases the demand for greater infrastructure to ensure the energy can be supplied. Which further increases the demand for both energy and infrastructure. From living, to transport, to work, to eating, each has resulted in an expansion of both energy and infrastructure. The automobile requires gasoline, gasoline requires refineries, refineries need trucks, pipelines and ports, both require paved highways, which requires asphalt. Energy and infrastructure feed each other, with both requiring greater amounts of the other.
However, in an energy or carbon constrained world, we are not able to continue to build energy demanding infrastructure or pursue infrastructure demanding energy, otherwise we hit the constraint before achieving our objective. A Cap & Trade may well limit the amount of alternative energy infrastructure that can be built as well as how far away one can commute to work. Distant infrastructure requires significant energy to maintain. Peak oil would have a similar impact. Yet this understanding is not present in any discussion on carbon limitations nor on how it could affect the real estate and construction industry.

LIFESTYLE & INFRASTRUCTURE

Lifestyle is a choice, one that has a significant impact not only on our infrastructure requirements but also on our energy demands. In the US we have chosen to live in suburbs and in distant communities and as the US covers a much larger geographic area than Europe, this choice limits our ability to build efficient public transportation systems. However, given this choice the country has had to develop significant highways, bridges, and streets thereby facilitating the ability to move by car. The challenge is that these infrastructure projects have allowed further developments in more distant suburbs, thereby increasing our energy demand.

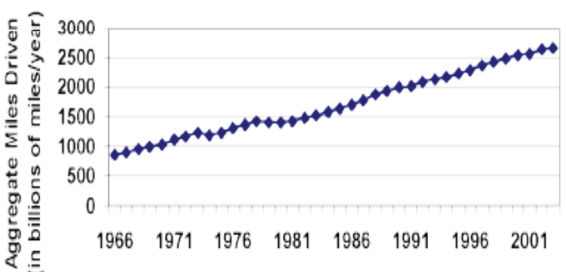


Figure 1: Aggregate Miles Driven in the USA

Source: FHA's *Highway Statistics* Table VM-1 (passenger cars plus single-unit 2-axle 4-tire trucks)

And although cars are more efficient than they used to be, Americans have chosen to drive more miles than they ever have before.

Year	Population	% Increase from Previous Decade	Millions of Vehicle Miles Driven	% Increase from Previous Decade
1970	203,302,031		1,039,986	
1980	226,542,199	11.4%	1,402531	34.6%
1990	248,709,873	9.8%	1,979,276	41.1%
2000	281,421,906	13.2%	2,523,346	27.5%

Within urban areas the public can rely on mass transportation (buses and subway), take a taxi or even walk as everything tends to be conveniently located. Cities, due to limited land availability and cost, favor apartments and high-rise buildings, while suburbs with cheaper land costs favor single homes. As a result of suburban sprawl, more infrastructure is needed to supply energy (power & gas lines, gasoline stations) as well as food, electronics and clothing (shopping malls, grocery stores). All which require more trucks to resupply.

A carbon cap or peak oil would have a significant impact on lifestyle as witnessed in this current recession. Both would increase the cost of existing energy sources resulting in economic disruption. As gasoline prices rise resulting in inflationary pressures throughout the economy, people became unable to pay their mortgages resulting in rising defaults. High transport fuel prices would favor infrastructure that uses less fuel, i.e. cities over suburbs, city center stores over suburban malls, and public transport over individual cars.

ENERGY & POWER UTILITY INFRASTRUCTURE

Based on the demand of cities and suburbs, along with industrial parks and government requirements, utilities planned and built in cooperation with the government an extensive energy and power network to meets the demands of society. With technology unable to provide distributive power in the quantities needed, large power plants were built to provide the power demanded.

With a massive increase in cars and miles of roads the oil industry had to build fueling stations and refineries to produce the gasoline, diesel and asphalt needed. This included a large increase in pipelines and trucks to transport the products to the ever growing and spreading population. Power utilities built large nuclear, hydro, coal and gas powered plants to provide electricity to the growing masses and to the economy. In each case when an oil company or a power plant company makes a decision to expand operations they take the assumption that they are price takers and that the energy source needed for their facility will be available in sufficient quantities to meet the demand of the society.

Today's society relies heavily on fossil fuels with transport being completely dependent on oil and electric generation relying on coal for 50% of power generation. However, under a regime of peak oil or carbon caps with naturally declining production or enforced cuts, prices would tend to rise rapidly significantly impacting infrastructure and energy demand.

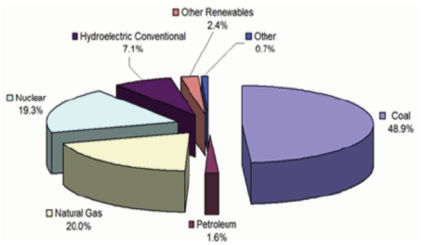


Figure 2: Electric Generation by Source

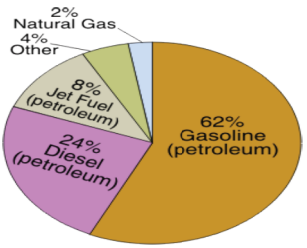


Figure 3: Transportation Fuel Use

Sources: http://www.eia.doe.gov/cneaf/electricity/epa/epat1p1/html and http://www.swivel.com/graphs/show/34587197

This is a significant threat to the current infrastructure in terms of maintenance and expansion, however, in planning, designing, approving and extending infrastructure projects this discussion is not taking place. In a country such as the US, if it were to achieve an 83% reduction in emissions of carbon dioxide equivalent (Energy 2009), then there would be need to be a corresponding decrease in the 200 million vehicles, 4 million miles of roads and over 1TW of electric generating capacity unless we are capable of restructuring our entire infrastructure from a high-carbon to low-carbon.

ECONOMIC GROWTH & PROJECTIONS

Rapid economic growth (as well as population) increased demand for energy significantly, not only in America but also in Europe, Japan and the Soviet Union after WWII. Recently the significant economic growth in China and India followed by Brazil and Russia has further increased the demand for energy. Economic growth and energy are closely correlated.

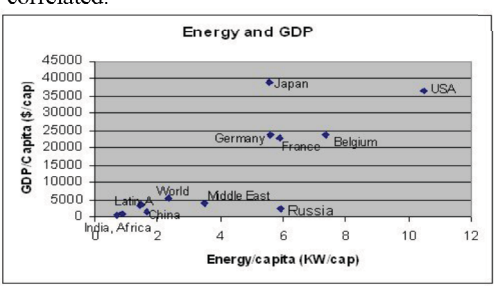


Figure 4: GDP versus Energy Consumed

Source: Graph produced from data in the 2006 Key World Energy Statistics from the IEA.

Based on the assumption of continued growth, agencies such as the EIA and IEA project global energy demand will rise significantly between now and 2030 based on rosy economic projections. This demand is due to increasing global infrastructure (roads, ports, pipelines, buildings, power plants) due to growing demand for vehicles and household appliances from increasing populations and increasing global GDP. The EIA in the International Energy Annual 2004 projects global energy demand to increase from 447 quadrillion BTU in 2004 to 702 quadrillion BTU in 2030

(International Energy Annual 2004). And while demand for energy within the OECD is only expected to grow by around 1% annually between 2004 and 2030, the projection for the developing world is between 2.5 and 3.75% annually for the same period (International Energy Annual 2004).

However, a key deficiency of these forecasts is the failure of them to take into account the supply of energy and the price of energy. These forecasts assume that energy sources, as they have always been available, will continue to be available at prices that will not impact demand. This can be clearly observed in the figures below, where energy demand continues to rise unhindered and the sources of these energy supplies are assumed to be available to provide for the demand. It is assumed that the demand and supply of liquid fuels (crude oil and petroleum liquids) will rise from about 120 quadrillion BTU in 1980 to almost 250 quadrillion BTU by 2030, the same holds true for coal, rising from around 70 to almost 200 quadrillion BTU, and for natural gas, rising from a little over 50 to over 150 quadrillion BTU (International Energy Annual 2004).

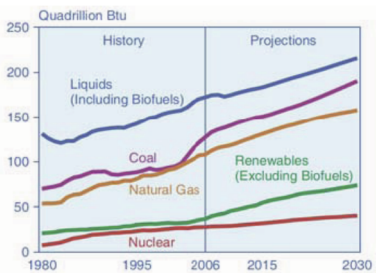


Figure 5: World Marketed Energy Use by Fuel Type, 1980-2030
Sources: http://www.eia.doe.gov/oiaf/ieo/world.html

The ability of the world, or for that matter OPEC, to supply the resources is not considered. The EIA and IEA project world oil production to rise from 80 million barrels per day in 2004 to over 120 million barrels per day by 2030. This estimate anticipates that OPEC will increase production from 30 to 50 million barrels per day and unconventional sources (tar sands, heavy oils and shale oil) will supply the remainder of 15 to 20 million barrels per day. There are several problems with these estimates, 1) OPEC and especially Saudi Arabia has publicly stated that they will not, 2) it does not take into consideration peak oil which is a real concern, and 3) there is a concern that the US pressured the IEA to be overly optimistic on supply forecasts.

More importantly with these projections of energy resources come forecasts of how much infrastructure will need to be built to extract those resources. For oil and natural gas exploration, development and production a significant number of drilling rigs, drilling muds, cement, and tubing among others need to be produced and delivered by truck or ship. As production increases or shifts to new areas this entails building new processing facilities, refineries, filling stations and roads, all of which require more infrastructure, particularly as more distant resources are brought into production. The same with electricity generation, expanding suburbs, and others, all of which require significant new infrastructure and will demand greater amounts of energy.

In 2000 the IEA (International Energy Agency) forecast that world energy investments would need to be $16.5 trillion between the years 2001 and 2030 (see table on next page) in order to supply the energy the world would need. Again, the key assumptions are very important, they are: 1) resources are available (geologically and politically), 2) peak oil and a carbon constrained world do not exist, and 3) that the world has the resources available (cash and materials) to build the infrastructure needed by the energy industry so that the energy industry can continue to supply the energy demanded by society.

The challenge with these projections however, is that they do not take into account how minerals are produced. In the case of oil production, a reservoir is discovered, it takes up to ten years before production begins, after several years production peaks and then declines. To achieve the goal of raising production to 120 million barrels per day by 2030, it would be necessary to stream (or bring into production) approximately 250 million barrels per day of capacity in order to raise total global production to the 120 million barrels per day. This is because on average production from existing fields is declining by approximately 4.5% per year.

Due to this concern, and the oil industry speaking out against these projections, the EIA and IEA have recently revised their forecasts to around 106 million barrels per day. However, the concern of a peak in production is not only an issue for oil production, but is also a significant concern for both natural gas and coal (McKillop 2006; Strahan 2008; Zittel 2007) which may also soon peak. These peaks are anticipated to occur after the peak in oil.

Table 2.2: **Global Energy Supply and Infrastructure**

		Units	2000	2030	Annual average rate of growth (%)
Oil	Production*	mb/d	75	120	1.6
	Refining capacity	mb/d	82	121	1.3
	Tanker capacity	million DWT	271	522	2.2
Gas	Production	bcm	2,513	5,280	2.5
	Transmission pipelines	thousand km	1,139	2,058	2.0
	Distribution pipelines	thousand km	5,007	8,523	1.8
	Underground storage working volume	bcm	328	685	2.5
Coal	Production	Mt	4,595	6,954	1.4
	Port capacity**	Mt	2,212	2,879	0.9
Electricity	Generating capacity	GW	3,498	7,157	2.4
	Transmission network	thousand km	3,550	7,231	2.4

* Oil production includes processing gains.
** The port capacity figures in this table do not include the capacity required for internal coal trade in China, India and Indonesia (cumulative additions for internal trade are 192 Mt of capacity).

Figure 6: Global Energy Supply and Infrastructure (Current vs. Forecast)
Source: EIA

The anticipated date for peak oil is sometime between 2008 and 2012. Peak oil while traditionally viewed as a geological phenomenon may also be a political phenomenon. After all political interference in oil production is very common and includes: the US government limiting exploration on over 75% of offshore coastal areas as well as Alaska; OPEC limiting international oil companies from exploring in their countries as well as national production limits; and the Russian government interfering with oil companies such as Yukos, Shell and BP. The biggest political limit could well be a cap-and-trade accord which by limiting emissions would significantly limit the amount of oil that could be consumed.

These individual country limitations as well as the geological limitations are not accounted for in the projections of how much energy resources will be produced in order to meet global demand. The assumption is that energy will be available to meet demand, without considering physical or investment constraints.

ENERGY INFRASTRUCTURE AND THE IMPORTANCE OF ENERGY

Taking natural gas as an example, as it is used heavily in both Europe and the US, one trillion cubic feet of natural gas (TCF) is sufficient to heat 10 million homes for one year. To bring that natural gas to market a significant amount of infrastructure needs to be in built to transport the gas from the field to the household. While this infrastructure is expensive to build and maintain, because of the previous availability of natural gas, the US is reliant on it for 23% of its energy needs.

To transport the natural gas, pipelines have been built across the USA and Europe/Russia. As older fields deplete it is necessary to add remote fields to the network. However, there is a supply constraint within the existing pipeline network, therefore the infrastructure needs to be expanded to accommodate the growth and the distance with which the newer gas needs to travel. In Europe, natural gas can travel over 3,000 miles in pipelines that connect Russian fields to European consumers. Greater distances require larger amounts of energy to bring the same amount of gas to market, thereby increasing GHG emissions for the same amount of natural gas supplied.

Of greater concern is that a cap-and-trade program on carbon would limit the amount of steel and concrete that can be used for energy each year, thereby limiting the ability to change the energy infrastructure the longer we postpone changing the infrastructure. Most renewable energy (wind, solar, geothermal) as well as nuclear power require significant amounts of concrete and steel. The majority of GHG emissions from these facilities are produced upfront during construction. Therefore, limited future emissions means renewable and alternative energy power plants need to be built sooner while caps and higher, as waiting could mean there are no excess carbon emissions allowed to build these facilities.

ESCALATING COSTS – THE LIMITS OF PRODUCTION

The major impact on both energy and infrastructure today is the escalating costs of production of energy and the resulting increase in the cost of infrastructure. These costs have been significant and are driven by the globalization process that has occurred worldwide. This globalization process meant that places like India, Brazil, China and Russia could join the world economy, grow rapidly, expand their manufacturing output and export their way to riches, much like Japan, Taiwan and Korea have done. This was possible during the 1980s and 1990s because the world was awash in excess capacity. This surplus capacity allowed for continuous rapid growth and besides the energy consumption of India and China was particularly low, so even though the growth was rapid it had a minimal impact on global demand. By the year 2000 things began to change, while rapid growth continued, the excess capacity began to dry up because growth was now significant. This impacted at first oil, then coal, steel, iron ore and many other minerals and fuels. China has had the biggest impact and it does not, for now, seem to be slowing down. This has led to rapidly escalating prices for all of these resources.

WORLD TRADE

Global trade has been based on cheap energy. China's and India's significant global expansion was predicated on cheap energy allowing corporations to take advantage of their cheap labor resources and manufacture goods for export without regard to transport costs or for that matter to the resulting pollution. However, as oil has risen from $ $30 to over $100 per barrel, transportation costs are beginning to have a significant impact on trade. At $100 per barrel transport costs are approximately 40% of total shipping costs and at $200 per barrel transport costs are 80% of total shipping costs (Hennigan 2008).

It may no longer be cheaper to move production from Europe and the US to China due to these significant transport costs, which would be exacerbated with peak oil. The labor cost advantage is being diminished by the energy cost of transporting goods thousands of miles. This could have a significant impact on future trade between countries, future growth rates, levels of pollution and per capita incomes.

Reverse globalization due to either increased oil prices or carbon limits would reduce pollution but this would also significantly impact world trade. The impact to world trade could result in more local construction but less heavy infrastructure used to move goods between nations. It is also important to note that while significant manufacturing capacity has moved to China in the past twenty years, this industrial capacity has been sustained by China only through the addition of significant coal generated electricity. This has generated significant construction activity, but made China the number one country in terms of GHG emissions. A move towards a carbon tax or a cap-and-trade that is properly applied to imports would end globalization as production center's move to demand centers.

THE FUTURE

The future depends significantly on the approach and policy of what we as a society decide with regards to energy and infrastructure. Let's examine two different approaches: 1) We seek to keep the infrastructure we have today while planning (hoping) to change the energy resources consumed, and 2) We attempt to keep using the same energy resources but change the infrastructure to make it more efficient. These two models will depend heavily on what we decide to do about global GHG emissions.

Infrastructure

Our current infrastructure is energy intensive. To replace oil, gas and coal it would be necessary to build an extensive energy system based on hydroelectric power, nuclear power, wind, solar, geothermal, and biomass. The need to replace the energy system is two-fold, 1) oil, gas and coal are carbon intensive and release significant levels of carbon along with other pollutants, 2) globally oil is projected to peak between 2008-2012, natural gas anticipated to peak around 2020-2030 and coal will peak in around 2025-2030 globally. With a global peak in energy, the cost of energy would continue to increase significantly. This increase is predicated on whether production peaks and then declines or peaks and plateaus for a significant period of time. The plateau would buy us time to change the energy used in the infrastructure. A world in this instance could develop battery powered cars, buses and trucks to save the oil for petrochemicals, plastics, medicines, and air travel. It could also develop hydrogen powered vehicles which could be extracted from nuclear, wind and solar. However,

solar and wind will not save the day, at least with present technology because of a lack of mega-storage facilities. But these sources could slowly replace oil, gas and coal and we could continue to live a similar life style, which is energy intensive, and revolves around the suburb.

Energy

Our current energy needs are derived from the infrastructure that we have developed, including large suburban areas, reliance on the car, and large homes as well as inefficient buildings. Given the fact of peak energy it would be necessary to improve our infrastructure to make it significantly more energy efficient. This could very well include a mass movement from the suburbs to the cities, resulting in the need for less cars and more public transport. This would be the high cost energy scenario where we continue to use our current energy resources, in great response to poor legislation from the government.

An alternative to this would be a pro-active government that stressed developing existing resources, including exploring for oil and gas offshore, in national parks, and in Alaska, as well as forcing other countries to abandon their national oil companies and closing down OPEC. This would entail the development of shale oil and a pro-nuclear policy to expand our energy resources.

The Impact of Carbon Limits

It is interesting to note that due to the hysteria of global warming, society or more aptly the politicians appear to be focusing their attention on limiting carbon and GHG emissions rather than understanding that should oil, gas and coal production peak within the next 5-20 years that this would in fact imply that the global emissions of carbon and GHG may have in fact a natural limit, which we cannot exceed. The danger being that unless alternative energy forms, along with more efficient buildings, infrastructure and transport systems are developed and made available, there could be a significant impact on economic growth and on the world's forests as people seek energy.

Should society decide to pursue carbon limits then it depends significantly on how the carbon limits are structured. We as an industry need to ensure that there are sufficient carbon emissions to allow for construction of new infrastructure that will utilize low-and-no-carbon emissions energy. An across the board carbon tax would be fairer but would impact agriculture, construction (infrastructure) and manufacturing. If levied properly it would provide no advantage to exporting pollution to other countries by moving manufacturing or energy production across our borders. The construction industry needs to ensure that the legislation moves towards a carbon tax rather than a cap-and-trade, otherwise it could significantly limit future construction.

This is because the current discussion in Congress focuses on a carbon cap-and-trade. A carbon cap-and-trade limits the amount of carbon that could be released within US borders, there is concern it will not cover imported goods. The legislation however would impact the cost of energy and reduce the demand for energy intensive infrastructure. This would be beneficial to the construction industry in terms of increasing demand for energy efficient buildings, because current building infrastructure consumes 40% of all energy and approximately 70% of electricity, 50% of which is currently derived from coal. The future of infrastructure with carbon limits and higher energy prices would result in greater density within cities, larger buildings

to accommodate the need to reduce travel, and could significantly reduce the number of cars the average family has assuming families migrate back to the cities to save costs. This could present a great opportunity for the industry as large buildings along with energy efficient ones are in high demand, this could well include retrofitting existing buildings for not only energy efficiency but also to accept solar panels and wind energy. However, it could well reduce the demand and maintenance for the transportation infrastructure as demand lessens due to emissions limits.

CONCLUSION

Peak oil, gas and coal, combined with rising energy prices and the high potential of carbon limits will result in demand for larger more efficient buildings, more energy efficient infrastructure, greater mass transport and more alternative energy resources (wind, solar, geothermal and nuclear). This presents an opportunity for the construction industry to ensure that they have access to not only people but to the raw materials needed for the coming construction boom to alleviate the energy shortages that the world is already experiencing. Those companies that develop a reliable supply chain of materials (with a focus on local sourcing) and people to build these projects will have greater opportunities as industry and people realize the impact of ever rising energy costs and how by altering the way they live and work can significantly improve their and their company's bottom line. To ensure this the construction industry needs to work with Congress to ensure that any carbon legislation includes provisions to allow for significant amounts of construction to replace the existing infrastructure to move the US into a low-carbon future.

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INTEGRATING GPS AND LASER TECHNOLOGY TO MAP UNDERGROUND UTILITIES INSTALLED USING OPEN TRENCH METHOD

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ABSTRACT

The U.S. continues to face the challenge of correctly identifying underground utilities before beginning a construction project. Having accurately mapped utilities and knowing their location will increase efficiency in the construction process, reducing accidents and utility interruptions.

A methodology to integrate Global Positioning System (GPS) and laser technology will be outlined. This process will assist field technicians in collecting underground utility field location data, accurately and consistently, in a minimal amount of time, with less effort, while maintaining maximum safety. It will also form a framework to develop a permanent data solution in which data collected can be stored in a database and retrieved in a three dimensional geo-referenced map for future use.

This research focused on utilities which were installed using an open trench method. The integrated technology was tested under construction field conditions. The results of the research indicate that utility data can be collected quickly and cost effectively through this process. The positional accuracy of underground utilities was mapped in three dimensions (3D) within ± 0.45m accuracy.

KEYWORDS: Underground Utilities; Damage Prevention; Global Positioning System; Laser; Utility Locating Methods; Urban System Framework; Utility Safety; Utility Mapping.

INTRODUCTION:

While the concept of a buried asset is not new, the function that the buried assets serve is vital to modern living. It is fundamental that the buried asset networks are recognized as an important resource and one that requires careful management. The

underground world has become increasingly complex and more difficult to manage. The United States has a massive network of underground pipelines and cables including such items as gas pipelines, telecommunications, water pipelines, fiber-optic cables, storm water lines, wastewater lines, steam pipes, conduit systems and hazardous waste lines. In all, the U.S. underground infrastructure comprises about 20 million miles of pipe, cable and wire. Construction related damage to gas distribution systems increased 50 percent from 1996 to 2005 (PHMSA 2006). Records of location of utilities are rarely available and if available, most of the data is located relative to the ground level or physical features which may no longer be available or have been altered. Thus the exact location information of many utilities is unknown or very inaccurate.

Ground Penetrating Radar (GPR), Global Positioning Systems (GPS), acoustic, seismic, Radio Frequency Identifiers (RFID), electromagnetic and low frequency electromagnetic, and gyroscopic duct runners are various geophysical methods available to locate underground utilities. Detection of buried assets without excavation is difficult because of the ground conditions, age of the asset, the material the buried asset is made from, its contents, and the condition of the asset and the number of buried assets at a given location. None of these geophysical methods provide the complete solution for locating the utilities. No single technology or combination of devices is available to locate existing underground utilities with 100 percent accuracy (Costello et al. 2007).

A method that is less costly and which uses common equipment to collect location data of utilities accurately, safely, with less effort, and time during their installation will provide a foundation for finding the location of buried utilities at a later time. A data base that provides information on all existing underground infrastructure over a geographic region is essential for efficient planning and construction of both surface and sub-surface infrastructure.

The nation's drinking water supply needs $334.8 billion in infrastructure investments over the next 20 years for thousands of miles of pipeline to ensure the public health and economic well-being of our cities, towns, and communities (EPA 2009). Since the U.S. Government is planning to invest a significant amount of money for new installation, replacement, or maintenance of underground assets, this gives an idea about the need to locate existing utilities when they are exposed for maintenance or new utilities during installation.

BACKGROUND

Many times the location of a utility shown on site drawings varies from the actual position on site. This happens due to changes during design or plans. For example, another utility is found on the proposed alignment and the location of the line was not known at the time of planning. Questions often arise: Is the location information accurate? Can the reference used be located? Is the information from an "as-built" drawing or its design location? "Current practice of data collection is done on an 'as need basis', that is, there is not much coordination between who is doing what and what is located where" (Baffour et al. 2002).

The Common Ground Alliance (CGA), a member-driven association dedicated to ensuring public safety, environmental protection, and the integrity of utility services, promotes effective damage prevention practices. In May 2007, the CGA launched a national "Call Before You Dig" campaign to increase public awareness about the importance of using 811 (CGA). Arizona Blue Stake is an organization developed in Arizona as a one call notification system to assist excavators in meeting statutory requirements of locating (within ± 0.6 m (2 feet)) underground utilities prior to excavation. For example, the Arizona State Constitution, Section 40-360.22, discusses excavation, determining the location of underground facilities and providing that information to excavators prior to excavation (Arizona State Constitution 2007). It is a damage prevention measure taken to avoid catastrophe during construction.

Conventional ground surveying and mapping are still the primary methods used to collect as-built location data of underground utilities. The advantage of conventional surveying techniques is that it provides a very accurate location data. However there are some disadvantages of using this method: it is time consuming, resource intensive and requires skilled technicians to reach a centimeter level surveying accuracy; it is difficult to operate conventional surveying equipment like an auto level and/or a total station in bad weather, or during night-times; data requires processing before any useful information is available and data collected with reference to physical features may be altered in the future.

Tulloch et al. proposed a model to provide location information where "as-built" utility data is collected using both photogrammetry and GPS. A GIS is also required to store and organize the utility information so that accurate asset management can be accomplished by municipal engineers (Tulloch et al. 2005). Drawbacks of this method include requiring a skilled person for operation in order to reduce human error. The camera should also be dust proof, cold and heat resistant, and moisture free to eliminate the addition of errors.

The Global Navigation Satellite System (GNSS) based technology can be used to map underground assets; however, for built up areas GNSS signals can be lost, unavailable or have large errors (Taha 2008). Taha proposed integrating GNSS and Total Station and developed a technique called Continuous UPdating Technique (CUPT) by which readings can be taken at centimeter level precision. This technique requires at least two people and is comparatively expensive. It would be difficult to use this technique at a construction site when a utility is exposed for a short period of time, for example, utility installation during road construction projects.

This paper proposes a model by which a single technician, without prior knowledge of surveying, would be able to take "as-built" readings of underground utilities, safely, correctly, and effectively during the installation process. Installations of utilities are usually done by one of two methods: trenchless and/or open trench. This paper addresses a system by which the location of utilities installed by the open trench method or exposed for maintenance or repair can be mapped, stored, maintained and retrieved when required.

MODEL FOR LOCATING AND MAPPING UNDERGROUND UTILITIES

Often, last minute changes are made to drawings and/or the alignment of utilities due to unknown existing field conditions. It is difficult to note on a drawing when a change is made. Furthermore, changes noted on site often do not reach the utility database. "As-built" readings help record the coordinates of installed utilities, as well as other utilities that are discovered during excavation. The proposed method integrates GPS and Laser technology to take "as-built" coordinates readings. Figure 1 proposed a flow chart for collecting, mapping and retrieving utility location data.

The data collected is then stored in a database where the data can be exported to 3D geo-referenced software such as Google Earth®, Minerva®, Virtual Earth®. This framework stores, maintains, and retrieves data using the Urban Systems Framework (USF) developed in the Digital Phoenix project at Arizona State University. USF framework is a structure that allows handling diverse data sets in a concise fashion. It provides methods for visualization, hookups to simulation tools, and supports web-access tools that allow working on datasets in a distributed fashion (Pahle et al. 2009). USF runs on the PostgreSQL database system. Metadata is stored in PostgreSQL and is compatible with the Open Geospatial Consortium standards (Pahle et al. 2009).

Data collected using the integration of GPS and Laser is differentially corrected and is uploaded to the USF framework. The steps in this framework are: first, calculation of best fit line through the collected data points; second, simulation of best fit line to resemble a pipe in 3D; third, visualization of results. Figure 2 shows the flow process of the data through the USF frame work. The program for best fit line was written such that it can be used for the pipes having turns and bends. Storage and organization of data, automation of data processing, conversion, automated execution of simulation, and interoperability of results are the challenges that were dealt with using the USF framework (Pahle et al. 2009)

With the available data in 3D and the simulated view of the location, the utilities can be located using a GPS receiver in open areas and survey techniques in built-up areas. It also provides information which can be useful during the pre-construction and/or construction phase of a project.

To check the accuracy that can be obtained using the integration of GPS and Laser technologies, a GPS Pathfinder Pro-XH receiver and TruPulse 360 laser receiver were used in field trials under construction conditions.

INTEGRATION OF GPS AND LASER (GPS-Las) – OVERVIEW

The GPS is a satellite-based navigation and surveying system for determination of a precise position in time, using radio signals from the satellites. The positional data can be determined in either real time or with post processing. GPS is a powerful tool which can locate utilities accurately in open areas. GPS receivers are portable and easy to use. It can be useful in bad weather or even at night. Nevertheless, the accuracy of GPS readings is reduced in built-up areas due to multipath and poor

geometry of satellites. Additionally, the issue of safety exists for a technician taking readings of utilities over an open trench (Figure 3).

By integrating GPS and Laser the issues of coverage and safety can be efficiently addressed. In addition, the data collection process is easier, faster, and more cost effective. The GPS and laser receiver are mounted on the same tripod stand and the field technician can record readings within a few minutes correctly and safely (Figure 4).

INTEGRATION OF GPS AND LASER (GPS-Las) - INFORMATION SEQUENCE OF METHODOLOGY

Visual representation of the flow of information from data collection to visualization is shown in Figure 5. Field data was collected using GPS and laser with TerraSync® software on a field tough book. The technician collecting data can stand at a safe distance from a trench while taking the coordinate readings. The GPS and laser are connected to the computer and the data point readings are collected by shooting a laser beam to the utility. Additional features of any data point can also be noted using the comment tool in the software. Once recorded, data is transferred to GPS Pathfinder for post processing which applies the differential correction to the collected data. Post-processed data can be exported in various formats such as CAD files (DXF, DGN, etc.) or Shape-files (SHP). Shape-file data is then stored and maintained using the USF framework. Utility "as-built" data (CAD file) can be superimposed on CAD site drawings. Once the utility coordinates are known in 3D the profile view of the utility with respect to the ground surface can be drawn. After analyzing data with CAD software, data can then be transferred as a Shape file to the USF framework. Data can then be retrieved and visualized as needed.

INTEGRATION OF GPS AND LASER (GPS-Las) - DATA COLLECTION AND RESULTS

To assess the accuracy of the integration of GPS-Las technology, five different field trials were accomplished at different locations. The data was collected by a single person. Table 1 shows the length of the various utilities, number of data points collected and the time needed to collect the points. The data collected were compared with site measurements to validate the accuracy of the data. Table 2 shows the accuracy obtained in the X, Y and Z planes using the proposed GPS-Las method. The GPS receiver used for this research was a post-process Trimble® GPS receiver which can achieve accuracy up to 0.3m (≈1 foot). The accuracy obtained by the GPS receiver depends upon the visibility and geometry of the satellites. By recording more points, the error due to the geometry of satellites can be reduced (Costello, 2007). To reduce the effect of geometry of satellites and to achieve accuracy of ±0.45m (≈1.5 feet), it is recommended that at least 5 data points be taken per 20 meters (66 feet) of utility length (Table 2).

CONCLUSION

This paper proposes a model of collecting and mapping location information for underground utilities. The use of integrated GPS and Laser technology has been identified for locating utilities in difficult GPS environments. This integrated technology enables a single person to record "as-built" readings of utilities safely, efficiently and quickly. The technology does not require a skilled technician for its operation. Accuracy of approximately ±0.45m can be achieved noting five points per 20 meter of utility length. Accuracy of the integrated system was limited to the accuracy obtained by GPS receiver. The accuracy recorded by this integrated system is within the bylaws outlined by the Arizona State Constitution (2007) and provides some information regarding the depth of the utility to the contractor. The framework noted in the paper is a simple three step process of collecting, correcting and uploading data to visualize a utility in all three dimensions. This technology should provide contractors and engineers an efficient and cost-effective method to map underground utilities and improve construction productivity.

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Table 1: Field trials for data collection using GPS-Las technology

Field Trails	Utility	Length of Utility (m)	Number of Points Plotted	Total Time Taken to Plot (sec)
Field Trail 1	Electric line	≈ 180	≈ 100	≈ 3600
Field Trail 2	Water pipeline	≈ 6	≈ 5	≈ 300
Field Trail 3	Communication line	≈ 60	≈ 35	≈ 1200
Field Trail 4	Electric line	≈20	≈ 10	≈ 600
Field Trail 5	Water and Gas pipeline	≈ 30	≈ 27	≈ 600

Table 2: Accuracy obtained in X, Y, & Z plane in various field trails

Field Trails	Points per 20 meter		10 points (m)	5 points (m)	2 points (m)
Field Trail 1	Accuracy	X and Y coordinates	± 0.45	± 0.45	± 0.60
		Z coordinate	± 0.45	± 0.54	± 0.66
Field Trail 2	Accuracy	X and Y coordinates	Equipment Malfunctioning*	± 0.30	± 0.60
		Z coordinate	Equipment Malfunctioning*	± 0.45	± 0.45
Field Trail 3	Accuracy	X and Y coordinates	± 0.45	± 0.45	± 0.60
		Z coordinate	± 0.30	± 0.30	± 0.36
Field Trail 4	Accuracy	X and Y coordinates	± 0.30	± 0.30	± 0.60
		Z coordinate	± 0.36	± 0.36	± 0.45
Field Trail 5	Accuracy	X and Y coordinates	± 0.30	± 0.30	± 0.45
		Z coordinate	± 0.30	± 0.30	± 0.30

(* Equipment Malfunctioning occurred – loss of battery charge on laser equipment)

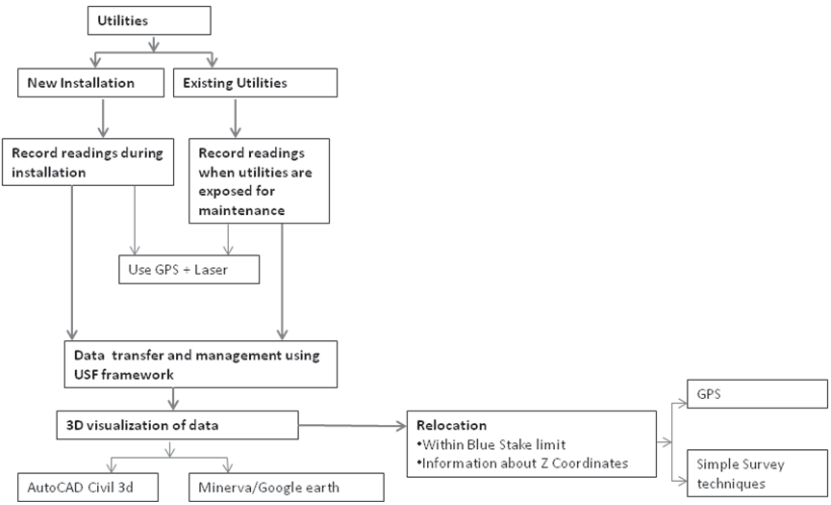


Figure 1: Proposed model locating and mapping underground utilities

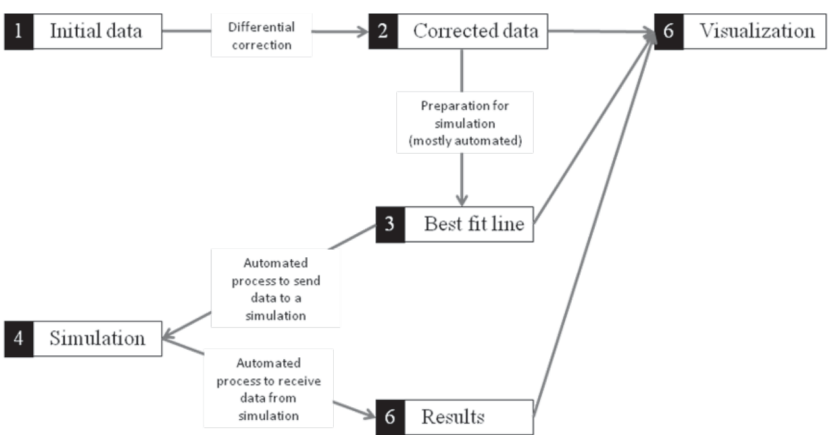


Figure 2: Data workflow in Urban System Framework



Figure 3: Field technicians taking readings using GPS receiver over an open trench



Figure 4: Recording "as-built" coordinates of utilities using GPS (top) and Laser receivers

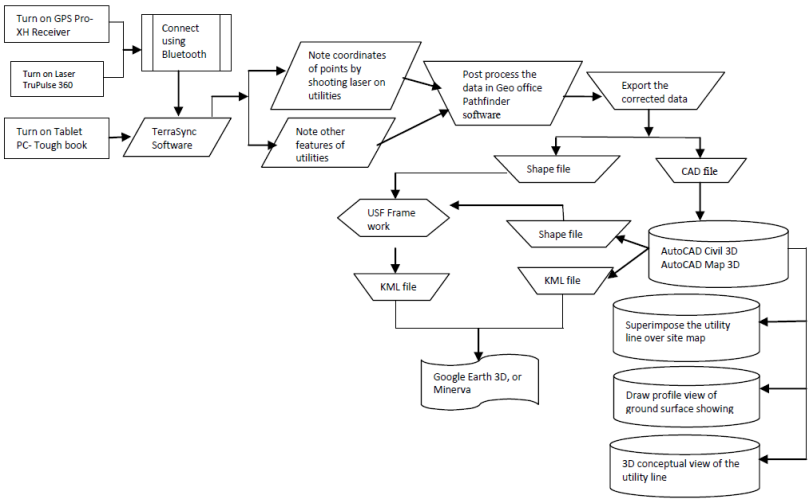


Figure 5: Information sequence of proposed methodology

Large-Scale Column Detection for Bridge Inspection

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ABSTRACT

Manually inspecting bridges is a time-consuming and costly task. There are over 600,000 bridges in the US, and not all of them can be inspected and maintained within the specified time frame as some state DOTs cannot afford the essential costs and manpower. This paper presents a novel method that can detect bridge concrete columns from visual data for the purpose of eventually creating an automated bridge condition assessment system. The method employs SIFT feature detection and matching to find overlapping areas among images. Affine transformation matrices are then calculated to combine images containing different segments of one column into a single image. Following that, the bridge columns are detected by identifying the boundaries in the stitched image and classifying the material within each boundary. Preliminary test results using real bridge images indicate that most columns in stitched images can be correctly detected and thus, the viability of the application of this research.

KEYWORDS

Column detection, bridge inspection, image stitching, image processing

1 INTRODUCTION

According to the latest data from the Bureau of Transportation Statistics, there are over 600,000 highway bridges in the USA (BTS 2009). Each of these bridges requires inspection at regular intervals (usually not exceeding two years) to ensure that they

continue to satisfy present service requirements (AASHTO 2001). Routine inspections are carried out manually by certified bridge inspectors following the National Bridge Inspection Standards by the Federal Highway Administration (FHWA 2004) and the Manual on Bridge Evaluation by the American Association of State Highway and Transportation Officials (AASHTO 2001). Inspection results represent the condition state information of the bridge elements (e.g. columns, abutments, decks/slabs, and girders) and are mainly based on the inspectors' visual observations. This information is then entered into a bridge management system to help transportation agencies make system-wide prioritization decisions with regards to the allocation of limited inspection and maintenance resources. Several limitations of manual inspections have been identified in previous research studies. For example, manual inspection results are subjective (Phares et al. 2004), and manually collecting bridge inspection data is costly and time-consuming (Koglin 2007).

In order to overcome these limitations, it is necessary to create an automated bridge inspection toolkit that can considerably reduce inspectors' field work as well as automatically produce bridge inspection reports. Toward this objective, several methods have been proposed, most of which focus on automating the collection of as-built bridge condition data (Jaselskis et al. 2005; Jauregui et al. 2006) and the detection of surface damage and defects (Abdel-Qader et al. 2006; Hutchinson and Chen 2006). The importance of detecting bridge elements (e.g. columns) in automated inspection lies in the fact that the damage measurements are of little value unless they can be spatially correlated with the member on which they lay. For example, a diagonal crack versus a horizontal (flexural) crack indicates a completely different type of damage on a column. Therefore, bridge elements have to be detected, so that the damage and defects can be automatically spatially correlated with the corresponding elements to produce relative measurements.

However, existing element detection work cannot achieve satisfactory results for bridge inspection purposes. This is because bridge elements are usually large-scale. In order to detect these elements and retrieve their dimensions, existing methods require structural elements to be completely visible in the field of view (FOV). Considering that the FOV of a typical compact camera is limited to 50°(H)x35°(V) but that of a human can reach 200°(H)x135°(V) (Freeman and Durand 2006), this forces users to fully extend the zoom of their cameras or stand far away when capturing large-scale columns (Fig. 1). Thus, the detailed defect information on these elements is lost, since the same amount of image pixels are used to capture larger element surface areas.

This paper presents a novel method for automated detection of large-scale concrete bridge columns in visual data. The method begins by combining multiple images containing different column segments of one column into one image using SIFT feature detection and matching, affine transform matrices calculation, etc. Then, the long vertical lines are extracted using edge detection techniques and the Hough Transform from the stitched image, and the bounding rectangle of each pair of long

vertical lines is formed. If the resulting rectangle resembles the shape of a column (i.e. the rectangle's width is smaller than its length) and the color/texture contained in the rectangle are matched with that of concrete samples stored in a knowledge base, the region between the pair of lines is assumed to be a concrete column surface. The method was tested using real bridge images. Preliminary results indicate that most bridge columns can be correctly detected in stitched images.

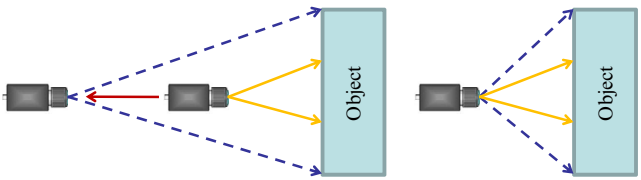


Fig. 1: Camera move-out and zoom-out to capture an object in a view

2 BACKGROUND

2.1 Manual Bridge Routine Inspection

Highway bridge inspections are carried out manually by certified inspectors following established National Bridge Inspection Standards AASHTO Manuals on Bridge Evaluation. During inspection, they record actual bridge conditions by observing existing damage and defects that lay on primary bridge components, such as decks, exterior beams and piers. This information is used to rate bridge conditions. So far, there are two rating systems that can be adopted, both of which are built upon qualitative definitions. The FHWA Recording and Coding Guide defines one system which uses the National Bridge Inventory zero to nine scale for rating a bridge deck superstructure and substructure. The other, the PONTIS rating system, uses a set of three to five condition states to describe the condition of bridge elements (e.g. column, girder and truss).

One inherent limitation associated with these manual inspections is their inefficiency. Reviewing previous reports, preparing inspection plans, and collecting and analyzing field data take a lot of inspector hours (Koglin 2007), which results in significantly large costs over time. In Tennessee, in 2006 and 2007, the annual cost of bridge inspections was $7.6 million; considering the Tennessee Department of Transportation lost $22 million in Federal bridge funds, some bridge inspections and maintenance projects had to be pushed back (Wasserman 2007). In addition, manual inspection results are subjective and highly variable. An on-site survey conducted by the Non-Destructive Evaluation Center indicated that manual inspections were completed with significant variability (Phares et al. 2004).

2.2 Recent Research Efforts towards Automated Bridge Inspection

Researchers have proposed many methods regarding the aim of automated bridge inspection. Much work has been performed in automating the collection of bridge as-built data and the detection of surface damage and defects. With regards to the data collection process, recent efforts mainly include the use of remote spatial sensing techniques, such as laser scanning and photogrammetry. Laser scanning is a terrestrial laser imaging system that can create highly accurate and detailed 3D range images and has been used in many bridge survey applications (Jaselskis et al. 2005). Photogrammetry relies solely on the present light energy to retrieve bridge as-built information. Examples of using photogrammetry to document bridge conditions were found in the work of Jauregui and White (2003) and Jauregui et al. (2006).

As for damage and defection detection, many automated detection methods have been created to detect surface damage and defects. These methods use image processing techniques, such as wavelet transforms and segmentation to extract this information from image background, and their effectiveness has been verified in inspecting concrete structures like bridges (Abdel-Qader et al. 2006; Hutchinson and Chen 2006) and concrete pipes (Guo et al. 2009).

2.3 Structural Element Detection

Automating the collection of bridge as-built data and the detection of surface damage and defects is not entirely sufficient to provide a comprehensive bridge inspection. The impact of existing damage and defects on bridge elements needs to be further evaluated, which requires the detected damage and defects to be spatially correlated with the member on which they lay. For this reason, bridge elements also need to be detected (Fig. 2).

In general, object detection is defined as locating a desired object in a scene (Ge et al. 2008). It can be performed in either range data or visual data. The methods of detecting objects in range data rely on the object's global or local shape features. According to Bosche and Haas (2008), these methods are computationally complex, especially when the number of search objects and the number of scanned points is increased. So, they suggested representing a 3D CAD model using range points so that the matching can be performed at the point level. However, this method requires the model to be registered first in the laser scanner's spherical coordinate frame.

Object detection methods in visual data are classified as: 1) scale/affine-invariant feature-based, 2) color/texture-based or 3) shape-based. Scale/affine-invariant feature-based methods use image scale/affine-invariant features extracted by feature detectors such as SIFT (Lowe 2004) to locate an object. Such methods are powerful in detecting a specific object, but they are not appropriate for object category detection. For example, they can match the same car in multiple pictures, but cannot detect similar cars. Structural elements are characterized by large topographical variations, and therefore, no simple scale/affine transformation can be used to characterize them.

Color/texture based methods rely on the objects' interior color and texture values. Neto et al. (2002) observed that the color and texture values for most materials (e.g. concrete and steel) in an image do not change significantly. Therefore, material regions in an image can be identified by checking their color and texture values, and a region's dimensions can be used to determine the type of structural element that the region represents (Brilakis and Soibelman 2008). Shape-based methods make use of object boundary information which is retrieved by analyzing the distribution of edge points, but the sole reliance on edge information renders these methods inadequate in complex scenes. Zhu and Brilakis (2009) therefore, recently proposed a new column detection method using both boundary and material information in an image.

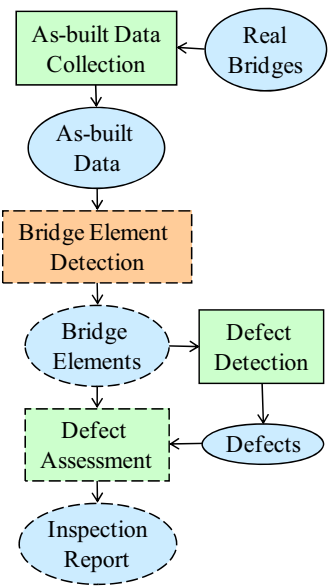


Fig. 2: Automated bridge inspection

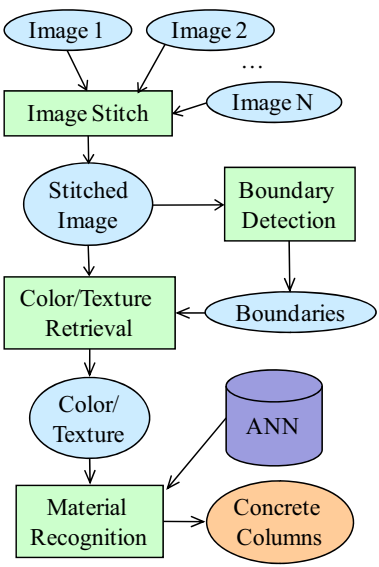


Fig. 3: The proposed method for large-scale bridge column detection

3 THE FRAMEWORK OF THE PROPOSED METHODOLOGY

In order to overcome the limitations mentioned herein, a novel method of detecting a large-scale bridge column captured in multiple images is proposed (Fig. 3). The method is divided into two chief stages: 1) image stitching, and 2) column detection, which includes three main steps: a) boundary detection, b) color/texture retrieval and c) material recognition using an artificial neural network. Details in each stage are explained in the following sections.

3.1 Image Stitching

The purpose of the first stage, image stitching, is to combine multiple images into one high-resolution image based on their overlapping FOVs. The motivation behind image stitching in bridge inspection lies in the fact that the FOV of a typical compact camera is limited to 50°(H)x35°(V) but the human's FOV can reach 200°(H)x135°(V) (Freeman and Durand 2006). This way, information concerning structural elements and defects that can be captured by the human eye cannot necessarily be captured by a single shot of a camera. Multiple shots are always taken of the different parts of one large-scale element.

In this research, image stitching is performed in the following order. First, the feature detector developed by Lowe (2004) is used to extract and match the features that are invariant to image scale and affine distortion between these images. The locations of these features are then retrieved. For any two images, the affine transform matrix between these two images can be calculated using Eq. 1 and Eq. 2, where $(x_1^1, y_1^1)^T, (x_2^1, y_2^1)^T \ldots (x_n^1, y_n^1)^T$ are feature locations in the first image, $(x_1^2, y_1^2)^T, (x_2^2, y_2^2)^T \ldots (x_n^2, y_n^2)^T$ are the matched feature locations in the second image and matrix $A^{12} = \begin{pmatrix} a_{11}, a_{12}, a_{13} \\ a_{21}, a_{22}, a_{23} \end{pmatrix}$ is the affine transform matrix that can transfer the locations of any image pixel in the first image to the second one. Thus, these two images can be combined into one image with the affine transform matrix. The combination can be performed iteratively until one composite image is created from all individual images.

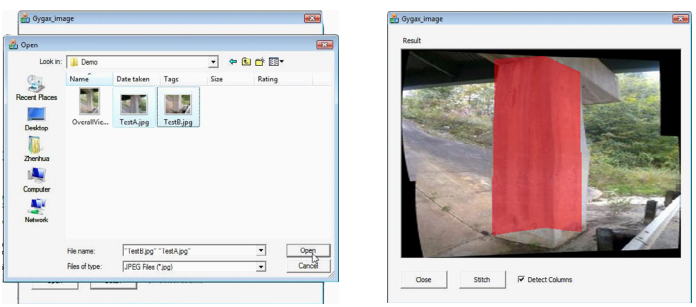
$$\begin{pmatrix} x_1^1, y_1^1, 1 \\ x_2^1, y_2^2, 1 \\ \ldots\ldots\ldots\ldots \\ x_n^1, y_n^1, 1 \end{pmatrix} \times \begin{pmatrix} a_{11} \\ a_{12} \\ a_{13} \end{pmatrix} = \begin{pmatrix} x_1^2 \\ x_2^2 \\ \ldots \\ x_n^2 \end{pmatrix} \quad \text{(Eq. 1)} \qquad \begin{pmatrix} x_1^1, y_1^1, 1 \\ x_2^1, y_2^2, 1 \\ \ldots\ldots\ldots\ldots \\ x_n^1, y_n^1, 1 \end{pmatrix} \times \begin{pmatrix} a_{21} \\ a_{22} \\ a_{23} \end{pmatrix} = \begin{pmatrix} y_1^2 \\ y_2^2 \\ \ldots \\ y_n^2 \end{pmatrix} \quad \text{(Eq.2)}$$

3.2 Concrete Column Detection

The second stage, concrete column detection, consists of identifying long near-vertical lines for each column surface as well as determining whether or not the material contained between two lines is concrete. In order to detect column boundaries, the Canny operator is used to produce an edge map, a binary image composed of edge points (marked as white) and non-edge points (marked as black). The Hough transform is then used to analyze the distribution of edge points and retrieve long vertical line information in the edge map. Each retrieved vertical line is compared to its neighboring vertical lines. If two vertical lines have similar size, they

are regarded as a pair. This comparison is performed iteratively, until no further pair can be found. A bounding rectangle for each pair of vertical lines is then constructed based on their Cartesian coordinates, and the aspect ratio (length/width) of each bounding rectangle is calculated. Considering the large-scale bridge columns investigated in this research, the ratio can be assumed to be on the order of six or seven.

An artificial neural network is designed to classify the material within a boundary. The network is composed of three layers (input, hidden and output). In the input layer, the network takes the visual features and transfers them to the hidden layer, where a material classification boundary in the feature space is created on each neuron-node. Then, these boundaries are combined together using an AND operation in the output layer to form a concrete material classification model. The number of neuron-nodes in the hidden layer is determined experimentally. Technically, the more neuron nodes in the hidden layer, the more classification boundaries can be found, which results in a more precise classification approximation. The network is trained through supervised learning (back-propagation). The training process is repeated thousands of times. Although it is possible to have more repetitions to further reduce the error rate, long training to achieve a very low number of errors will result in an overtraining problem.



(a) (b)

Fig. 4: The process of column detection using the prototype

4 PRELIMINARY IMPLEMENTATION AND RESULTS

The methodology presented in this paper is implemented into a C++ based prototype. The prototype was written in Microsoft Visual Studio 2005. Intel® Open Source Computer Vision Library was used as the prototype's main image processing toolbox. The Fast Artificial Neural Network Library was used to implement neural-network based material classification. The work developed by Brown and Lowe (2007) was used for image stitching.

Figure 4(a), an open file dialog, popped up to allow the user to select multiple images for stitching. Figure 4(b) is the resulting column detection in the image

stitched by these selected images. The image shown is slightly stretched because it is resized for display purpose only. Figure 5 shows an example of column stitching and detection. Table 1 illustrates the detection precision and recall for five stitched images, which are combined from two to four images separately. The final average precision and recall for the 114 concrete bridge column images stitched from 373 original images are 89.7% and 84.3%, respectively. The detected column surfaces are compared with the manually identified surfaces to determine the true positive (TP), false positive (FP) and false negative (FN) of the method (Wickens 2002). Then, the detection precision (TP / (TP+FP)) and recall (TP / (TP+FN)) are calculated. It can be seen that large-scale concrete bridge columns can be correctly detected in most stitched images. Image 4 in Table 1 represents the columns that could not be detected due to their large curve edges in the stitched images (Fig. 6).



Fig. 5: An example of column stitching and detection

No.	TP	FP	FN	Precision	Recall
				TP/(TP+FP)	TP/(TP+FN)
1	1	0	1	100.0%	50.0%
2	2	0	0	100.0%	100.0%
3	1	0	0	100.0%	100.0%
4	0	1	2	0.0%	0.0%
5	1	1	1	50.0%	50.0%

Table 1: Detection precision and recall

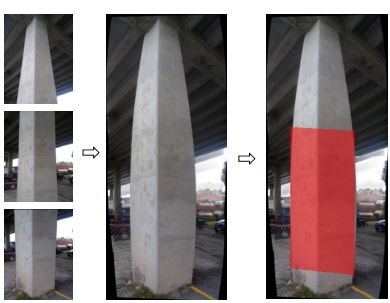


Fig. 6: Failed detection of column with high curve edges

CONCLUSION

Manual bridge inspection has several inherent and fully-recognized limitations, such as high cost, subjective results and the requirement of experienced inspectors. Therefore, the concept of automating the current manual practices in bridge inspection is proposed to overcome these limitations. Much work has been performed in bridge as-built data collection and surface damage and defect detection. In order to evaluate the impact of the detected damage and defects on bridge elements, the property measurements of these detected damage and defects have to be spatially correlated with the member on which they lay. Therefore, bridge elements have to be detected from the collected as-built data for the sake of this spatial correlation. Existing detection methods require that structural elements be completely in the FOV for detection and property retrieval. However, due to the limited FOV of a camera, it is always impossible to make large-scale bridge elements (e.g. columns) fit entirely in the view and at the same time, maintain proper view of all detailed defect information (e.g. cracks) on the element.

This paper presents the authors' recent work in detecting large-scale concrete bridge columns. Image stitching techniques are first used to combine multiple images containing different FOVs for one bridge column into a stitched image. Then, the Canny operator and the Hough Transform are used to recognize the pair of long vertical lines of a concrete column in the stitched image. The visual features of the region of the line pair are presented to an artificial neural network to indicate whether the region contains concrete or not, so that a concrete column surface can be detected. Real bridge images were used to validate the work presented in the paper. The preliminary test results indicate that a large-scale bridge concrete column that is captured in multiple images can be detected in the stitched image in most cases. Future work will focus on removing the effects of curve edges introduced in the image stitching process and testing more images to confirm the method's validity.

ACKNOLEDGEMENT

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Review of Wireless Sensors for Road and Bridge Asset Management

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Abstract

According to the Ministry of Land, Transport and Maritime Affairs, the price of social infrastructure asset, including nation-wide roads, railways, airports, harbors, water and sewage systems, and water resources management facilities, amounted to 515.2 trillion won as of 2004 (Ministry of Land, Transport and Maritime Affairs, 2007). When it comes to social infrastructure, the emphasis has been placed on the construction aspect for decades. But the need is being raised for more comprehensive management of the infrastructure. In most of developed countries, infrastructure asset management has been implemented for the effective and efficient operation and management of infrastructure. Infrastructure asset management is also being implemented in Korea. The purpose of this study was to review the current data collection methods to help implement better asset management and to address the need to utilize wireless sensor technologies and propose implementation strategies for the implementation.

Keyword: asset management, RFID, USN, measurement

1. Introduction

1.1 Background and Purpose

The Ministry of Land, Transport and Maritime Affairs of the Republic of Korea estimated that as of 2004 the price of nation-wide social infrastructure (road, rail, airport, harbor, water and sewer system, water management facility, etc.) stock amounted to KRW 515.2 trillion (Ministry of Land, Transport and Maritime Affairs, 2007). The social infrastructure is maintained under the supervision of a full-time management agency appointed by the government. The maintenance, however, remains at the individual optimization level, failing to involve comprehensive management based on accurate value appraisal of various facility assets at the national level. Such management approach could cause unexpected budget problems in the future. For instance, the costs of maintaining social infrastructure constructed in the 1950s and 60s in the US, Australia, and Canada soared during the 1990s, threatening national financial safety. The countries have since treated social infrastructure as state-owned comprehensive assets and

introduced asset management techniques to systematically manage the facilities and solve related problems. Observed effects include cost reduction and increased usability.

In Korea, the majority of social infrastructure was built in the 1970s and 80s. Given that, the rapid increase in upkeep costs is expected in 2010 and beyond. However, the current maintenance program focuses on individual facility management as mentioned earlier. The downside calls for an approach from systematic asset management based on accurate appraisal of state and value of state-owned social infrastructure. To address the issue, the Ministry of Strategy and Finance passed a bill in October 2007 with the legislation of the National Accounts Act (enforcement scheduled to begin on 1 January 2009), introducing the accrual accounting. And the Ministry of Public Administration and Security introduced in 2007 the double entry book-keeping system which includes information on assets and liabilities in the book, via "Guidelines for Implementing Double Entry Book-Keeping on the Accrual Basis by Local Autonomous Bodies" to lay the foundation for managing social infrastructure as collective assets (Ministry of Land, Transport and Maritime Affairs, 2008). The Korea Institute of Construction Technology (KICT), too, began a research program on collective asset management of social infrastructure called "Development of a Public Infrastructure Asset Management System (KTAM-40)" in 2008.

To implement asset management programs, accurate data collection must first be ensured. The purpose of this study was to review the methodological problems in the current data collection stage which is the early phase of asset management implementation and to address the need to utilize IT technologies (RFID/USN) and propose strategies to implement them.

1.2 Scope and Method

In general, asset management is implemented as shown in Figure 1 below. First, asset management strategies are established; then the target asset data are collected; and lastly, the performance is analyzed. This is followed by analysis/forecast of asset demand, based on which asset management plans are established and implemented. This paper focused on the data collection stage and in particular asset management data collection methods being adopted locally as well as internationally. Then problems in the stage were identified, and implementation possibilities of RFID/USN technologies were reviewed based on local case studies. This paper also addressed RFID/USN technology implementation strategies and considerations as the introduction of social infrastructure asset management is being considered in Korea.

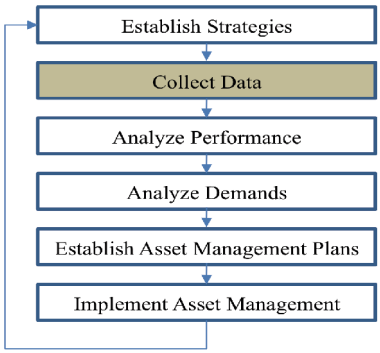


Figure 1. Stages of Asset Management Implementation

2. Asset Management Data Collection Method

2.1 Asset Management Data Collection Methods used in Korea and Elsewhere in the World

Asset management data are roughly divided into inventory data and condition data as summarized in Table 1 below. Inventory data refer to the data for physical components of assets, such as location and traffic lanes, that change very little with time. Condition data, on the other hand, are the data that concern the condition of asset components and change with time (The World Bank 2005). In this paper, local and international asset management data collection methods were reviewed with emphasis on condition data that can be measured.

Table 1. Types of Asset Data

Data type	What is indicated	Time-induced change	Techno-logical reliance	Details of information	Application
Inventory data	physical elements of the assets	very little	relatively low	location, specific description, history (design, construction, management)	asset information
Condition data	condition of elements of the assets	some	relatively high	condition, performance, risk	decision-making support

Condition data collection methods are divided into: (a) routine inspection and precision inspection (special inspection) based on collection time (cycle); and (b) visual inspection and survey/monitoring (destructive and non-destructive) based on collection technique. Some of the examples of collection methods are described below.

Figures 2 and 3 each show the hydraulic lifts and snooper-type trucks used in bridge substructure inspection. The equipments are easy to use, have excellent trafficability and accessibility, offer sufficient work space, and can be used with

various transportation means like automobiles and vessels (The World Bank 2005). They are frequently used in the local construction industry as well, mainly during precision inspection for bridge structures.

Figure 4 shows an equipment used by the British Columbia Ministry of Transportation (BCMoT) in Australia to investigate damages to road pavement and evenness of road surface. Inspectors of the agency routinely use the equipment as they drive around their district and collect data on road condition (NAMS et al. 2006).



Figure 2. Hydraulic lifts



Figure 3. Snooper-type trucks

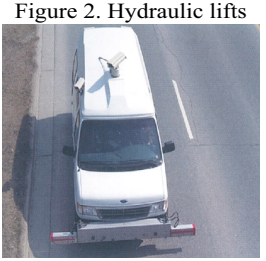


Figure 4. Road condition monitoring vehicle



Figure 5. FWD

Korean institutes such as the Korea Institute of Construction Technology (KICT) and the Korea Expressway Corporation, too, are using similar equipments. One such example is the falling weight deflectometer (FWD) shown in Figure 5.

2.2 Summary

In addition to the facility condition inspection using the aforementioned equipments, various visual inspection and site survey techniques are being utilized to collect data on the condition of assets. However, the majority of the equipments are expensive and cause traffic problems when used. They also pose problems such as longer data collection period, subjective evaluation by inspectors, and difficulties in identifying long-term behavior of structures due to time constraint during investigation. Therefore, new methods allowing continued monitoring of facilities at reasonable pricing are needed.

3. Local Case Studies Using RFID/USN in Infrastructure

Gong Jeong-sik et al. (Gong Jeong-sik et al. 2007) analyzed technological trends in social infrastructure asset management adopted by a number of countries and introduced the possibilities of using various information technology (IT)

programs such as 3D-based design drawing and RFID programs for future development in the field. Examples described below verify such application possibilities.

3.1 Examples of Bridge Survey

The Korea Institute of Construction Technology (KICT) conducted between 2006 and 2007 SK Telecom-sponsored monitoring of a bridge structure in service, using USN technology (see Figure 6).

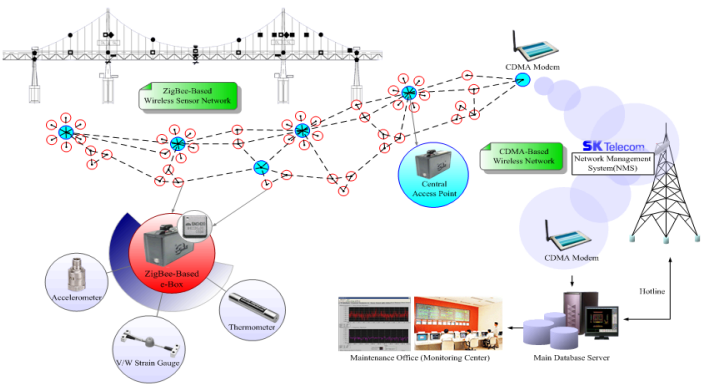


Figure 6. Example of Bridge Monitoring Project by KICT and SK Telecom

During the monitoring, static and dynamic surveys were conducted to measure acceleration (vibration), strain, temperature, and wind direction and speed as the testbeds were operated for three months. Results of the surveys showed performance that was equivalent to that of the current monitoring systems. The data also showed superior installation and removal convenience and a 30 percent reduction in costs (economic benefits) based on an assumption of six years of service. The example verified the application possibility of USN system for routine monitoring of bridge structures.

3.2 Examples of Road Survey

The Korea Institute of Construction Technology (KICT) and SK Telecom jointly established a cheap USN sensor-based monitoring system in roads constructed in a mountainous region where heavy rain and snowfall are frequently reported to monitor freezing and flooding incidents and ran testbeds for three months. The installed system was geared to collect data on road surface temperature, surface moisture level, and saline contents to help determine the status of freezing and flooding. The system was found to be able to monitor road conditions more accurately than some of the current systems and to offer an approximately 20 percent cost cut (economic feasibility). This case study, too, verified the application possibility of USN system as it was used for routine road-condition monitoring.

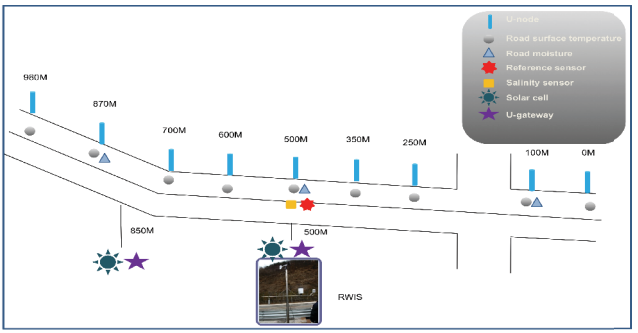


Figure 7. Road freezing/flooding monitoring system

4. Strategies to Utilize RFID/USN Technology

4.1 Considerations to Make to Implement RFID/USN Technology

In addition to the aforementioned case studies, a number of research projects are underway, using USN to collect facility data for bridges, sloped surfaces, roads, and construction structures and satisfactorily verifying the applicability of the technology. Therefore, a long-term monitoring program focusing on survey fields that are core areas and can accommodate the characteristics of USN would greatly increase the efficiency in social infrastructure asset management, despite its foreseeable limitations in replacing all monitoring programs.

The World Bank proposed considerations to be made while collecting data for asset management as listed below (the World Bank 2005).

- What kinds of decision-making are needed when managing and maintaining road networks?
- What types of data are required by such decision-making?
- Can the data be collected during the early stage of the implementation?
- Can the data be stored for longer terms?

The considerations listed above are some of the essential questions to be asked when selecting data collection methods in the entire asset management system implementation. Therefore, based on the questions suggested above, considering the information listed in Table 2 during RFID/USN technology-based data collection will likely ensure effective implementation of RFID/USN technology.

Category	Description
Survey importance	better for monitoring items that directly affect structural characteristics and aging of material
Survey frequency	better for monitoring items with higher survey frequency (allows necessary frequency for items that used to limit frequency due to cost and technical limitations)

Accessibility	better for survey items concerning survey sites posing access problems for routine inspection, precision inspection, and field survey
Cost efficiency	consider economic feasibility while replacing with USN
Technical difficulty	technological possibilities of USN-replaced monitoring
Wireless communication possibilities	wireless communication environment of the target structures

Table 2. Types of Asset Data

4.2 Strategies to Coordinate RFID/USN Based Survey

Implemented in long-term data collection, RFID/USN technology will help identify the long-term condition of each facility network and will enable the operators of each network to obtain overall information on each facility's performance distribution. The technology can be used in asset management as summarized in Table 3 below.

Table 3. Types of RFID/USN Application in Asset Data Management

Technology	Application
RFID	a tool to integrate inventory data and condition data
USN	a tool to collect condition data of assets

RFID technology can be used for entering accurate condition data in an accurate asset inventory via RFID reader which will be carried by investigators during visual inspection while USN technology can be applied to monitoring condition changes in each facility.

Figure 8 shows the asset management implementation process using RFID/USN technology. Though it cannot replace all of the current data collection methods being used (visual inspection, site survey, etc.), the technology is able to monitor long-term behavior of core components of each facility. And based on the long-term information, specialized routine inspection and precision inspection can be implemented for each facility, which will likely increase the accuracy of the inspections and make the prioritization of inspection and placement of staff more efficient. In addition to the longer-term monitoring benefits, RFID/USN based field investigation applications will also bring benefits.

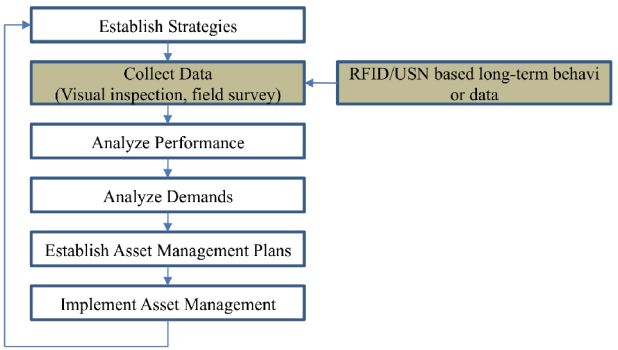


Figure 8. Strategies to coordinate RFID/USN based asset management

5. Conclusion

This study reviewed local and international asset management data collection methods used in the data collection stage, i.e., the early phase of asset management implementation, identified problems, examined local case studies of RFID/USN technology to review the possibilities of RFID/USN technology application, and proposed the technology implementation strategies for managing and maintaining local social infrastructure as collective assets. Given the accelerating aging of social infrastructure, introducing the asset management concept and implementation of IT technology (RFID/USN) which Korea is known for among a number of outstanding industries will help the country carry out social infrastructure asset management with more international competitive power.

Acknowledgement

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Semantic Representation of Infrastructure Interdependencies: Rethinking infrastructure design and management

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Abstract

This paper presents a semantic system for coordinating the management of infrastructure projects. The proposed system starts from three fundamental premises: the use of knowledge (through ontologies and semantic systems), covering all facets of infrastructure projects (products, processes and human actors), and consideration of project aspects other than direct costs.

Introduction

There is a need for a new paradigm in the design and management of infrastructure systems. Traditionally infrastructure has been designed at the project level without much consideration to the overall performance of the network. With increasing concerns over interdependency, we have to address the impact of a new project on the overall performance of the network(s). Projects were further designed according to pure technical specifications (engineering-dominated design) that are normally influenced by short-term business requirements (mainly project direct costs). The fact that these infrastructure systems are being rehabilitated in the midst of congested urban areas requires more rigorous consideration for the impacts on individual projects on local communities.

A semantic system for coordinating the management of infrastructure projects is proposed. The proposed system starts from three fundamental premises:

1. Focus on knowledge: The management of infrastructure utilizes multitudes of data, information and knowledge. Data is a representation of the simplest facts about a system with a limited usability or meaningfulness. Information is the

composition of various data to establish a meaningful representation of facts. Knowledge is the wisdom gained from experience. Knowledge can be seen as spanning three spheres: software (means for static capture of knowledge), work processes (reflection of best practices and value generation), and human judgment (the wisdom/intelligence of human experts). It is sad to notice that except for the software facet, knowledge management practices in the infrastructure domain have lagged almost every other industrial sector. Semantic (ontology-based) systems represent the state-of-the-art means to encapsulate knowledge in any management system.

2. Infrastructure projects are connected complex systems: Infrastructure is composed of a set of over-layered, interlinked networks of heterogeneous systems that span vast geographic areas. Each project (shown as a circle in Figure 1) is composed of a set of interlinked components (shown as a square in Figure 1). Theoretically, each project (no matter how small) at one end of a single network (a sector) can have an impact on other projects in the other end (impacts are denoted with triangles in Figure 1). The optimum design of one project has to take into consideration all related projects within the same sector and across related sectors. It could be infeasible/unnecessary/overwhelming to consider all possible impacts on all possible projects. Consequently, we need to devise tools to investigate in a hierarchical way different scenarios and different scales of these interdependent networks.

3. Expanded view of project costs: several new costs are assuming a greater importance in the context of the design of urban infrastructures systems:

    - Indirect costs: The majority of our infrastructure systems are located in urban areas, leading to an ever-increasing importance to indirect costs over direct costs such as business and traffic costs (especially during construction).
    - The costs of sustainability: real dollars can now be associated with the negative impacts of an infrastructure project on sustainable development (especially the environment).
    - Costs of interdependency: greater concerns are now being expressed over the analysis of interdependency. While business requirements are pushing for a minimalist design of projects with elimination of any redundancy or unneeded capacity (to reduce costs), addressing interdependency concerns requires embedding adequate redundancy in individual projects to enhance the resilience of the overall network.

The Proposed Framework

A common knowledge management system for collaborative design of infrastructure is envisioned to allow stakeholders to work so closely that there are ***interoperable computer systems*** that allow partner *A* to seamlessly access the corporate data of partner *B*, manipulate certain data in compliance with pre-agreed ***profit sharing/collaboration protocols*** that are encouraged by incentives from ***government policies.***

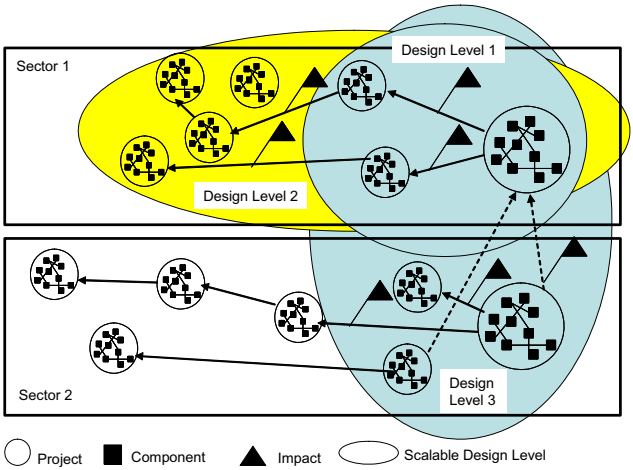


Figure 1: Outline of Project Interdependency

An interoperable knowledge model is at the core of the proposed architecture (see Figure 2). This includes a set of ontologies that encapsulate knowledge of different domains/ stakeholders (for example, El-Diraby and Kashif, 2005). In addition, a set of related ontologies for products (Osman and El-Diraby 2006), processes (El-Gohary and El-Diraby 2008) and actors (Zhang and El-Diraby 2008) are also included. These ontologies define the basic interrelationships between different infrastructure systems.

The portal integrates CAD and GIS tools to visualize information. The portal provides access to information at three levels: corporate level (full access to corporate information), partner level (access to certain information to partner organizations) and public level (free access to a limited set of information). This is done through a basic access policy protocol.

Information will be also viewed in product, process and actor view. For example, all technical details of the infrastructure system being designed or managed will show up on the product view. A set of decision making services are provided to study the overlap and interaction of different product designs. Workflow and business transactions will show on the process view. Here, web services help visualize the work processes of parties involved. In addition, the portal allows system users to weave a new work process for project partners based on the semantic description of their processed (which is established by accessing the ontology). Status, interest, and tasks of stakeholders will be shown in the actor view. This view utilizes publish-subscribe technology to pull and push relevant information to the proper person at the right time. Future development will focus on using data mining to enrich the ontologies. In addition, a set of semantic web services, agents and other software tools will be built to provide services to stockholders, analyze information exchange patterns and wrap existing software system.

Four major components have been implemented in this architecture—they are:

Ontologies and ontology merger

A domain ontology for construction has been developed. The ontology describes major domain concepts and their interrelationships. It also describes the basic and most common axioms relevant to infrastructure construction. Three additional sub-domain ontologies have been developed to represent construction knowledge in products (Osman and El-Diraby 2006), processes (El-Gohary and El-Diraby 2009) and actors (Zhang and El-Diraby 2009). A set of application ontologies have been developed to handle specific tasks (for example, routing pipes in urban streets). By defining computer-understandable models, ontologies facilitate computable interoperability. Ontologies are thus the foundation of content-based information access and semantic interoperability over the web, providing the construction industry with the opportunity to create semantic interoperable environments for seamless exchange of information. However, the development of a single shared ontology to serve as 'the one and only one' process model for the whole domain is not feasible. No single ontology can fully cover a domain of interest (Gruber 1995) and no single optimum way for modeling a domain exists (Taivalsaari 1996). Given the inevitable existence of a set of heterogeneous and distributed ontologies within one domain, an ontology merger becomes essential for facilitating computable interoperability. Ontology merging is the process of deriving a new ontology based on two existing ontologies in order to facilitate interoperability. A standalone software was created to help merge other ontologies with existing ones. Finally, a software wrapper has been developed to link ontology representation to GIS standards.

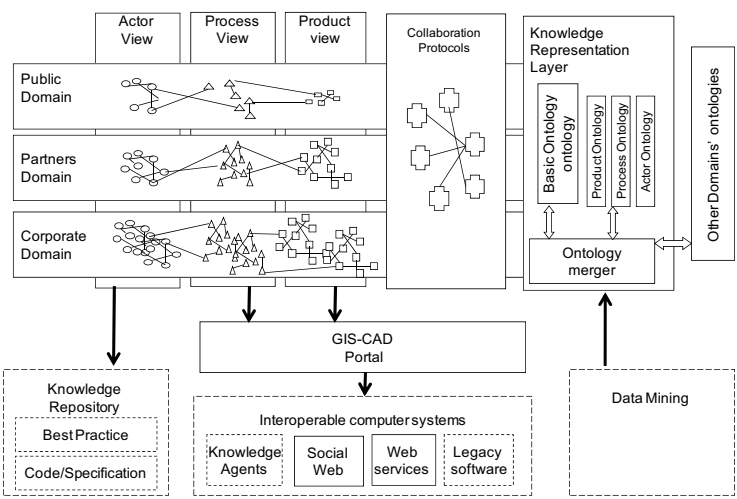


Figure 2: Portal Architecture

Product Analysis Portal:
This software is intended to assist infrastructure designers to optimize the routes of such utilities on a macro-level (which streets to use) and on the micro-level (which side of the street to use). The portal can also support the coordination of infrastructure routing in urban streets. First, the user interfaces with the Ontology Portal (entry point to modify/extend the ontology). The user then can upload route options as GIS layers. The user can then select the constraints to be checked. An OWL Spatial Constraint Satisfaction Reasoner (OSCSR) builds a 3 dimensional database that relates the attributes of route and those of surrounding area/products to the constraints. The database is subsequently examined by the constraint violation algorithm. The algorithm iterates through instances of all products and checks to see if any routing constraints have been violated. Products that violate a constraint are added to a database that links instances of products (infrastructure products and generic products) with violated routing constraints.

The main components of the software are:
1- User interfaces with a Fuzzy DSS through Product Portal
3- Wrapped OWL instance file is sent to spatial reasoner for decision-support
4- Wrapped OWL instance file is sent to Fuzzy DSS
5- OWL wrapper exchanges mapping and XML files with XMLINOUT module
6- XMLINOUT reads standard mapping files
7- XMLINOUT reads GIS data
8- GIS files exported into standard XML files as per the ESRI geodatamodel.
9- Matlab used to create standalone Fuzzy Inference System

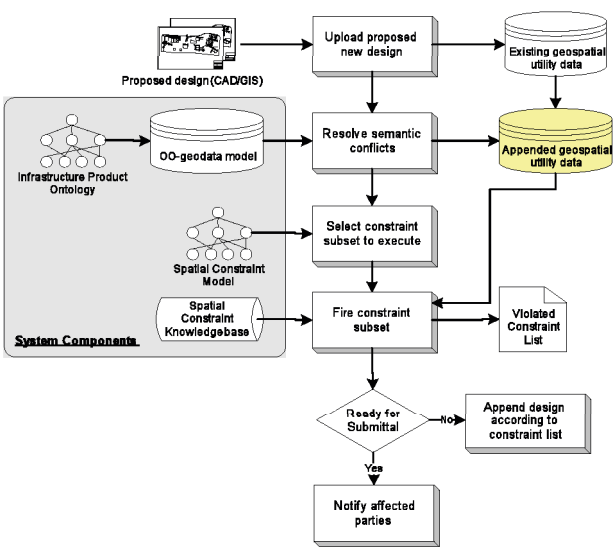


Figure 3: Product Portal

Process Coordination Portal

The importance of understanding and modelling the construction process to enhance the performance of construction projects has been emphasized by many researchers in the construction domain (Abeysinghe and Dominic 1999; Halpin 1993). Process orientation allows construction organizations to depict and manage resources, information, and people in a more integrated way (Lindfors 2001).

The proposed web portal is founded on two main pillars: an ontological representation and an ontology merger. Ontologies and ontology mergers, integrated in one portal, will support the knowledge-based integration of several processes in a dynamic way. Each collaborating entity can semantically represent its processes through an ontology. The portal will allow stakeholder ontologies to evolve over time, as their processes and/or nature of collaboration change. The merger would then dynamically merge these ontologies to create an integrated ontological representation of stakeholder processes. Each collaborating entity can use the integrated ontology, in a drag-and-drop-like fashion, to independently build its structure of processes (sequential flow of knowledge-carrying processes). The portal automatically analyzes these individual process structures for identifying similarities and interactions between these processes. Based on this analysis, a user (or portal coordinator) can build an integrated, knowledge-carrying process for all participating stakeholders. The integrated process encapsulates valuable knowledge: who is involved in the project at which time, what products (or parts of products) are being designed at which time and by whom, what are the constraints affecting each process?, etc.

A prototype portal was developed to help streamline a common workflow for project parties. The aim is to get a representation of each party's process structure and then allow an administrator to discover, dynamically, synergies and communication needs to weave a common process structure (for these independent agencies) without changing their internal process structure. The portal functions are (see Figure 4):

1. Semantic representation of processes: The portal starts by collecting the current process structure for each stakeholder. Partners can use the proposed process ontology to model and enter their processes. If a partner has an independent ontology, they can upload such ontology and use it to enter/model their work processes. Parties that do not have an ontology and are not willing to use the proposed ontology, can enter a simple semantic table of activities and their attributes. Using an algorithm, this will be transferred to a simple ontology, which can be used by this party to model their processes.

2. Semantic interoperability: The ontology merger then starts to discover similarities between all ontologies and create a common (ad hoc) ontology through communication and consultation with users.

3. Process analysis: now that all processes are represented in an interoperable semantic fashion, system administrator can find activities with similar requirements, matches between attributes, etc. the administrator can create a common work flow for all related parties.

The kernel layer is to provide: 1) semantic representation of user-individual process knowledge (ontologies) and processes, 2) merging user-individual process knowledge (ontologies) and processes into an integrated ontology and/or process sequence, and 3) navigation and exploration of the defined process knowledge. The following functionalities are available for users. .

- Process-structure builder and editor: to build a sequence (a Critical-Path-Method-like sequential flow) of processes from processes defined in the integrated ontology.

- Process-structure merger: to perform merging of two or more process-structures into an integrated process-structure.
- Process explorer: to navigate and explore the knowledge defined in the process-structure. This includes: navigation of process knowledge (as defined in the ontologies), developing schedules of integrated processes, sorting processes according to defined sorting criteria, automated identification of related processes, creation and exploration of other sequences (such as 'actor-sequence' which shows when each project actor is involved in the project), and semantic search of process knowledge. A wrapper exports and imports schedule information to and from Microsoft Project.

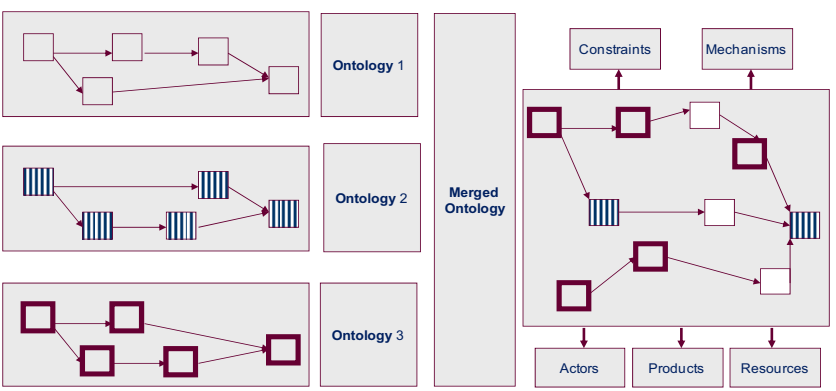


Figure 4: Process Portal

Actor Communication Portal

The goal of the communication portal is to facilitate information exchange and knowledge sharing in the AEC industry is to deliver the right information and knowledge to the right party in a timely manner. Three services must be effectively performed if this goal is to be achieved: (1) the semantic linking of people with project information, (2) the semantic linking of people with domain knowledge, and (3) the social linking of people with their peers. Based on these three requirements, three service scenarios have been suggested in the CIKP framework.

In the first service scenario, various individuals and organizations coordinate actions with each other by effectively exchanging project information and knowledge. Each industry participant (either an individual or an organization represented by someone) is treated as an actor in the system. The system will inform its users of the information and knowledge that they really need in a timely manner, based on their profiles (the actor they claim to be and the role that the actor is playing). In this way, people are linked with project-specific information.

The second service scenario envisions the sharing of domain-specific knowledge. The experience and lessons learned in the course of construction projects, whether successful or not, should be kept and shared among the people who need them. Knowledge sharing will help the industry to avoid mistakes from previous projects and people will not have to constantly reinvent the wheel. In this way, people are linked with domain-specific knowledge.

The last service scenario supports the knowledge learning and sharing process through the creation of virtual teams or Communities of Practice (CoPs). For a variety of reasons, industrial people have interests in information and knowledge not only about projects and science, but also about other people in industry.

Social networking is partially included in the CIKP framework through the creation of CoPs, although the functions of social networking are limited. Currently, system users are able to send a piece of information or knowledge to all group members of any CoP by assigning the suggested destination, but there are no other social networking functions suggested. Deeper social networking interaction should include finding and connecting with friend's friends, following up friends' events and thoughts, communicating through private messages, etc.

The system serve three purposes: exchange project related information, share general domain knowledge, and link industry people. A prototype application has been developed to be a showcase of semantically-rich, socially-savvy and technically-efficient system to support effective flow of information. Each user has access to some basic functions: (1) edit profile by claiming who you are, what role you play, and what attributes you have, (2) publish information and knowledge item by describing the item as complete as possible, (3) subscribe to information and knowledge items of interest by defining the attributes of those items, (4) browse items published and profiles of other users, (5) query the system by submitting a specific one-time subscription, (6) tag any item/profile using ontology concepts to enrich the description of that item, (7) express opinion about tags placed by other users by "agree", "disagree" and "flgs" buttons, (8) comment on any published item, (9) approve or reject tags placed by other users on items this user published, (10) join, leave, or create any virtual communities or team and interact with members, and (11) manage everything in a user interface page, including user profile, communities, published items, received items, participated items, etc.

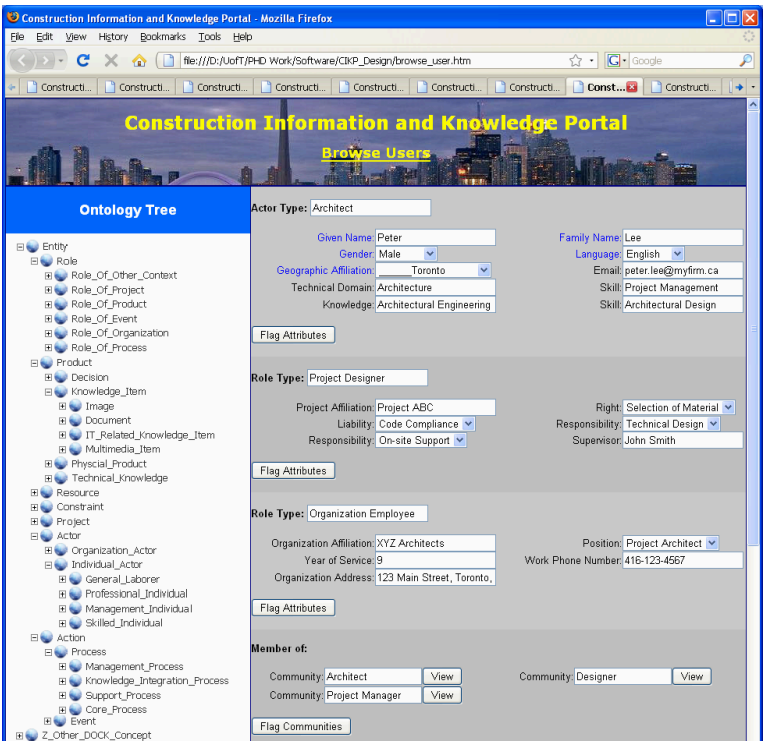


Figure 5: Actor Communication portal

Future Work: Virtual e-City Organizations

The realization of e-city is a necessary component for achieving the green city. Future projects will focus on creating an e-city platform for knowledge brokerage in the green city. The proposed platform will be a venue for creating dynamic virtual organizations to harness collective intelligence of knowledge hubs to analyze and manage sustainability knowledge in urban areas. Knowledge assets of participating organizations will be presented in three dimensions: process structures, human profile and software systems. These three facets of knowledge will be accessible and viewable through a self-describing mechanism. Cities can post their geospatial and real-time data on project network. Relevant environmental and energy-use data will be extracted using topic maps and data extraction services. Local decision makers can synchronize work processes (from participating hubs) to create an integrated workflow for a new ad hoc virtual organization to collaboratively analyze the multifaceted nature of sustainable decision making.

Fundamentally, the aim is to build a user-friendly service-oriented integration platform. This platform sits on top of existing software systems, databases and process structures of civil infrastructure.

The e-city platform will be realized through intelligent, agent-like, domain-specific middleware (KnowWare). Through triangulation between people, software and processes, these KnowWare will discover, negotiate, integrate, reason and communicate knowledge (related to energy and environment) from across organizations to the right person at the right time. KnowWare is fundamentally, a portal of social semantic services that resides on a cloud computing infrastructure. Knowware exploits thee main tools: 1) existing ontologies to represent knowledge in a semantic manner, 2) topic maps to profile sources of knowledge and match these to the complex needs of sustainability analysis, 3) domain-specific middleware for knowledge integration and reasoning.

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TOWARDS OPTIMUM CONDITION ASSESSMENT POLICIES FOR WATER AND SEWER NETWORKS

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ABSTRACT

With ageing water and sewer infrastructure in North America, assessing the condition of these assets has received increased attention in the past few years. Condition assessment is an integral component in any asset management program. Determining the condition of buried infrastructure tends to be more cumbersome, costly and error-prone compared to other surface infrastructure like roads and buildings. For sewers, CCTV is considered the industry standard for condition assessment technologies. For pressurized water pipelines, technologies tend to be more costly and uncertain (e.g. electromagnetic, sonar, acoustic leak detection, infrared etc…). Faced with constrained budgets and the need to obtain reliable condition information to drive their asset management processes, infrastructure owners must balance the value of information obtained through condition assessments with the cost of obtaining this information.

This paper presents an analytical framework and decision support system to evaluate the value of information for condition assessments of water and sewer infrastructure. The framework considers: 1) risks associated with operating the asset, 2) potential direct and indirect costs of infrastructure failure, and 3) customer expectations for the system's level of service. The decision support system utilizes Partially Observable Markov Decision Process (POMDP) to compare between the reliability and cost of the condition assessment technology.

The system is demonstrated on the water and sewer networks for the City of Hamilton, Canada.

Introduction

Condition assessment is one of the cornerstones of any infrastructure asset management program. Obtaining reliable condition information is a necessary precursor to the development of asset rehabilitation policies, setting levels of service and determining the true value of an infrastructure network (FCM, 2005). Compared to surface infrastructure systems like roads and buildings, condition assessment of water and wastewater infrastructure tends to be a time consuming, costly and error-prone activity. For pressurized water pipelines, direct assessment technologies (e.g. electromagnetic, sonar, acoustic leak detection, infrared etc…) tend to be costly and uncertain. Indirect assessment of water pipelines are common practice and include measuring factors like corrosivity potential, water quality, and surrounding soil properties. Indirect assessments tend to more affordable but correlation with actual pipe deterioration is not as accurate as direct assessments. Faced with constrained budgets and the need to obtain reliable condition information to drive their asset management processes, infrastructure owners must balance the value of information obtained through condition assessments with the cost of obtaining this information. In order to develop a condition assessment policy, the asset manager must answer the following question: 1) What condition assessment technique should be used and 2) What is the most suitable frequency to inspect or re-inspect an asset. The answers to these questions rely on the expected condition state of the asset, the risk associated with asset failure and the user's tolerance of a reduction on level of service. This paper presents a framework for developing condition assessment polices that balance the cost of assessment with the value of information revealed by the assessment.

Condition Assessment of Water and Sewer Infrastructure

Condition assessment facilitates the ongoing estimation and tracking of asset condition. Without reliable data, no rational decisions are possible. Inspection technologies enable detecting the deterioration processes of a pipe via identifying distress indicators and aggregation of all measured indicators to establish condition states. Non-destructive techniques (NDT) refer to inspection methods that provide conditional information about pipes without destroying them or impairing their future usefulness. Generally speaking, techniques for buried pipe condition assessment fall into two categories – direct and indirect. Direct techniques are based on the physical properties of the pipe wall. Ultrasonic technologies (UT), remote field eddy current (RFEC), visual inspection (CCTV), techniques are examples of direct techniques. These techniques all require the direct examination of the pipe and tend to be costly in most cases. On the other hand, indirect techniques rely on assessing environmental factors surrounding the pipe that are likely to influence deterioration rate (e.g. soil properties, presence of stray current, excessive pipe loading, etc….). Indirect

techniques tend to be less costly and cause less disruption but are less accurate compared to direct assessment.

The past decade has seen the adoption of new technologies for the condition assessment of water and sewer pipelines. Many of these technologies were initially developed for other domains like the oil and gas industry for pipeline integrity management. The economic viability of their application in municipal infrastructure applications has been questioned. Ageing pipeline infrastructure, coupled with the interest in adopting these technologies motivated the development of a model to assess the value of information provided by the technologies. The following section presents the framework of the model.

Optimized Condition Assessment Model

Developing optimum condition assessment policies basically involves answering two fundamental questions; 1) What technology should be used for a particular asset, and 2) How frequent should a condition assessment be performed. In order to answer these questions the asset manager must consider several factors simultaneously. These factors can be grouped into two sets of attributes; infrastructure asset attributes and condition assessment technology attributes (Figure 1). Asset attributes that have a strong impact on determining condition assessment policies include asset criticality and required level of service (LOS).

Asset Criticality: This attribute describes the risk associated with operating the asset. More specifically it is a measure of relative consequence of failure associated with operating the asset. High criticality assets exhibit high economic, social or environmental consequences upon failure. Examples would include large diameter transition mains, assets on busy downtown streets, or those close to environmentally sensitive areas. For high criticality water and sewer infrastructure the cost of using accurate condition assessment technologies at relatively short intervals would be justified due to the dire consequences associated with their failure. Quantifying asset criticality in strictly monetary terms is a difficult undertaking especially when indirect costs are considered. The OCAP model utilizes the Grand Central Model (Cromwell, 2002) for calculating social costs.

Required Level of Service: Customer expectations for LOS are core to developing asset management policies (NAMS, 2007). When customers expect higher levels of service and municipalities aim to meet those expectations, spending on asset maintenance, repair, rehabilitation and condition assessment will increase. In order for a municipality to meet higher LOS standards they are likely to become more proactive in the inspection of their assets. Adopting a more proactive approach will lead to more frequent inspections and less tolerance for uncertainty in condition data. As such when required LOS increases, more frequent and reliable condition assessments are likely to be deployed.

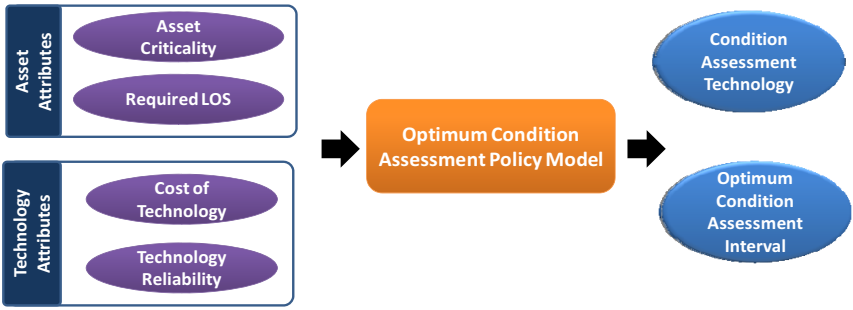


Figure 1. Framework for optimum condition assessment model

The OCAP model aims to that allocate the most suitable condition assessment technology to the right infrastructure asset. The two key attributes of the inspection technology that are considered in the model are the cost and reliability.

Technology Cost: Condition assessment costs for buried infrastructure tend to be higher compared to surface infrastructure like buildings and pavement. As such the OCAP model aims to strike a balance between the value of information revealed by the technology and the costs required to obtain this information.

Technology Reliability: The reliability of some condition assessment technologies for water and sewer infrastructure cast a shadow of doubt on the usefulness (and certainty) of inspection results. For water infrastructure in particular, the use of indirect assessments has shown to weakly correlate with actual pipe condition. Even when direct assessment techniques are used (e.g. electromagnetic detection of broken pre-stressing wire in PCCP pipe) perfect correlation between distress data and pipe condition cannot be guaranteed (Semanuik and Mergelas, 2006).

The OCAP model relies on special form of Markovian Chains called Partially Observable Markov Decision Process. The following sections present the theoretical background of the models.

Markov Decision Process

Markov Decision Process (MDP) is a decision tool to model several sequential decision-making situations involving uncertainty and multiple objectives, including applications related to infrastructure maintenance problems (Scherer and Glagola 1994.). MDP is based on determining of the state variables (asset states in different time horizon), determining transition matrices (asset deterioration through lifecycle), identifying controlling decision (maintenance actions), and calculation of the rewards (costs) associated with taking actions in each time step. Markovian models have been used to model bridge, pavement and road deterioration. One of the shortcomings of Makovian models is that they consider that a

condition assessment will always yield a perfect estimation of the current asset condition. Subsequently the MDP model assumes that the forecast of future condition is perfectly accurate. Partially Observable Markov Process is a modeling approach that overcomes this shortcoming. Jiang et al. (2000) and McCann (2000) incorporated a measure of inspection reliability in the MDP to compare the accuracy of various condition assessment techniques of bridges.

Partially Observable Markov Decision Process

POMDP is an approach towards a more realistic model for infrastructure deterioration where there is inherent uncertainty in the results of a condition assessment. Different inspection technologies have different costs with varying reliability; however no inspection technique can always yield a perfectly true state. Accordingly, POMDP adds another space to the MDP; namely the 'observation space'. The observation space represents the relative reliability of an assessment technique. The mathematical background of POMDP is discussed explicitly in (Ellis et al 1995, McCann 2000 and Cassandra 1994). As such the following discussion is limited to applications of POMDP for developing optimum condition assessment policies.

The variables $[X^t, t\epsilon T, X^t \epsilon S]$ represent the core evaluation processes of the system so that x_t represents the state of the system at time t and S= $(0,1,2, \dots m)$ is the state space of m states. The set of T is consisting of non-negative discrete time points where the system is observed and controlling decision is taken. Since the system is modeled as discrete time MDP and every successive state is independent of the previous state, the stochastic process can be represented as $\Pr(x_{t+1} = j | x_0 = k_0 \cap x_1 = k_1 \cap \dots x_{t-1} = k_{t-1} \cap x_i) = Pr(x_{t+1} = j | x_t = i)$. For t ∈ (0,1,2 ,…) and every possible subsequent decision $i, j, k_0, k_1 \dots \dots k_{t-1}$. In this equation conditional probability $Pr(x_{t+1} = j | x_t = i)$ is called one step transition probability and it represent the probability that variable X will be in state j after one step given the current state is i. The one step transition probability is said to be stationary if $Pr(x_{t+1} = j | x_t = i) = Pr(x_1 = j | x_0 = i)$ and also implies that $Pr(x_{t+n} = j | x_t = i) = Pr(x_n = j | x_0 = i)$ for every i, j and n= (1, 2, 3,..n). This is called n-step transition probability (p_{ij}^n). Transition probability follow probability axiom $p_{ij}^n \geq 0$ for all i, j and $\sum_{j=1}^{m} p_{ij}^n = 1$ for all i where m is the number of the discrete states of the system.

Based on observation an action $a_t \in A$ is performed to control the behavior of the system. Each action has a corresponding transition matrix $P(a_t) \in \hat{P}$, and this represents the system evolution processes till next decision is made. Since no inspection technique is cable of yielding a complete estimation of the actual condition, an estimation of the actual state will be through incomplete observation Y_t. This observation process is donated by $(Y^t, t\epsilon T, Y^t \epsilon O)$ where O is the observation space. Relationship between the observation at time t and core process is given by $R(a_{t-1}) = r_{jo}(a_{t-1}) = Pr(Y_t = O | x_t = j, a_{t-1})$ where $R(a_{t-1}) \in \hat{R}$ is called the relationship matrix. Each $r_{jo}(a_{t-1})$ donates the probability that observation O is received when the system is in state j at time t and action a_{t-1} is performed at time t-1.

Model Implementation

The model is implemented on a programmable Excel spreadsheet with links to a GIS system for visualization. The case study presented in this section illustrates how an observation matrix for a condition assessment technology is used to modify the predictive capability of a Markovian state transition matrix. The case study presented in this section is for the City of Hamilton (ON, Canada) water main network. The City of Hamilton owns 1950 km of water distribution infrastructure with an estimated value of C$1.5 Billion (SOI Report, 2005). In 2006, the City embarked on a series of studies to develop an integrated management framework for managing their water main inventory. As a part of this exercise the City developed a criticality model that serves as a risk-based classification of water mains based on their consequences of failure and LOS.

The risk analysis for the city network divided the network in to three main categories; 'A' which represent the highest and the most critical categories asset, 'B' which represent assts that have less significant cost of failure compared to 'A' category and 'C' which represent the type of assets that have lowest failure costs and reduced LOS that can be tolerated. The case study focuses on selecting optimized condition assessment policies for high and medium criticality water mains (A-B). These assets pose a significant risk in case of failure and hence the there is a need to proactively collect condition assessment information in order to prevent failures from occurring. Roughly 30% of the network has been categorized as critical (10% as 'A' and 20% as 'B'). The following discussion will focus on these ~ 600 km of water mains.

A five-state annual Markov transition matrix for water main assets is shown in **Error! Not a valid bookmark self-reference.**. The Markov transition matrix was developed based on CCTV sewer inspections. Lacking a reliable water main deterioration model, it is assumed that the deterioration of water mains will follow a similar pattern to sewers. This is a somewhat loose assumption that will need verification once sufficient condition data are available for water mains. Penalty costs are associated with the 'Poor' and 'Failure' states and reflect the actual cost of a water main failure and the costs associated with a reduced level of service. The failure costs are taken as $5,000 for criticality 'A' pipes and $2,000 for criticality 'B' pipes. The model also considers costs associated with reduced level of service. Reduced level of service could include factors such as poor water quality, insufficient water pressure or planned water shut downs for maintenance activities. A cost of reduced LOS of $700 is taken for pipes that reach a state of 'Poor'.

Table 1. Markov annual transition probabilities for water main assets

	Excellent	Good	Fair	Poor	Failure
Excellent	0.9	0.1	0	0	0
Good	0	0.96	0.04	0	0

Fair	0	0	0.92	0.08	0
Poor	0	0	0	0.9	0.1
Failure	0	0	0	0	1

To account for differences in cost and reliability of condition assessment technologies, observation matrices are defined for three technologies. The observation matrix relates the percentage of observed to actual condition state. For example in

Table 2. Observation matrix for three condition assessment technologies

below, using the medium accuracy technology only 90% of those assets observed as being in a state of 'Excellent' are actually in that state as 10% of them are actually in a condition state of 'Good'.

Table 2. Observation matrix for three condition assessment technologies

	Low Accuracy	**Cost/m:$5**

		Actual				
	State	1	2	3	4	5
Observed	1	0.85	0.15	0	0	0
	2	0	0.85	0.15	0	0
	3	0	0	0.85	0.15	0
	4	0	0	0	0.85	0.15
	5	0	0	0	0	1

	Medium Accuracy	**Cost/m $15**

		Actual				
	State	1	2	3	4	5
Observed	1	0.9	0.1	0	0	0
	2	0	0.9	0.1	0	0
	3	0	0	0.9	0.1	0
	4	0	0	0	0.9	0.1
	5	0	0	0	0	1

	High Accuracy	**Cost/m $100**

		Actual				
	State	1	2	3	4	5
Observed	1	0.98	0.02	0	0	0
	2	0	0.98	0.02	0	0
	3	0	0	0.98	0.02	0
	4	0	0	0	0.98	0.02
	5	0	0	0	0	1

State 1= Excellent, State 2 = Good, State 3 = Fair, State 3 = Poor, State 5 = Failure

The model calculates the transition matrix which represents the expected deterioration processes of the single asset in the future. As the information reliability of the conducted inspection affect the accuracy of determining the current condition of the assets, asset assumed condition is calculated via different inspection techniques. The condition that is calculated via observation matrix and transition matrix is called belief state. Determining the difference between the transition matrix and the belief state will result in obtaining the expected error. The result of multiplying of the error matrix via the associated costs of failure and reduced LOS costs yields the cost of imperfect information. The value of information is shaped by adding the inspection costs to the costs of imperfect information. The optimum policy for the segment pipe is determining by choosing the least of these added costs. Table 3 show an example on determining the optimum policy for various inspection accuracies with different conditions assuming pipes are inspected every five years.

Results of the analysis highlight the interaction between value of information revealed by condition assessment and the cost of obtaining that information. For example the cost of imperfect information of a low reliability condition assessment technique for criticality 'A' pipe in poor or fair condition is quite high ($380.9 and $290.4 respectively). This high cost swings in favor of conducting a high-reliability condition assessment as the added cost of assessment does not outweigh the costs that are a consequence of low reliability assessment (high cost of failure and impact on reduced LOS). Looking at criticality 'B' pipes, it seems that high-reliability assessments are not a good investment as the added value of reliable information is still less than the cost of obtaining this information. Pipes that are in deterioration state of 'Poor' are not recommended to be inspected with low reliability assessment methods. This is due to the high cost associated with a 'misdiagnosis' and subsequent possible failure of the asset. Figure 3 shows the result of the analysis on a portion of the water main network assuming a 5-year inspection frequency.

Table 3. Results of value of information analysis using partial observation matrix

					Cost of Inspection			
					5	15	100	
Criticality	Condition State	Cost of imperfect information			Total Cost			Decision
		Low	Medium	High	Low	Medium	High	
'A'	Excellent	$4.4	$2.9	$0.7	$9.4	$17.9	$100.7	Low
	Good	$73.9	$49.3	$4.4	$78.9	$64.3	$104.4	Medium
	Fair	$290.4	$193.6	$32.8	$295.4	$208.6	$132.8	High
	Poor	$380.9	$253.9	$50.8	$385.9	$268.9	$150.8	High
'B'	Excellent	$2.5	$1.7	$0.4	$7.5	$16.7	$100.4	Low
	Good	$37.8	$25.2	$2.3	$42.8	$40.2	$102.3	Medium

	Fair	$126.6	$84.4	$14.8	$131.6	$99.4	$114.8	Medium
	Poor	$132.9	$88.6	$17.7	$137.9	$103.6	$117.7	Medium

At the global level, results are quite intriguing. The majority of water mains (around 85% by length) are recommended to be inspected using a low accuracy inspection technology. High accuracy inspection technologies, (shown as red in Figure 2) are only recommended for less than 2% of water mains. As such the results allow the asset manager to target high cost assessment technologies to only those assets that need are in greatest need. It should be noted that the analysis assumed that an unlimited inspection budget is available. Attempting to allocate a limited inspection budget to all assets is an interesting application of the model that is currently under investigation.



Figure 2. Condition assessment policy map – 5 year inspection interval

Summary and Conclusions

Condition assessment facilitates the ongoing estimation and tracking of water main asset condition. The lack of reliable condition data is a tremendous impediment to any asset management program. Water and wastewater infrastructure condition assessment is costly and uncertain compared to other surface infrastructure. Decision makers need to 'sell' the idea of obtaining condition data to drive their asset management programs. This paper presents the results of an ongoing research effort to create a framework for rationalizing condition assessment policies across water and wastewater networks. An illustrated example of the City of Hamilton water network was presented to showcase how the model can be deployed. Further extensions to the framework are underway to assist in 1) Optimum allocation of condition assessment budgets across assets and 2) Setting condition assessment budgets taking into consideration potential failure costs and reduced levels of service.

In order to balance the value of information revealed by a condition assessment technology

with the cost of obtaining the information, the decision maker must consider several factors simultaneously. The first factor that needs to be considered is a quantification of the direct, indirect, and social costs associated with an asset failure. In order to prevent costly failures, decision makers are more likely to spend money to obtain condition information for assets that have a high cost of failure. The second factor that needs to be considered is the desired Level of Service (LOS). User expectations for higher LOS will translate into more proactive asset management practices that involve more comprehensive assessment of asset condition. As such an integrated framework for Optimized Condition Assessment Policies (OCAP) has been developed to assist asset managers in striking this delicate balance between value and cost of condition assessment information.

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e-Society: A Community Engagement Framework for Construction Projects

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Abstract

A majority of construction projects often have a significant impact on the surrounding neighbourhoods and the environment at large. In city scale infrastructure projects, this impact can be detrimental to project success. The affected populations often have concerns and more importantly local knowledge relevant to the project. Capturing and integrating this feedback enhances project sustainability. This integration is a feature of smart city initiatives that have increased collaboration between regulatory bodies and project planners. However, the community has not been able to effectively engage in this process. Accordingly there is a need to facilitate two-way communication to promote community involvement beyond the capabilities of a smart city; this will be achieved through e-Society. An e-Society boosts citywide sustainability by contributing to an expanding pool of knowledge. This research investigates the use of semantic and social web technologies and Information and Communication Technologies (ICT) to facilitate public engagement in construction projects. The proposed framework features a core ontological model that is integrated with web-based middleware. It will contribute to the sustainability of construction projects through enhanced two-way communication and enriched public participation.

Introduction

As most urban areas are heavily developed, a majority of new projects in those areas involve rehabilitation rather than raw construction. Rehabilitation often requires disruption of existing infrastructure operations such as flow in transportation networks. In addition, there is the effect on the environment among other impacts. To the residents of these cities, this disruption has a direct impact on their day-to-day activities. Infrastructure projects, in general, have an impact that spans several communities. It is thus required by law in most cases that the public are well-informed and involved in the planning and decision-making process.

The importance of this kind of community involvement is evident in regulations for Environmental Impact Assessments (EIA) in many countries, including Canada. There has also been a recent shift in focus to low impact development in construction (Yu et. al, 2008). This shift promoted an emphasis on minimal disruption as it minimizes costs and the chance of introducing delays to the project. In addition to the introduction of enhanced construction technologies, public participation has been an integral component of this minimal disruption trend.

The aim of this project is to establish a social, web-based, semantic environment in which community ownership of construction projects is encouraged and facilitated. This research investigates the use of semantic and social web technologies and Information and Communication Technologies (ICT) to facilitate public engagement in construction projects. The proposed framework features a core ontological model that is integrated with web-based middleware. It will contribute to the sustainability of construction projects through enhanced two-way communication to enrich public participation and the planning process.

Similar studies in this area have emphasized the need for promoting effective public participation using visualization and web tools. A recent example is the implementation of several projects that use Public Participatory Geographic Information Systems (PPGIS). Meng and Malczewski (2009) evaluate these tools and specifically web-based PPGIS which focuses on usability by making the process more intuitive and collaborative. They also present a Canadian case study which will be discussed later in this paper.

In this paper, we will establish the need for public participation in the area of construction engineering through a review of the literature. This review will be followed by our proposed framework and validation method.

Public participation

The current process typically takes the traditional form of an open house meeting. Members of the public are provided with a chance to request and review certain documents relevant to the project under consideration. The meeting then takes place at a specific time and venue where members of the public attend a presentation by the project planners, usually accompanied by maps and other forms of visual aid. Attendees can then respond with concerns and questions. Periodically, the planning committee proceeds to acknowledge the public's concerns in the order they are received, and provides responses to some of them within the time limitation of the meeting. Forms of concern are also accepted within a certain deadline, usually a few months after the meeting. The main limitations identified in this process are: 1) need for physical attendance, 2) time limitation, 3) space limitation, and 4) limited media of communication.

In current systems, the involvement of the community is often perceived by the participants and practitioners as a costly and inefficient process. This perception leads to resentment on part of the construction planners as well as the members of the community; hence, undermining the role of community involvement in the planning process. In the case that the rationale behind a project is not communicated clearly nor efficiently, the project could be affected adversely by not meeting the actual needs of the public or through misuse in the future. Furthermore, construction

projects often have significant impacts as mentioned earlier. Impacts such as traffic holdups can be detrimental to project success as they raise legitimate concerns that need to be addressed. Besides those concerns, community members could also possibly have suggestions that need to be tested and local knowledge that should be captured. An example would be a substitute route that would fit as an alternative implementation of a project. They need the means to experiment with the options, perhaps through a model, so that the communication would be two-way rather than one-way information flow from the construction team. The project proposed here offers a solution that builds on current projects while utilizing the best available collaboration technologies to promote community involvement.

Several channels have already been made available through recent advances in web technologies and the recognition of the importance of engaging stakeholders. Evidently, smart city initiatives have increased collaboration between regulatory bodies and project planners. However, the community has not been able to effectively engage in this process. As mentioned earlier, the social aspect of the project would allow for more efficient community involvement as the project would link people as a community rather than acquiring individual responses. In order to achieve a wider community reach, the participation process should be web-based. This web-based nature will provide greater accessibility and less logistical limitations. Finally, in order to bridge communication between people and computer systems (in other words, the linguistics of the people and the way computers process data), this process necessitates the integration of semantics. This bridging enables the project planners to interact with the public in a language that they understand, rather than have them inconveniently adapt to technical language. The semantic web presents the best available technology to represent knowledge. Effective knowledge retention and community involvement have both been proven to develop a sense of community ownership that is vital for achieving sustainability within an e-society.

E-society

An information society is defined as a community that employs a smart infrastructure to exchange information. An e-society builds on that definition as an engaged community that effectively utilizes a smart infrastructure to facilitate two-way communication and the exchange of knowledge. Within our context, in addition to the usual economic dimensions of a construction project, an e-society enables the incorporation of other dimensions within the scenic, environmental, historic, aesthetic and social context. To achieve that broad context, the concept of e-society involves several disciplines, shown in Figure 1.

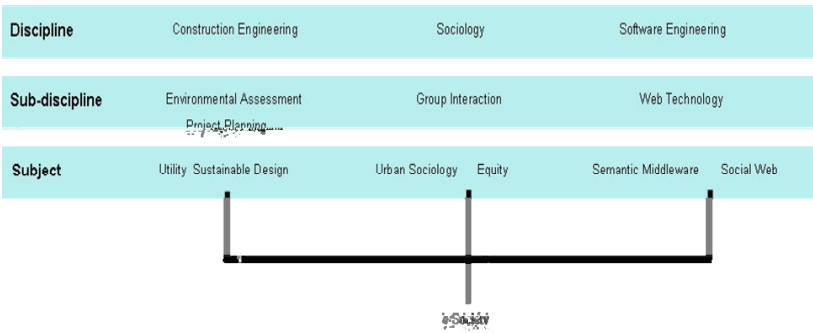


Figure 1. Disciplines involved in e-Society

A review of the literature

The focus of this review is the role of collaboration and, more specifically, public participation in construction projects. There is an abundance of literature on the use of software to enable visualization of building models, facilitate communication of information, and develop Building Information Models (BIM). While these tools are an essential component of the practitioners' work, they are not utilized to their best in information gathering and knowledge management for the purpose of sustainability.

This review starts by describing the processes involved and the social aspects. Relevant projects are discussed as a sample of current work in this area. This description is complemented by a compiled definition of an e-Society in relation to a smart city.

Smart city and e-society

A community in which ICTs are used to enable and enhance two-way communication between the public, organizations and governing bodies formulates the basic definition of an e-society. The core of this system is the existence of two-way communication. The literature reveals a number of initiatives that involve the creation of smart cities as a backbone to aid in the realization of an e-society. What makes a city a "smart city" is discussed by Hollands (2008) who explains that it is not just a connected infrastructure but also the "human capital side" or the culture on a city-wide scale.

For further effectiveness, communication between the members of this society should be empowered through the use of technologies such as social networking applications. The creation of an e-society involves a social, economic, technological and political aspect, in addition to the engineering component in infrastructure projects. Naturally, an e-society would be based on a web-based portal as the core engine of the system. While a few portal implementations have been developed, the literature lacks a comprehensive implementation of a portal in the construction domain that would enable full integration of existing software applications, in addition to the use of social web technologies.

On the other hand, in order to achieve an e-society, cities must first achieve e-readiness. An annual report by the IBM Institute for Business Value and the Economist Intelligence Unit ranks countries according to an e-readiness score, which measures the capacity to use ICT to develop a country's economy. The Economist Intelligence Unit has assessed the world's leading economies on their ability to absorb ICT since 2000. In 2009, Canada came in 9th place with a score of 8.33 on a scale of 10, trailing behind a mix of European and Asian countries in addition to the United States. While this score reflects an overall good world ranking, it shows that there is still a lot of room for improvement. The detailed e-readiness report (EIU, 2009) focused on various aspects of e-readiness such as connectivity, e-inclusion programs and Internet literacy, and adapting the legal system and policymaking.

Process

Public participation has become a common component of the construction process in most projects, specifically infrastructure projects. The Canadian Environmental Assessment Agency encourages public participation in the federal environmental assessment to promote quality through a process that is equitable and non-biased (CEAA, 2003). In addition, the local and traditional knowledge about a project's physical site can help to identify and address potential environmental effects at an early stage of the environmental assessment process (CEAA, 2003).

Infrastructure construction projects that involve transportation are among the projects that have higher impact on the public. In the Greater Toronto Area, Metrolinx (2009) succeeded in creating a two-way communication channel through an online portal. On the Metrolinx portal, members can register as consultees to express their own opinion and post comments or as agents that would make comments on behalf of other individuals or organizations. A list of projects is available for the user to navigate. An additional view is available through a map that can be pointed to a specific postal code. Since the nature of most transportation projects is based on proximity, the map view would prove to be a very useful tool. This portal provides improved accessibility to the public, yet it might not intuitively support collaborative participation or predictive features.

In addition to maps and visualization techniques, there is increasing interest in the prospect of social networking as a potential means of collaborative participation and networked decision making. Several studies provide evidence that supports the importance of public involvement at a normative level in reducing delays and conflict in the different stages of planning. For instance, Smith (1983) emphasized the lack of public participation at a normative level in Ontario in 1983 when three alternative approaches were presented for the specific case of Ontario Hydro. The recommendations proposed by Smith include: 1) instituting a representative public advisory board, 2) that board should ensure that the release of major position papers is synchronized with public involvement, and 3) facilitate public review of energy planning a standing committee for legislation (Smith, 1983). This kind of public involvement at an early planning stage ensures that potential issues can be addressed promptly or preemptively. There is evidence of a social need for public participation.

Public participation in construction

In the aforementioned projects, it is evident that more emphasis is being placed on the public as more decision makers are taking into consideration that engineering projects, by design, involve the creators and the users: the public in this case. Nevertheless, many of the mechanisms available today do not provide sufficient tools to aid in effective public participation. The Canadian Environmental Assessment Agency (CEAA) emphasizes that public participation in the general environmental assessment process guarantees the openness, proper balance and credibility of the process. More importantly, the public can help identify and address potential problems at an early stage through their first-hand knowledge about a specific site (CEAA, 2003). Another facet of public participation is the review panel: a group of experts who contribute their knowledge to a project. The review panel is as important as other forms of public participation as it provides a way for the public to offer their expertise. The capture and retention of this experience as knowledge can have a major role in the sustainability of infrastructure projects. This practice is heavily used in an area known as Knowledge Management.

To enable public participation successfully, the technology has to support those initiatives at the process and social level. There is evidence that the current technology and existing standards are capable of nestling the aspired level of public participation in infrastructure projects. A review of the current use of ICT in the area public participation presents evidence that a significant amount of work is needed for integrating the existing technologies and making better use of social networking technologies (Rivard et al., 2004).

Middleware

Middleware systems facilitate integration by modeling common services of software applications. The World Wide Web (the Web) itself is an example of a networked environment. An issue that had to be dealt with on an urgent basis was the successful integration of legacy systems that contained highly sought information that should be accessible over the Web (Perrochon, 1995). Application integration is a relatively seasoned yet very current field. It has seen great progress from tedious custom-made interfacing software to the creation of Web-based middleware. For the purpose of this review, the interest is in the integration capabilities of middleware. In principle, middleware enables communication between applications that can be geographically separated or designed to run on different platforms, while providing additional functionalities.

Best practices for middleware mash-ups

In an interesting position paper, Ankolekar et al. (2007) explain how the semantic web and Web 2.0 are complementary rather than competing. Both approaches lack certain aspects. For instance, building semantic web infrastructure would not be an easy task without the creation of online communities through Web 2.0 to aid in knowledge mining (Ankolekar et al., 2007). IBM provides examples of distributed middleware with business applications in the areas of asset management, transportation, trade and banking (IBM middleware, 2009). These applications focus on interactive two-way communication applications like integrated mobile fleet

management. IBM's Maximo middleware introduced this functionality in transportation while other middleware systems provide integration of fleet management with supply chain management systems. Through better management of information, these systems can be easily integrated with other IBM software systems to provide additional functions such as security. The best practices outlined by IBM (IBM middleware, 2009) included a combination of context-aware middleware, event-based publish/subscribe system, domain-specific ontology and social networking tools. Web-PPGIS is an example of such mash-ups that hide the complexity of underlying technologies from the users. Meng and Malczewski (2009) assessed its positive contribution to the process of siting a parkade in Alberta, Canada. They indicated that Web-PPGIS enhanced the quality of the experience for the users, while it lacked features that could aid the users in making decisions.

Ontology & semantic web

The semantic web is an extension to the Web which adds context and meaning to the content, and improves predictive capabilities. In the engineering context, many of the terms and standards have not been unified across the industry yet, and this dynamic, distributed environment paves the way for semantic web applications. Figliozzi and Tufte (2009) discuss the essence of adding semantics to enable the integration of freight data. An Internet-based system is proposed that also provides visualization through semantic data models. These models facilitate the use of existing applications. It has become a best practice to use ontologies to represent entities, relationships and axioms within models in semantic web systems. SWIM is a framework that combines the semantic web, and virtual organizations to enable the management of traffic incidents on freeways in a real-time manner (Abou-Beih et al., 2009). In this project, taxonomy has been built to model the incident management process, including the actors, rules, relationships and products. This taxonomy forms the base of the interaction of different parts of the system while efficiently routing incident information. This kind of mash-up usually requires the development of a separate middleware system to handle this integration. Semantic middleware systems are used to reduce the complexity of the integration process with examples from the software industry (Oberle et al., 2004).

Proposed framework

The proposed framework will include a web-based portal with an ontology as a core component. This portal will employ semantic and social web principles for enhanced usability. These principles employ relatively well-tested technologies that can be integrated into the middleware system. A semi- or fully-automated middleware component is currently being designed as the core engine of this project. Figure 2 shows the main aspects that would be featured in the portal.

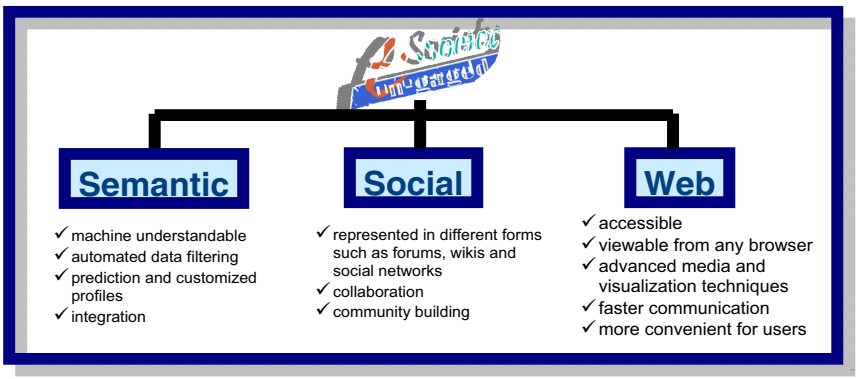


Figure 2. Main elements of the e-society portal

The methods used to carry out this research follow the standard research methodology which involves incrementally designing, implementing and assessing the ontology and portal system. Surveys and literature reviews are the primary tools used for building the ontologies and formulating the model. On the other end, validation is the main tool used to ensure that the different modules of the ontology properly model the processes they represent.

As a first step, the current public participation process is being modeled. This step is performed using the literature as well as passive and active observation of public meetings. Following the completion of that model, the main products have been identified as: 1) a comprehensive ontology (following the method outlined by Grüninger and Fox (1995)); 2) prototype implementation of portal and social software; 3) use cases for validation; 4) pilot project for benchmarking. The pilot project would validate that "better" participation is attained, based on the following criteria: number of visits by participants, quality of participation (diversity and quality of feedback) and feedback from project managers on the quality of feedback and potential integration into design. The main tasks can be summarized as follows:

1. Describe current processes and online participation practices in the construction domain. This process involves identifying roles, common issues and mechanisms, as well as best practices.
2. Build an ontology to represent knowledge in the public participation process. This stage of research involves developing a set of requirements or questions that the ontology should answer (Grüninger and Fox, 1995).
3. Conduct interviews to validate the concepts, relationships and axioms.
4. Analyze requirements for the social web-based portal.
5. Create a web-based portal implementation that incorporates the ontology.
6. Test and validate the system with the integrated ontology. Validation would involve benchmarking the performance of the system.

The validation process here is a primary component of the research methodology. In addition to the benchmarking criteria already mentioned, validation will include tools such as interviews, focus groups and surveys for gathering primary

data. The subjects of these interviews are practitioners who are directly involved in the planning and design process of selected construction projects. In addition, use cases outlining several scenarios such as that shown in Figure 3 will be used to define the scope of validation and acceptance criteria.

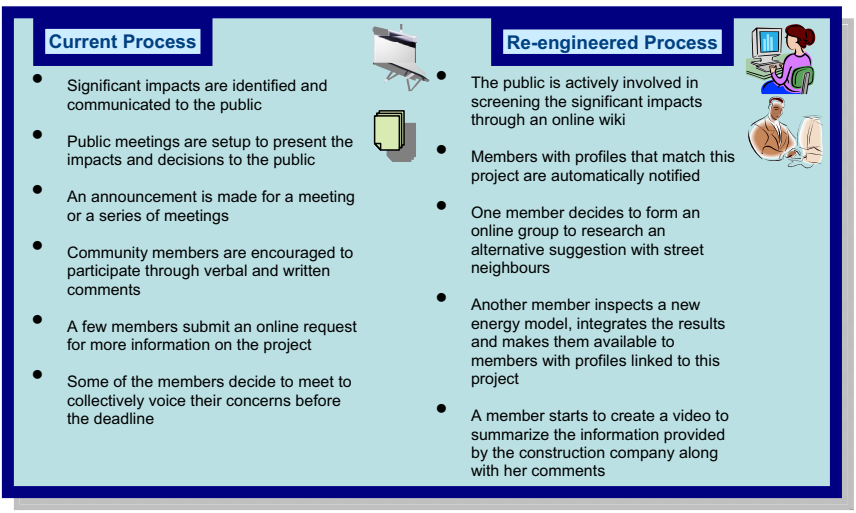


Figure 3. A typical scenario comparing the current participation process and the future vision

Conclusion

Within the context of construction projects, this paper has established a need for public participation that is based on two-way communication. An important tool for achieving the facilitation of this type of participation is the Web and its various collaboration and visualization tools. Similar projects have been shown to successfully foster public collaboration, with success of web-based PPGIS projects which focus on usability. However, the paper reveals that many of these systems lack the semantics specific to the construction domain, which would enhance the user experience as well as help in gathering information and retaining the knowledge component. This knowledge can be transferable from one project to another.

The review shows that Canada has a high rank in e-readiness, yet also indicates that there is a lot of room for growth. With regards to the construction industry, public participation seems to be one of the potential channels for promoting sustainability of projects by focusing on engaging the users. We have proposed a framework that utilizes semantic web-based middleware and web-based concepts such as social networking. This middleware will interface with users in the form of a web-based portal for easy access. A validation plan has also been outlined to test the first prototype and final product with the aid of practitioners from the construction industry. Despite concerns raised by some scholars around the usability and long-term sustainability of similar systems, we believe that its semantic and social networking

features place this framework as a replacement and not just a supplementary system to the current process in the construction domain.

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Knowledge Management Systems for Construction

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Abstract:
Over the last ten years, there has been growing interest in the implementation of knowledge management (KM) systems within the construction industry. The fragmented and transient nature of construction project teams makes the industry ideally suited to benefit from improved management of the knowledge generated in the course of construction projects. This paper is concerned with the evolution of knowledge management systems for construction. It starts with an exploration of the adoption of KM systems by construction sector organizations over the last decade and identifies some of the emerging trends. It also reviews some of the major knowledge management systems developed over the period and highlights the strengths and limitations of these systems in relation to what the industry needs. It argues for a new generation of knowledge management systems that are better suited to the dynamic, global and complex environment within which contemporary construction projects have to be delivered. The key features that such next-generation KM systems should have are also discussed and conclusions drawn on their significance.

1. Introduction

According to Quintas (2005), "it is palpably obvious that without creating, accumulating, sharing and applying knowledge, no human civilization could have existed. Even though the phrase 'knowledge management' only came into common usage in the West during the last five years of the 20th century, it is emphatically *not* the case that the management of organizational knowledge processes began in the mid 1990s". He feels that the case studies of Honda, Matsushita and other firms in Nonaka and Takeuchi's influential and widely quoted book *The Knowledge Creating Company* (1995) were not examples of designated 'knowledge management' initiatives but rather descriptions of actual knowledge processes such as knowledge sharing, knowledge combination, etc.

Knowledge Management (KM) is a relatively new concept and there are many definitions, generally illustrating the variations in scope and content. KM is narrowly defined, in some instances, to emphasise the capture, access, and reuse of information and knowledge using information technology. This definition implies that tacit

knowledge can be converted to explicit knowledge using IT. However, it is generally accepted that tacit knowledge is more difficult to capture and manage. Examples of knowledge management definitions are shown below:

- Knowledge management is the discipline of creating a thriving work and learning environment that fosters the continuous creation, aggregation, use and re-use of both organizational and personal knowledge in the pursuit of new business value definition from Xerox Corporation Source: Cross (1998);
- Knowledge management is 'any process or practice of creating, acquiring, capturing, sharing and using knowledge, wherever it resides to enhance learning and performance in organizations' (Scarbrough et al, 1999).

There are several other perspectives on knowledge management. For example, there is the social/human resource perspective which focuses on knowledge management as 'the distribution, access of human experiences and relevant information between related individuals and work groups' (Excalibur Technologies, 1999). The IT/technology perspective focuses on the 'capture, access and reuse of knowledge using information technology' (O'Leary, 2001). There is also the intellectual capital or economic perspective which sees knowledge management as the 'systematic and organised attempt to use knowledge within an organization to transform its ability to store and use knowledge to improve performance' (KPMG, 1998). Irrespective of the different KM perspectives, all definitions focus on the fact that knowledge is a valuable asset that needs to be managed and that managing this knowledge is important to improve organizational performance.

Within the context of this paper, Knowledge Management (KM) can be simply defined as a systematic process of capturing, transferring, and sharing knowledge to add competitive value (Drucker, 1993; Skyrme and Amidon, 1997) and to improve performance (Robinson et al, 2001). KM provides several benefits such as facilitating staff training, problem solving, and decision-making. It also enables the intellectual capital of an organization (its skills, knowledge, and processes) to be used effectively, creatively, and consistently to improve business performance and customer satisfaction (TFPL Ltd, 1999). KM is therefore critical to an organization's survival in competitive markets and it is becoming a strategic necessity for organizations willing to lead the market and even to those just wishing to keep their places in the market.

The rest of this paper focuses on knowledge management within a construction context. The importance of KM in construction is explored and is followed by a discussion of the industrial uptake of knowledge management. A brief review of KM systems is then presented and the features expected of next-generation KM Systems for construction sector organizations outlined. The concluding section of the paper summarises the salient points.

2. Importance of Knowledge Management in Construction

Much of the training and experience of construction professionals is based on a balance between codified (explicit) knowledge and tacit knowledge. Case study interviews with structural design firms shows that about 80% of knowledge used during concept design is tacit compared to about 20% of explicit knowledge, whilst the reverse is true at the detailed design stage - 20% tacit and 80% explicit (Al-Ghassani, 2003). It is the dynamic interactions between tacit and explicit knowledge, which facilitates decision making in the implementation of construction projects. This is why construction project documents are understood and interpreted by those who have been through the same or similar type of training. For example, structural

engineers could extract meanings from design codes or interpret construction drawings easily whilst accountants cannot.

Research conducted by den Hertog and Bilderbeek (1998), and Windrum et al (1997) identified design, architecture, surveying and other construction services as knowledge-intensive service sectors. An important feature that distinguishes knowledge intensive sectors from manufacturing firms is the type of 'product' they supply and, following this, the role they play in regional and national innovation systems. Whereas manufactured products and processes contain a high degree of codified knowledge (they are 'commoditization' of knowledge), knowledge intensive sectors' are characterised by a high degree of tacit ('intangible') knowledge. Specialised expert knowledge and problem-solving know-how are the real products of knowledge-intensive industries (Egbu and Robinson, 2005).

Professional knowledge (i.e. knowledge produced by consultants while interacting with their client's settings) is deeply embedded in a mutual socialisation process, where consultants and their clients design together their final output. This is often seen in the kinds of services provided by professional/ consultancy firms of architects, quantity surveyors and engineers. For consultancy or professional firms, their main capital is intellectual assets, and most of their processes are geared towards the exploration, accumulation and exploitation of individual and firm expertise (Egbu and Robinson, 2005).

3. Industry Uptake of Knowledge Management

Knowledge Management as a practice has a trajectory in many other industries and professional practices. At its core, KM provides tools that enhance and support the core functions of an organization. It facilitates the objectives of any team, department, organization and industry. Because its principles are granular, they can be easily interchanged with project management or change management practices. For any industry, the successful adoption of KM represents a managerial commitment and often a cultural change. Therefore, its adoption is often slow, starting with a particular initiative or department. It then gradually spreads or diffuses throughout the organization, eventually becoming an integral part of its practice or operations.

In the US, the A/E industry `is just beginning to address the relevance and benefits of KM. The term is not commonly used and very few AE firms hold a position for a KM leader. The concept of knowledge as an asset that must be supported and managed is being discussed for the first time in many architectural and engineering forums. More than tradition and success in the use of technology and management of information, specifically CAD data and presentation materials, knowledge encompasses more than simple data, thus requiring a holistic or enterprise approach to information and its management.

Understanding knowledge at the enterprise level requires an awareness and balance between the day to day tasks, the generation of data, the collection and communication of data, fostering and sharing of unique ideas, and the goals of the organization. All these components interact within the context of new technologies and business trends.

For the AE industry, the challenge to successfully adopt KM is to expand its definition and implementation beyond the project and the project team; to understand the interdependencies and need for integration among the various groups and departments of the business and not to reduce KM to the use of technology and implementation of CAD/BIM standards.

In the airline industry, the practice of KM faces similar challenges; the large size of the airlines and their longevity in the business makes for slow KM adoption. Newer airlines tend to have faster successes because they are able to define and build a culture of knowledge from the ground-up. Specifically, technology platforms, business processes, and incentives that will guarantee the identification, collection, and sharing of corporate knowledge.

Civic agencies such as the United Nations are currently exploiting KM by adhering to its technology applications and idea sharing principles. By providing incentive programs for groups to share successes and best practices; and implementing Web-based portals and social networking tools, certain sectors of the UN are able to help governments in smaller countries solve a variety of socio-economic issues. Employing KM, the UN is able to provide advice and connect various segments of the population and even different governments so they can share their experiences and successes. In so doing, these countries are able to foster a culture of knowledge among its government groups and private institutions.

Many consulting firms have based their practice on KM principles. However, in today's global economy, the commercial aspects and competitive environment that consulting firms operate in makes it difficult to reconcile and benefit from the idea of knowledge as a common, shared resource. With the proliferation of information management mechanisms, consulting firms are challenged to re-evaluate their approach to knowledge management and sharing to find ways in which their KM practice helps differentiate their practice and becomes an integral part of their value proposition.

The longevity of construction as a business and the structured approach to its practice provide unique challenges and opportunities to implementing KM. For example, the business of construction is highly regulated. There are many standards, codes and guidelines that shape or even dictate the processes involved. Since many of the processes are repetitive and common from one project to the next, the use of technology, templates and technical standards are also in existence. Because of this, there are many technology solutions to help support these practices - that is, the standardization of tacit processes and the redundancy of technology systems.

4. Knowledge Management Systems

A knowledge management system is the technology platform and infrastructure that an organization employs to support knowledge management (Robinson et al, 2010). It typically consists of a set of tools, made up of technologies (IT Tools) and techniques (non-IT tools). Both technologies and techniques are equally important to support different KM processes (Anumba et al, 2005) and are briefly described below.

4.1 KM Technologies

KM technologies rely on an IT infrastructure. Examples of KM technologies for capturing knowledge are: Knowledge Mapping Tools, Knowledge Bases, and Case-Based Reasoning. Although there is a debate about the degree of importance of such technologies, many organizations consider these important enablers that support the implementation of a KM strategy (Skyrme and Amidon, 1997; Kanter, 1999; Anumba *et al*, 2000; Egbu, 2000; Storey and Barnet, 2000) as they consume one third of the time, effort and money required for a KM system. The other two-thirds mainly relate to people and organizational culture (Davenport & Prusak, 1998; Tiwana, 2000).

KM technologies consist of a combination of hardware and software technologies. Hardware technologies and components are important for a KM system as they form the platform for software technologies to perform and are the medium for storage and transfer of knowledge. Some of the hardware requirements of a KM system include personal computers or workstations to facilitate access to knowledge, powerful servers to allow the organization to be networked, open architecture to ensure interoperability in distributed environments, media-rich applications requiring Integrated Services Digital Network (ISDN) and fibre optics to provide high speed and use of the public networks (e.g. Internet) and private networks (e.g. Intranet, Extranet) to facilitate access to and sharing of knowledge (Lucca *et al*, 2000). Software technologies play an important part in facilitating the implementation of KM. The number of software applications has increased considerably in the last few years. Solutions provided by software vendors take many forms and perform different tasks. The large number of vendors that provide KM solutions makes it extremely difficult to identify the most appropriate solutions. This has resulted in organizations adopting different models for establishing KM systems. Tsui (2002) identifies five emerging models for deploying organizational KM systems where one or a combination may be adopted: customised off-the-shelf, in-house development, solution re-engineering, knowledge services, and knowledge marketplace.

4.2. KM Techniques

KM techniques do not depend on IT although they provide support in some cases. Knowledge sharing, for example, is a sub-process of KM, which can take place through face-to-face meetings, recruitment, apprenticeships, mentoring, and training. The importance of KM techniques comes from several factors. Firstly, KM techniques are affordable to most organizations as no sophisticated infrastructure is required. Some techniques, however, require more resources than others (e.g. training requires more resources than face-to-face interactions). Secondly, KM techniques are easy to implement and maintain due to their simple and straightforward nature. Thirdly, KM techniques focus on retaining and increasing the organizational tacit knowledge, a key asset to organizations.

KM techniques are not new; most organizations have been implementing these for a long time under the umbrella of management approaches such as organizational learning and learning organizations. Using these tools for the management of organizational knowledge requires their use to be enhanced so that benefits, in terms of knowledge gain/increase, can be fully realised. Examples of KM techniques include brainstorming, communities of practice (CoPs), face-to-face interactions, post-project reviews, recruitment, mentoring, apprenticeship and training.

4.3 Examples of Knowledge Management Systems

There are a variety of tools to support knowledge management implementation. However, very few of these adequately address all the stages in the KM lifecycle. Examples of some research prototypes, which address critical and problematic areas for many construction sector organizations, include: CLEVER_KM™, IMPaKT, STEPS and CAPRI.NET. These were developed to facilitate (respectively) the development of knowledge management strategies, evaluation and benchmarking of knowledge management initiatives, assessment of an organization's KM maturity, and to enable the live capture and reuse of knowledge in construction projects.

CLEVER_KM: The CLEVER_KM tool provides a structured approach to KM problem definition and strategy formulation based on specific steps shown in Figure 1. The CLEVER tool consists of several stages that take an organization from an initial definition of a knowledge problem, an identification of where they wish to get to, specification of the critical migration paths required, through to the provision of appropriate knowledge management processes to aid in the resolution of the organization's knowledge management problem (Anumba *et al,* 2005a).

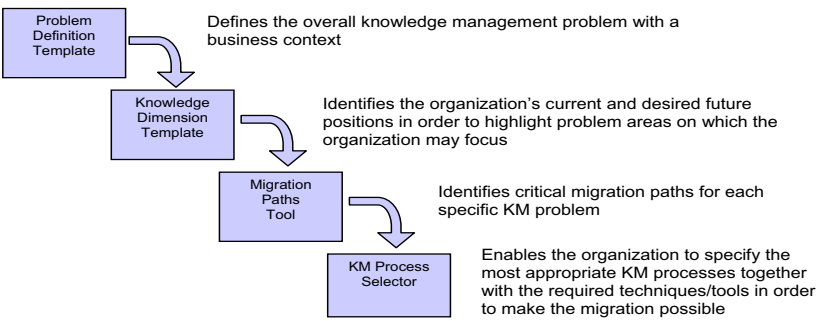


Figure 1: Steps in the CLEVER_KM Tool

The CLEVER_KM system has been commercialised and is useful for KM strategy formulation at both organization and project organization level.

IMPaKT: The IMPaKT framework enables organizations to evaluate the business impact of their KM initiatives (Carrillo *et al*, 2003; Robinson *et al*, 2004). The framework facilitates: (1) an understanding of the strategic context of business problems and their knowledge management implications; (2) the planning and alignment of KM strategy to address business problems or objectives so as to ensure that they are coherent and consistent with the overall strategic objectives of an organization; and (3) an evaluation of the impact of KM on business performance in terms of effectiveness and efficiency by providing a set of complementary measures for assessing the impact of KM initiatives on business performance. Evaluation with industrial practitioners showed that the framework could significantly facilitate the implementation of a KM strategy in construction project organizations. The framework enables a useful thought process, is well focused and easy to use, and is considered to be an innovative KM tool that incorporates issues not adequately addressed in other frameworks.

STEPS: The STEPS maturity roadmap provides a structured approach to determine the steps and action plan required and to benchmark knowledge management implementation efforts (Robinson et al, 2006). The five steps in the maturity roadmap, (Start-up, Take-off, Expand, Progress, and Sustain) reflect varying levels of knowledge management maturity. Each level of maturity is characterised or associated with certain attributes and attribute dimensions, reflecting the different emphases at various stages.

CAPRI.NET: The Capri.Net system resulted from the Caprikon Project at Loughborough University (Tan et al, 2007). It is based on a framework that enables construction project organizations to undertake 'live' capture of knowledge on projects such that the knowledge can be reused at the later stages of the same project and/or subsequent projects – see Figure 3. The framework comprises:

- A Web-based knowledge base – This is where the Project Knowledge File (PKF) of a project is stored. The PKF contains relevant project information and project knowledge that can be reused both during the execution (e.g. in subsequent phases) and after the completion of the project;

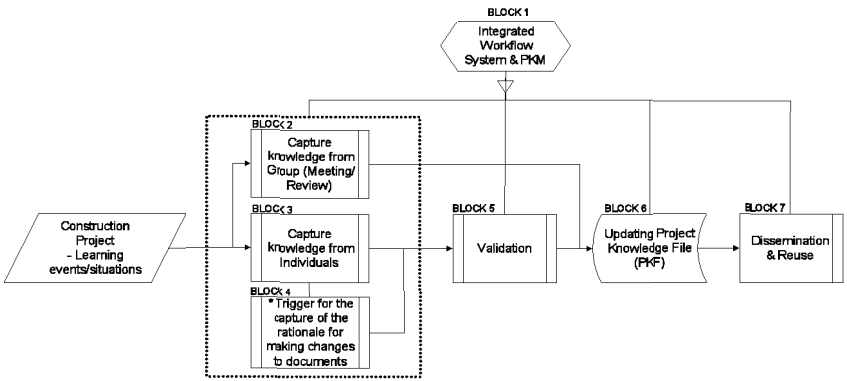


Figure 3: Framework for Live Capture and Reuse of Project Knowledge

- An Integrated Workflow System (IWS) - It delineates, executes and monitors the mechanisms for the capture, validation and dissemination of the project knowledge captured; and

- A Project Knowledge Manager (PKM) – This is a designated person who manages the knowledge base (i.e. the development of a Project Knowledge File for a project) and the Integrated Workflow System (IWS) for a given project.

5. Towards Next-Generation KM Systems for Construction

The longevity and stability of construction management tasks and build processes led to the definition and implementation of construction standards. These standards have facilitated the creation of software applications to support the processes. These two conditions give the construction industry the false sense of having accomplished KM objectives.

The various technology systems, although commonly used and very similar to each other, do not necessarily foster a culture of knowledge. The basic architecture of the multiple systems commercially available and in predominant use by the construction industry today tackle the various phases and tasks of the construction process as isolated events and in a proprietary manner.

In order to benefit from the identification, collection, and sharing of ideas and best practices the basic infrastructure of any software system must facilitate the exchange of data and provide easy access to information and knowledge. The

information and knowledge must be collected from different systems, at different phases, and remain available to the organization beyond the completion of any and all constructions projects. Higher function knowledge (organizational wisdom, if you will) that derives from the integration and awareness of needs and contributions among the participant parties is often obstructed by the technology platforms in which these tools are built.

With the advent of BIM, there is the need for reconciliation and integration of practices and standards among the AE and Construction industries. This reconciliation transcends the organization of the BIM model and the level of detail /nomenclature of the BIM components; it impacts the economic models that have been in place within the design/build umbrella for more than half a century.

The current generation of knowledge management systems are proving reasonably effective in helping organizations to manage their intellectual assets. While many organizations are content with the small gains made, others are wondering what to do next. The true test of the extent to which a KM system has transformed an organization lies in the answer to the question: 'To what extent are our knowledge management practices now regarded as regular business practice?' The more fully integrated that KM processes, tools, techniques and practices are with a company's business processes, the greater the potential benefits. This is a trait that will be commonly exhibited by next-generation KM Systems (Anumba, 2009).

Just as the phrase 'Computer-Aided ...' was widely used in the 70s and 80s but is now declining in usage (as computer-based systems are now mainstream business systems), next-generation KM systems are expected to make seamless the linkage between KM processes and business processes, thereby leading to relative disuse of the term 'KM'. In addition to this, next-generation knowledge management systems for construction sector organizations will (Anumba, 2009):

- Have demonstrable or self-evident performance benefits such that Knowledge Managers no longer have to justify investments in KM. No universally accepted metrics exist and it will become increasingly necessary for organizations to develop measures that are tailored to their circumstances; these will have to be linked to higher level corporate objectives;
- Have an intelligent agent-based component. Such systems will be able to act on behalf of their owners in interacting with any existing IT tools and knowledge repositories, and can build user profiles based on a course of interaction;
- Incorporate more sophisticated tools and techniques for knowledge capture and reuse, some of which will be based on artificial intelligence (AI) techniques. These will enable more automatic capture of knowledge as it is generated and facilitate knowledge sharing across organizational boundaries.
- Enable more ubiquitous, context-specific and, where appropriate, location-based delivery of knowledge and associated services. This will allow an unprecedented degree of personalisation, while enhancing the utility and relevance of these systems;
- Support effective integration of personal knowledge management systems with corporate knowledge management systems in such a way that organizations can better leverage the knowledge held by their employees without privacy violations;
- Have sophisticated mechanisms for supporting communities of practice and, in particular, capturing storytelling and anecdotes which are rich in knowledge content;
- Support the development and management of 'knowledge chains', which facilitate the flow of knowledge within and across construction supply chains;

- Contribute even more to the market value of construction sector organizations as the value they provide becomes more of a distinguishing factor in the evaluation of organizations;
- Be supported by an increased number of people whose roles involve the management of knowledge assets in organizations.

The above are just some of the elements that next-generation KM systems are expected to have. The list is not exhaustive but it is indicative of what is possible.

6. Summary and Conclusions

Knowledge management is very important for the success and continued improvement of construction projects. It offers numerous benefits that can help to increase the returns for construction-sector firms involved in collaborative projects. This paper has sought to provide a review of knowledge management systems for construction. It reviewed aspects of KM adoption and KM systems, and outlined the key features that need to be incorporated into next generation KM systems.

The complexity associated with the delivery of construction projects by a transient project team made up of individuals/teams from a variety of organizations makes the implementation of knowledge management systems in construction challenging. However, it is also for the same reasons that construction sector organizations cannot afford to ignore KM. They must embrace the core principles and tailor their KM strategy and implementation to the needs of their particular firms. At project level, next-generation KM systems will better facilitate the 'live' capture and reuse of knowledge, and collaborative learning during the course of the project. It is important that construction sector organizations continue to invest in knowledge management as it offers considerable benefits at both corporate and project organization levels.

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The Embedment of a Knowledge Management Program in an AEC Organization

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ABSTRACT

This paper examines the embedment of a knowledge management (KM) program within an individual global engineering organization, Fluor Corporation (Fluor). Although many knowledge management initiatives fail, the program established by Fluor achieved increasing legitimacy and became a taken-for-granted practice over time. This paper examines the process of embedment by analyzing the changing use of the program through participant quotes. In addition, it identifies factors that contributed to the ongoing use and embedment of the KM program in Fluor's operations. These include the alignment of the program with Fluor's culture, the continued maintenance and ease of use of the program, social influence factors, and external changes that together evolved the KM program into a well-used, award-winning program around the world. This case study offers the rare opportunity to investigate a KM program that has been established in the AEC sector for almost a decade and offers insights and suggestions to firms seeking to implement knowledge management programs in the industry today.

INTRODUCTION

Over the last decade, interest in knowledge management has surged. Although the importance of knowledge to organizations was recognized in the past, the knowledge-based-view of the firm brought new meaning to the value of knowledge to an organization by identifying it as a resource with at least as much importance as capital (Conner and Prahalad 1996; Grant 1996; Spender 1996). In the increasingly competitive and global marketplace, firms are especially keen to integrate and capitalize on the knowledge of their employees and make it available when and where it is needed. As a result, many organizations implement KM initiatives. Unfortunately, while estimates vary, most (over 50%) KM systems implemented in practice fail to achieve their original goals(Akhavan et al. 2005). As Argote noted, more attention has gone into identifying knowledge as a source of competitive advantage than in realizing how organizations can actually acquire, integrate and share their knowledge (Argote et al. 2003). Organizations wishing to implement KM programs are left to grapple with how to develop an effective and sustainable KM program.

Knowledge Management in the AEC industry

Like other sectors, the engineering/construction industry began recognizing the need to share knowledge, diffuse best practices, respond quickly to customers and reduce re-work (Carrillo et al. 2004). As a result, many companies in the industry are starting to embrace KM programs to combine and share their knowledge more effectively. A recent survey of firms in the UK found that approximately 40% of engineering design and construction organizations have a KM strategy, and another 41% plan to have one within a year (Carrillo et al. 2004). In an attempt to uncover best practice within the United States AEC sector, Carrillo and Chinowsky found that there is still confusion amongst companies over KM terminology, however, some are starting KM initiatives, and KM is beginning to gain ground within the United States AEC sector (Carrillo and Chinowsky 2006).

Due to the relative infancy and paucity of KM initiatives within the US construction industry, few studies have been able to follow the implementation and embedment of a knowledge management program over time. Of the existing studies, some have focused on demonstrating the need for knowledge management programs, such as a study by Robinson and colleagues that presented a framework to develop a business case for KM (Carrillo et al. 2004). Others have identified factors that appear to influence or hinder knowledge sharing within the company. For instance, Fong and Chu found that the top three critical factors for sharing knowledge successfully included an understanding of the benefits provided by knowledge sharing, time, and participation and cooperation from colleagues (Fong and Chu 2006). Another study found similar strategies including demonstrating the benefits and obtaining "buy in" from the employees through communication initiatives (Chinowsky and Carrillo 2007).

These prior studies address some of the common barriers to, and critical factors affecting, knowledge sharing within organizations. However, KM is still in the early stages of development within the AEC industry. A gap exists in our understanding about how companies can gain value from a KM program by embedding it within a firm over time. In an ongoing effort to identify how different types of organizations are able to acquire, integrate and transfer their knowledge, we witnessed a KM program that has become integrated within a single global engineering firm. The motivation for this particular paper came from a desire to understand how the KM program became embedded within the company's culture over the last decade. Therefore, this paper extends past research with an in-depth case study on the process of embedment of a KM program within a company and examines the dynamic factors that appear to have encouraged the program's success and maintenance over time. By identifying some of these factors, this research offers suggestions for practices that can be used in other KM initiatives being implemented today.

METHOD

A single case study is used for this analysis. This case was part of a research project that investigated how multinational organizations acquired, integrated and transferred local area project knowledge. This paper analyzes one of these companies, Fluor, to analyze the embedment of Fluor's KM program. Fluor is a global, publicly owned engineering, procurement, construction and maintenance service (EPCM) company. Fluor was selected as a case study due to its award-winning KM program. It received

the North America Most Admired Knowledge Enterprise (MAKE) in 2005, 2006 and 2007 and is the only company within the AEC Industry to be a Global MAKE winner (in both 2006 and 2007). The MAKE research program seeks to "identify organizations which are using knowledge-driven strategies to out-perform their peers by able average growth in intellectual capital and wealth creation".

I visited Fluor in their Aliso Viejo office over a three-day period. Following the ethnographic approach recommended by Spradley (Spradley 1979), I conducted open-ended interviews with the KM team and various engineering employees within the firm. This technique provided the opportunity to question participants regarding the history of the KM program and the employee's use of the program. In addition, I was able to observe knowledge searches in action. During the data collection, I wrote field notes and audiotaped interviews. The informants also provided various forms of documents, including presentations, statistics, examples, system print outs, success stories, and other evidence. The combination of interviews, observations and documentation enabled the triangulation of data to enrich the case analysis and view the system in a larger context.

The interviews were transcribed and imported along with field notes and collected documents into a computer software program, NVivo, by QSR. This data was coded and analyzed using the grounded theory method (Eisenhardt 1989; Glaser and Strauss 1967; Miles and Huberman 1994). During this highly iterative phase of the process, evidence emerged that helped identify critical success factors that helped to embed the program into the overall organizational culture.

THE FLUOR CORPORATION KNOWLEDGE STORY

The Fluor KM initiative began in 1997 but officially kicked off formally in 1999. The company wanted to link people and provide timely solutions to address project and customer demands. To address these goals, it put together a small KM team that collaborated with consultants. Due to the company's size, scale, and global presence, the team knew that technology would be a significant part of the solution; however, they wanted to ensure that people-to-people connections remained strong. Originally, they planned to implement a consultant's system, believing that they could:

> *"plug their system in ….and one year later the team would be done. The system would be handed over and the business units would be charged to use the system".*

However, the team quickly discovered that using another company's system was the wrong answer. While the proposed system worked well for the client's consulting organization, it did not fit within Fluor's existing culture; therefore, they decided that they had to create a custom, tailored solution to fit Fluor's culture and operations:

> "*We needed to build a solution that would work for **our** company and **our** culture…we quickly got into the software development business because we couldn't find what we wanted from a commercial solution".*

Knowledge Online

The resulting solution was a web based KM platform called "Knowledge Online" [KO]. In order to link people and documents globally, the KM team knew the solution would require a strong technical platform. KO uses the technology to combine social networking and document management to meet the business objectives of the firm.

The document management tool contains up-to-date processes, procedures and data to ensure that all employees use correct information. In addition, KO includes people profiles and discussion forums to encourage people-to-people connections.

The home page of KO features a news story that is updated twice a week, a member spotlight (the most recently updated member profile), and other featured content. In addition, the home page takes employees to the two most commonly used features of KO: Knowledge Communities (or Communities of Practice) and the global knowledge search function.

Knowledge Communities

Fluor recognized the need to align the platform to the company's existing social structure; therefore, they established knowledge communities around the existing functional and business lines. In 1999 they deployed two communities as a test run. After the successful implementation of these communities, Fluor quickly added other communities. By 2000 they had 32 communities and 4,000 members enrolled in KO. Membership grew rapidly and as of March 2008 there were over 26,000 members and 43 communities. The knowledge communities include everything from functional lines (i.e. Civil, Electrical) to business needs (i.e. Strategy, Business Intelligence).

Similar to KO, each community has a homepage. This can feature news stories, links to other news sites, knowledge objects (documented practices, guidelines, etc.), and featured content. In addition, the homepage contains community information with community-specific help, a list of the community's leaders and Subject Matter Experts (SME) with contact information, and orientation material. It also provides links to the community's discussion forums, community members, calendar and a search function.

Searches

One of the most commonly used features within KO is the "Search" feature. After searching for a subject, the employee may chose to view "All Results", "Knowledge" (knowledge objects), "K-Packs" (packs of knowledge grouped together), "People" (SME or people with the subject in their profile), "Forum", "News", or "Resources". In accordance with its mission to link people with people, each knowledge object or forum discussion lists the contributor and provides a link to their profile. The profile link enables the searcher to both evaluate the response by looking at the knowledge provider's experience and past projects and contact the person for additional information. In addition, search results are sorted by relevance. This means that the results are scanned for the number of times the keyword appears in a document, the location it appears (such as the title), and the form of knowledge (forum, etc.).

Forums

Although Fluor encourages "Searching First", employees can start a discussion forum within their communities by "Asking a Question". To start the discussion forum, they add the title, question, context and required response date. These questions are sent automatically to the inbox of community subscribers, including the community leaders and SME. The email contains a link to the forum and to the responses for ease of use.

THE EMBEDMENT OF FLUOR'S SYSTEM

KM was originally a strategic management initiative introduced by top management. Luckily, this gave the program the attention and support of leadership within the firm. The company funded the development of tools and dedicated a team to oversee the

program and implementation. At the beginning of the KM initiative, Fluor was focused on creating a system to capitalize on and access the firm's collective knowledge around the globe. They customized the tool to align it to their business and focused on linking people globally within existing Fluor communities. After the platform was created, they shifted their attention to enrolling employees and producing communities that added value to the business. This shift is often where KM initiatives fail to deliver desired results.

Obtaining Employee Participation

In order to educate its employees and achieve the necessary critical mass, the knowledge management team realized that it needed global buy-in from the employees around the world. The team focused on making the program a global initiative, emphasizing the benefits that all Fluor employees could receive, regardless of location. To underscore this, they chose to conduct 24-hour community launches in order to call each office location on their own time zone.

Once employees were aware of the system and the communities, the team focused on getting them enrolled and using the system. Originally, the team planned to offer incentives to employees who used the system on a point basis, for instance, if you used a knowledge object or submitted a knowledge object; you would receive a point for various prizes. Fluor ultimately decided against the strategy as it was thought to encourage "junk" and today they are happy they made the decision. As one employee commented, *"management by tokens doesn't work"*.

Instead, they chose to integrate the program into employee's daily lives at Fluor. They placed resources that employees needed to access on the system. They focused on showing the employees the benefits KO could provide on a daily basis, highlighting that the tool developed enabled them to locate solutions quickly. In addition to educating existing employees, they made KO a key feature of new hire orientation to engage new employees from the start.

Global communications, including emails and newsletters, played a key role in promoting the benefits of KO. They started an annual "Knowvember Campaign" in 2002 to promote knowledge sharing behaviors by increasing awareness of the program and recognizing outstanding members within the knowledge communities. For instance, the KM "Pacesetter" Program awards employees through peer recognition. Similar to rankings of buyers and sellers on Amazon, these selected employees receive a "Pacesetter star" on their KO profile for each year they receive the award. The KM team believes that the peer-to-peer recognition that this program is the best way to promote KO. In prior KM efforts like Xerox's acclaimed Eureka project, this kind of status recognition accorded to members of a "natural community" has been found to be equally or more effective than financial incentives for employees to formalize and share their knowledge (Moore 1999).

The campaign also gathers and shares "Success Stories" of the specific ways employees (and the company) have benefited from using KO. For instance, in one story, an employee asked a question regarding a leaking fired heater transfer line. The leak was costing approximately US $120,000 per day and time was of the essence to obtain a solution. Without the expertise available locally, he posted a discussion forum topic to the piping community and within 2 days received responses from Houston, Haarlem and New Delhi providing the answers needed to fix the plant.

Over the years, KO grew from 4,000 employees in 2000 to over 25,000 members today. Fluor's KM team recruited new members through three primary means: the directive of global management to establish communities and encourage knowledge sharing expectations; the education of employees through global launches, new hire orientation and Knowvember campaigns; and by highlighting the benefits of the program through success stories.

Producing Communities

The Knowledge Communities are the primary location for people with similar functions or business objectives to capture, share, improve and apply their collective knowledge. Fluor chose to organize around the "natural communities," that already existed. The communities are central to KO; therefore, the first challenge was to get the communities deployed so that communication within these communities would be online.

Fluor has a stringent process for deploying a community. The community leadership must prepare a charter and undergo a series of readiness assessment meetings with the KM Team. Each community must prove that they have an existing network of people, available leaders, executive support and resources. In addition, they must have business objectives that would benefit from the use of KO. The preparation for community deployment can take 6 months to complete. As one member said:

> *"We only deploy knowledge communities when there is a strong business justification and committed people resources.… The KM team will push back on the community to ensure that they have identifiable business objectives that will add value to Fluor."*

Fluor helps the community to identify the most critical knowledge that they need. Originally, the KM team provided the communities with lists of types of knowledge and asked the communities to identify ***all*** of the types of knowledge they would need. They learned that too many types of knowledge and choices for navigating create barriers as it confuses users searching for knowledge. Now they push the community to identify the ***minimum*** amount of knowledge types/categories that the community needs. They also help them create a plan to collect data and eliminate redundant knowledge databases. They ask the leaders to identify the content that belongs within the community and where it currently resides. They then eliminate all of the old information and place the up-to-date knowledge on the system. This not only helps Fluor ensure that employees are using the latest, up-to-date system, but it also forces individuals to familiarize themselves with KO and use it as the primary source of their information.

In order to launch a community, all critical and available content must be uploaded. The community is then ready for deployment with live, up-to-date knowledge. The KM team has a simple philosophy:

> *"We do not open the store until our shelves are fully stocked with fresh information".*

Adding Value through Embedment

Although Fluor continues to educate employees on the benefits of KO, the goal has shifted from obtaining employee participation and establishing communities to adding value for the company. This was always the original goal; however, the team

"needed to get a critical mass [of participants] who understood Knowledge Management before we could get to that point".

For instance, judging the "Success Stories" has changed over the years. One employee commented that they are now much more critical of the stories they judge. What was once a great story is now commonplace. They are now looking for additional value that was received through the success story. As an example, a recently awarded knowledge sharing story resulted in the elimination of a salt bed dryer, which saved the client over $1 Million Euros and resulted in new work-orders between the client and Fluor.

In order to add value, Fluor had to ensure that the communities were meeting their objectives. The Fluor KM team works with the community leaders on a regular basis to maintain a level of consistency, keep the front page updated and steward the content. They make sure that each knowledge item is only uploaded once—others can link to this information but not repost it. In addition, every piece of knowledge content has a review and expiration date to maintain accuracy. Finally, the KM team uses community audits to ensure community performance. As one executive commented:

"Other companies just stop when the community is launched. We don't stop at that point. We set up performance objectives…There is not a lot of breathing room after they launch before the community hears from us."

Due to its success, KO has also become a platform to push other initiatives within the organization. For instance, when distributing work across offices was the exception, they launched a "workshare" community. Today, worksharing is the standard way Fluor operates; the "Workshare" community has disbanded and the content was moved into the individual functional and business communities. As one employee commented:

"We are now using KO to launch other company objectives. KO is so popular that other communities within Fluor want to use it to update staff on other events. It really is a statement of how engrained the knowledge community has become within the organization."

Fluor's KM program has become embedded within the overall Fluor culture. Once a management directive, the program is much more of an employee driven initiative as more people use and gain value from KO. The embedment of the program can be seen via the changing use of the system (enrollment to meeting business objectives), changes witnessed in judging the knowledge stories (answering a question to providing added value), and the increased participation in the program. For many within Fluor, KO has become a taken-for-granted means to get their work done. For example, one employee commented that people are asking questions within the forum and getting responses from within the same office. In one case, a person posted a question and received an answer from a colleague three desks away.

UNPACKING THE BLACK BOX: CRITICAL SUCCESS FACTORS

Recognizing the failure of many KM programs, this paper now analyzes the factors that contributed to the ongoing use of the Fluor program. During the data analysis, 4 overarching themes became prevalent, including the alignment of the program with Fluor's culture, consistency and maintenance of the program, social influence factors, and external causes that together enabled the embedment of the program into culture at Fluor.

Alignment of the program with Fluor's Culture

Many employees commented that the system was easy to use because it was aligned to the existing Fluor culture. The knowledge communities were drawn from existing functional and business lines within Fluor. Because the communities already existed, the platform was used as a ***tool*** to ask and answer questions and establish even stronger connections between people. In other words, it was used primarily as a tool to improve the existing communities and not to create new communities. In addition, many of the processes had already existed within the overall Fluor community, such as the audit process. Use of these existing tools helped to ease employee's familiarity with the system and make it a natural and seamless fit within the company.

Maintenance of the Program

Employees feel confident with the responses and knowledge in the system. Within the forums, the combination of the written response with the link to the personal profile allows the employee to assess the validity of the response to their specific situation. In addition, the required review dates for knowledge and community audits provide additional measures to ensure up-to-date and non-duplicated knowledge within the community and the firm. The elimination of other databases also helps to confirm that the latest knowledge and best practices are being used throughout the globe.

Social Influence Factors

One of the primary elements that continued to emerge from the data analysis was the importance of social influence factors. Social influence has been studied as a persuasive tool in marketing campaigns and the workforce. In his book, "Influence: The Psychology of Persuasion" (Cialdini 1993), and other articles, he identifies six "Weapons of Influence": reciprocation, commitment and consistency, social proof, authority, liking, and scarcity. Many of these "weapons" were identified as potential reasons why people used KO. But two in particular, "Commitment and Consistency" and "Liking" stood out.

Commitment and Consistency

"Commitment and Consistency", indicates that once people commit to a cause, they are more likely to continue to honor and sustain that commitment. Studies have shown that this is particularly true if people have voluntarily stated their commitment either verbally or in writing (Cialdini 1993; Cioffi and Garner 1996). Although it may not have been intentional, Fluor's use of the "Community Franchise" concept and the "Pacesetter" awards encouraged this level of commitment and consistency. The process of creating and deploying a community requires a considerable amount of effort and time. In addition, the community leaders and knowledge managers are required to commit to keeping the material up-to-date and remaining active within the community. In order to ensure that they are consistent with these earlier commitments and to get value out of the system they worked so hard to create, most chose to remain actively engaged in the community. The "Pacesetter" awards also encourage this consistency. Previously nominated or awarded members feel the need to live up to expectations for the award.

Liking

People are more easily persuaded by people they like. By observing the implementation and auditing of the communities, the KM team discovered a direct correlation between the community leaders and the performance of the community.

The involvement and enthusiasm of the leader and SME's were identified as critical factors; and the ongoing level of participation of the leaders is now examined during the audit:

"You will often find that the whole community will be performing based on the commitment and involvement of the leader."

In some cases, Fluor decides to replace a leader, identifying a replacement from a pool of enthusiastic, well-respected and liked candidates. This has helped revamp underperforming communities.

Other Social Influence Factors

The other "weapons" identified by Cialdini were also important to the development of KM within Fluor. *Social Proof* was critical. People will often follow a trend and conform to the behaviors of others. Fluor needed to obtain a critical mass of users onto the system for others to follow. In addition, *Reciprocation* is often involved in sharing knowledge with colleagues. Sharing knowledge takes time; however, the majority of people feel a natural indebtedness that comes from receiving help. If people receive help from KO, they often wish to reciprocate and provide responses to others questions.

External Influencing Factors

The establishment of KO coincided with the use of external platforms, such as Google, and a changing strategy towards work execution that helped to encourage the use of technology for handling exceptions (Galbraith 1972) — i.e., for answering questions that arise in the course of attempting to complete tasks. One employee commented that Fluor purposefully designed the search tool to be similar to Google because Google had already trained people to search for information. In addition, networking sites such as Facebook have made people more comfortable interacting on web forums. As one employee stated: "*KO makes the company a bit smaller for me".* The convergence of external factors with the development of a program aligned to the company's culture that focuses on maintenance, value, consistency and social influence has resulted in an award-winning, embedded program within Fluor.

CONCLUSION AND PRACTICAL IMPLICATIONS

This study uncovers critical success factors enabling a KM initiative to succeed and become embedded within an organization over time. Although there is great interest in KM, the relative infancy of programs in use within the AEC sector has left a gap regarding how these programs can become embedded within a company's practices. Through a qualitative case study, we uncovered factors that appear critical to the program's success. The combination of management directive, communication of the benefits of the system, and a changing work strategy encouraged employees to begin using KO. These findings are in line with previous research that identified the demonstration of benefits, obtaining employee participation and the use of a corporate mandate (Chinowsky and Carrillo 2007; Fong and Chu 2006). Furthermore, we examine the factors encouraging the continued use of the program. These include the alignment of the program with the existing Fluor culture, the consistent and continued maintenance of the program, social influence factors and a changing external environment.

Companies trying to implement KM programs and initiatives today can gain valuable insights from this study. Instead of purchasing an "off the shelf solution",

businesses should consider their specific company culture and create a strategy aligned to their practice and existing networks. In addition, they should identify a set of natural communities within the company, and choose leaders who exemplify knowledge sharing behaviors and who are well-liked members of those communities to encourage participation. Finally, companies need to realize that KM is not something that can be "plugged in" and left to run itself. It is an ongoing, continuous program that involves the commitment of staff time and effort to ensure that communities are performing and adding value and that the knowledge is up-to-date.

Past research, such as a study conducted by Hansen and colleagues has identified two distinct strategies for KM solutions: *codification* and *personalization* (Hansen et al. 1999). Codification revolves heavily around the use of technology tools for connecting people to reusable, explicit knowledge. Personalization, on the other hand, relies primarily on social processes to share tacit knowledge. Companies choosing a strategy thus invest more heavily in IT if they choose the codification strategy while those emphasizing personalization invest more moderately in IT, choosing to emphasize personal interaction (Hansen et al. 1999). This case study has shown that heavy investment in IT can also facilitate personal connections, enabling employees to respond quickly to questions from colleagues around the world. As many employees noted during the interviews, this often required additional interaction and communication to provide needed context and the more "tacit" knowledge; however, the IT software enabled them to identify the appropriate people rapidly, reducing the time required to determine an appropriate solution for a given problem. Additional research can expand these findings to determine the extent to which IT centered approaches can follow a personalization strategy and whether "people-centered" and "IT-centered" KM solutions can overlap.

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Using Lean Theory To Identify Waste Associated With Information Exchanges On A Building Project

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Abstract: Building Information Modeling (BIM) provides a means for owners, designers, contractors, and operators to generate, organize and use detailed information throughout a project lifecycle. When properly implemented, these models can improve the efficiency of designs, allow for better feedback from project participants, and improve the accuracy and effectiveness for performing future construction tasks. An important aspect to the success of BIM is the process in which information is exchanged. Information should be both accessible and usable when required. This paper serves to identify categories of information exchange (IE) waste on a building project through the application of lean theory. Using this methodology, a pilot study was performed on a laboratory facility being constructed on The Pennsylvania State University campus. The results determined that lean theory can be applied and adapted to effectively determine IE waste. Future work includes calculating the cost associated with this waste, and converting the waste into an efficient information exchange process.

Key words: Building Information Modeling, BIM, Information Management, Lean Thinking

Introduction

The U.S. construction industry is currently going through a large transformation to improve efficiency. An important factor in improving construction efficiency is the emergence of Building Information Modeling (BIM) technology. The National Building Information Modeling Standards (NBIMS) Committee defines BIM as "*a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis*

for decisions during its life-cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder (NIBS, 2007)." For Building Information Modeling to be an effective tool, all parties involved must work together towards a common goal to produce an accurate representation of a building project including information that is necessary to operate the facility (see Figure 1). However, many owners and project teams are struggling with defining the appropriate level of modeling to perform on a project based on the current state of practice and future information needs. This has led to a very interesting agenda focused on the collaboration between the project team members, such as Owner, Architect, Engineers, Contractors, and Facility Manager in the development of a BIM Project Execution Plan.

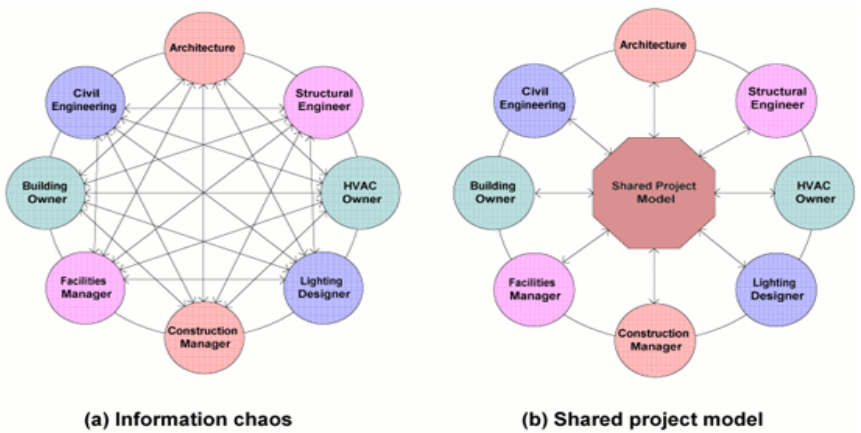


Fig. 1. BIM Concept – Eliminating Information Chaos (IAI, 2009)

Project Execution Planning for BIM

BIM Project Execution Planning is "a process performed by a project team to design the execution strategy for implementing BIM on the project. The final product of the execution planning process is a documented BIM Project Execution Plan (CIC, 2009)." In order to maximize the effectiveness of BIM, the execution plan should be designed in the early stages of a project and focus on the decisions required to define the scope of BIM implementation on the project, identify process impacts of using BIM, define the team characteristics needed to achieve the modeling, and quantify the value proposition for the appropriate level of modeling at the various stages in the project lifecycle.

During the development of a BIM Project Execution Plan, four steps should be followed: 1) Identify BIM Goals and Uses; 2) Design the BIM Project Execution

Process; 3) Develop Information Exchanges; and 4) Define Supporting Infrastructure for BIM Implementation (CIC, 2009). These steps, depicted in Fig. 2, have been developed by the CIC Research Group through the BIM Execution Planning Research Project. Prior to implementing BIM, the project team should identify the appropriate tasks that the team would like to perform using BIM. This analysis of BIM Uses should be focused initially on the outcomes desired by the overall process. Therefore, the team should start with the Operations phase, and identify the priority for each of the BIM Uses on the project (High, Medium or Low priority), and then move through the project phases in reverse order (Operations, Construction, Design and Planning). This perspective of 'starting with the end in mind' will identify the downstream desired uses of BIM which should be supported by earlier processes in the lifecycle of the project.

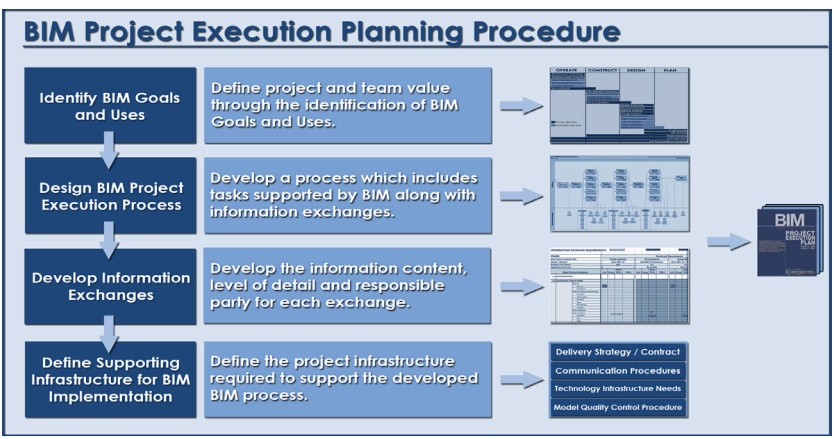


Fig. 2. BIM Project Execution Planning Procedure (CIC, 2009)

Research Methods

The focal point of step three for the aforementioned procedure is to development an effective information exchange (IE) process which the project team can use to add value to downstream BIM Uses. In the development of the IE process, the first step was to review and compare any ongoing project with a similar approach. Next, the information exchange process should add value to downstream BIM users. According to lean principles, adding value means eliminating waste (Womack, 2003) Therefore, the goal of this paper is to identify the categories for waste associated with the information exchange process. The following research steps were conducted to develop the concepts addressed in this paper:

1. Identify categories of waste through a content analysis of lean theory literature;
2. Conceptually map the categories of waste to inefficiencies in the information

exchange process; and
3. Perform a pilot analysis of a case study project to determine the actual waste that occurred through the information exchange between Design and Construction teams.

The case study results were gathered through the participation in meetings and interviews with project participants. Research team members attended each of the following meetings to evaluate the information exchange process: BIM Execution Planning meeting, Pre-Coordination meeting, four 3D Coordination meetings, and a 4D schedule review meeting. In addition to meetings, the project manager responsible for BIM implementation was interviewed using the breakdown of information exchange waste categories in this document. During the semi-structured interview, the lean concepts were described in terms of information exchange, and the interviewee identified waste that pertains to each topic area. This structure was used to determine the effectiveness of lean theory as it pertains to the IE process.

The Information Exchange Process

One of the largest challenges of implementing Building Information Modeling on a project is the transfer of information between disciplines (buidlingSMART Norway, 2009). To improve the effectiveness of BIM, information required should be both accessible and usable when needed. This is the goal of the Information Delivery Manuals (IDMs) being produced by the buildingSMART International Alliance for Interoperability (IAI). According to the IAI, an IDM will specify (buidlingSMART Norway, 2009):

- Where a process fits and why it is relevant
- Who are the actors creating, consuming, and benefitting from the information
- What is the information created and consumed
- How the information should be supported by software solutions

Although the concept of the IDMs will greatly benefit BIM software developers and ultimately project team members, it is difficult to standardize the information exchange process for unique project implementation processes at the project level. Each project team members uses different means and methods when implementing BIM. The goal of the BIM Project Execution Plan is for the information exchange process to be tailored to fit each project team member's needs and capabilities. Therefore, the development of the information exchange process should focus on the value stream associated with the transfer of models.

Applying Lean Theory to Information Exchange

Lean Theory was developed by individuals that would not settle for "How things were always done." They questioned each method of production to invent a better way to manufacture a product: lowering inventory and moving decision making to production workers (Womack, 1990). Over the years, these theories have been applied successful across many disciplines. For example, Microsoft used lean theory to balance the

interaction between operations and managers by standardizing practices and centralizing information (Herbold, 2002) When appropriately applied, lean thinking is a well-tested and well understood platform upon which to build an effective information exchange process.

Taiichi Ohno, the mastermind of the Toyota Production System, defined several areas of manufacturing waste (Ohno, 1988). Table 1 is a summary of seven types of waste along with a definition that pertains to production systems. According to Ohno, overproduction means to produce sooner, faster or in greater quantities than the absolute customer demand. When applied to information exchange overproduction occurs when the author includes additional information that is not needed for any downstream users. This leads to end users having to: 1) delete unnecessary components / information, 2) group and sort elements, and 3) manipulate large files.

Table 1. Seven Types of Manufacturing Waste (Ohno, 1988)

Production System Waste	Definition
1. Overproduction	To produce sooner, faster or in greater quantities than the absolute customer demand
2. Inventory	Any raw material, work in progress (WIP) or finished goods which are not having value added to them
3. Extra Processing Steps	Processing beyond the standard required by the customer
4. Motion	Individuals move more than is necessary for the process to be completed
5. Defects	A component which the customer would deem unacceptable to pass the quality standard
6. Waiting	People or parts that wait for a work cycle to be completed
7. Transportation	Unnecessary movement of parts between processes

In table 2 the seven types of waste are translated to define information exchange waste. This breakdown of waste was used to identify the waste associated with the transfer of information on a case study project at Penn State.

Table 2. Seven Types of Waste adapted for the Information Exchange Process

Production System Waste	Information Exchange Translation
1. Overproduction	More information than required by BIM users Revisions to Model after release
2. Inventory	Early delivery of information Push instead of Pull – take what is given approach
3. Extra Processing Steps	Producing more detail than required by users
4. Motion	More file transfers than necessary Not placing the model in a common location
5. Defects	Model inaccuracy / Incorrect information
6. Waiting	Late delivery of information
7. Transportation	Inoperable hand-off of information - file type & version

Case Study Results

The Pennsylvania State University is currently constructing a large laboratory science facility. When the project was in the schematic design phase, the owner and design team decided to implement BIM, therefore the architect, structural engineer and MEP engineer were contracted to develop 3D information models for the design. Using a CM Agency delivery method, the contractor was brought onboard during design development with intensions to use the design team's model for 3D coordination and 4D planning (a 3D model with a time-based simulation).

In terms of the information exchange process, the design team produced an element structure breakdown of the components in the model including: Structural, Mechanical Equipment, Exterior Façade, Interior Walls, and Ceilings. The level of detail was determined by the design team, and was delivered to the contractor as an Autodesk Revit model via an ftp site. The results of the actual waste which occurred through the information exchange between the design team and construction team on the case study are shown in Table 3. These results are the product of meeting evaluations and interviews of project team members.

Table 3. Seven Types of Waste related to the IE for the Case Study Project

Production System Waste	Description	Waste
1. Overproduction	Furniture and Electrical Outlets were modeled	Delete additional items
	Building not broken into areas	Break-up model
2. Inventory	Push rather than Pull – use what was provided	Model whatever is needed and not included (ceilings)
	Several ceilings were not drawn	
3. Extra Processing	Additional detail in lab rooms for space studies	Remove detail
4. Motion	Files were made available in a central location	None
5. Defects	Wall type was not confirmed	Model Validation
	All walls were modeled to under-slab	Reduce height of some walls
6. Waiting	Information for 4D Model should have been delivered earlier	Time lost due to delivery
7. Transportation	Revit –Navisworks; Revit–Synchro	None

In detail, overproduction occurred on the project because the design team modeled the furniture and electrical outlets. Although, these items may be considered valuable for a downstream use of BIM, this led to the construction team having to delete all furniture and electrical outlets because they were not needed in the coordination process. Also, the floors in the model were not divided for planning procedures. the contractor spent time and resources reorganizing the design team model in quadrants for the 4D model, and to simplify the coordination process. If this simplification was not done, the file size would have slowed down meeting productivity because of sluggish model manipulation. According to the project manager responsible for BIM on the construction team the "most difficult task was breaking up the model into quadrants. Any revisions also needed to be broken up – and it was very time consuming."

Conclusions and Future Work

This paper presented a method for evaluating the waste associated with information exchange on building projects. Specifically, lean theory was utilized to identify seven areas of waste that relate to the IE process. According to the project team on the case study project, when this method was applied to the project, the seven areas of waste led to an accurate identification of the problems that arose from the information exchange process. When applied to information management, these concepts provide a broad framework for an effective process for standardization. To improve information exchange between project team members, it is essential that the non-value added processes are eliminated.

The overarching goal for this research is to provide a standardized method in which

future studies can more precisely measure the waste associated with the information exchange process. Although this paper provides an initial pilot study aimed toward this goal, additional research needs to be conducted to develop a standardized process. Potential research could include the identification and analysis of the cost of the waste by allocating time and resources to each non-value added aspect of information exchange. This could provide additional insight to the industry related to high potential value added improvements to the IE process, and could also document the scale of the economic benefits that may be achieved by the industry. For example, currently the most frequently cited study related to the scale of the challenges related to inefficient interoperability is the important study performed at NIST (Gallihar et al. 2004) which projected an overall industry cost of $15.8 billion in 2002 due to poor interoperability. This counterfactual analysis study provides significant value toward identifying the scale of the challenges related to interoperability, but further, more detailed project analyses can provide additional insight into the root causes for the waste in the process and identify more accurate means of measuring this waste at a project level. To extrapolate any future findings, case studies with different project characteristics would need to be evaluated to ensure the process can be standardized.

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A GAME THEORETIC APPROACH TO UNDERSTAND OPPORTUNISTIC BEHAVIOR IN PROJECT NETWORK SUBCONTRACTOR SELECTION

H. I. Unsal[1] and J. E. Taylor[2]

Abstract
The construction industry has been shown to suffer from poor productivity performance and a lack of innovation. One area where substantial improvement potential lays is subcontractor selection. Subcontractor selection strategies employed by contractors can significantly impact the success of individual organizations and the overall efficiency of the market. Long-term partnerships are promoted by experts from both academia and industry as a means of achieving improved project network productivity; however, opportunistic bidding behavior that may accompany its implementation has been largely ignored. We conducted a bidding experiment to simulate whether opportunistic behavior would emerge in the subcontracting process. The purpose was to observe whether the hold-up problem occurs as previous simulation research focused on game theory indicates. The empirical data was collected through an internet based interactive bidding simulation developed by the investigators. The findings contribute to the project management literature by empirically demonstrating how opportunistic behavior occurs in the bidding process and how it leads to different partner selection strategies by contractors and different market outcomes in terms of efficiency.

Introduction

Research that links subcontracting strategy to improved performance and faster innovation adaptation is abundant (Kumaraswamy and Matthews 2000; Russell et al. 1990; Holt 1998). Many researchers suggest that through a collaborative approach, firms can minimize their transaction costs and maximize inter-organizational learning. They argue that this will lead to higher productivity. In the 1990s this approach was investigated exhaustively under the term "partnering" (Chan et al. 2004). During this time period, the Construction Industry Institute (CII) prepared a report describing the benefits of and the barriers to partnering (CII 1991). Several

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case studies also found that partnering improved firm productivity and innovative capacity (DeVilbiss and Leonard 2000; Barlow 2000). Partnering can refer to project partnering where companies form an alliance for the duration of the project or long-term partnership where companies agree to work together over several projects. The focus of this paper is on long-term partnerships as these partnerships have a strong impact on the structure and efficiency of the industry overall.

A recent simulation study argued that in a more relationally stable environment where firms subcontract from fewer firms, the inter-organizational networks adapt to changes faster (Taylor et al. 2009). Relationally stable networks realized the benefits of innovation sooner. There appears to be a continuum where at one extreme is the pure market transaction and at the other extreme is long-term partnerships. The argument made by Taylor and colleagues (2009) would indicate that project networks get more efficient as they become more relationally stable. However, despite the benefits, not all construction networks eliminate the bidding process and employ long-term partnering strategies. One cause may be related to a fear of opportunistic behavior by partners in the project network. In this paper we seek to first ascertain whether opportunistic behavior will emerge in a project network over repeated bidding interactions and second to examine the impact this may have on overall market efficiency.

Background

The concept of opportunism in inter-organizational interactions originated from the work of Williamson (1975) and has since been central to discussions of inter-organizational collaboration. Strategy researchers adopt a transaction cost economics perspective to demonstrate the existence of opportunistic behavior potential in different industries, how it impacts the outcome of collaboration or the managerial decision making of the parties involved (Provan and Skinner 1989). Some provide contractual remedies for avoiding the threat hence providing a hope for more effective collaboration (Rogerson 1992). The definition of opportunistic behavior is made by Williamson (1975: p. 9). Williamson distinguishes the opportunism from hyper-rationality as the hyper-rational "economic man" is self-interest seeking whereas opportunistic behavior is "self-interest seeking with guile." Organizations are vulnerable to opportunistic behavior for two reasons. The bounded rationality of the agents combined with the uncertainty of future makes it impossible to write complete contracts that will cover every contingency. However uncertainty by itself would not be a problem if the resolution of the conflicts between parties was not costly. Firms would adapt the contract to the changing conditions and requirements of the transaction and eliminate the asymmetric bargaining power. However the cost of using the legal system to arbitrate disputes creates a zone for parties where they can take advantage of the situation.

Opportunistic behavior in the context of project networks drew attention from construction researchers as well. Chang and Ive (2007a) focused on the bargaining power that the contractor has over the client after the project initiation and discussed the opportunistic behavior potential that emerges as the design is modified throughout the project. If the client wants to discontinue working with a contractor in case of any dispute, they are left with two options: terminate the project and try to get a salvage

value out of the completed portion or switch the contractor. Either of these two options is costly which gives the contractor bargaining power. Lo et al. (2007) examined the impact of opportunistic bidding behavior in construction markets. They mainly focused on the fact that the contractors submit abnormally low bids and try to increase their margin by cutting corners or finding loopholes in the contract in order to charge more for change orders. The enabler of the opportunistic behavior for both examples is the post-contractual dependency of the client on contractor.

Dependency between firms is caused by asset specific investments which by definition lose value significantly if not usable for their intended purpose (Williamson, 1975). The asymmetric bargaining power caused by the asset-specific investment will create what the transaction cost economics (TCE) literature refers to as the "hold-up problem." In a case study of the Chunnel project, Chang and Ive (2007b) demonstrated the existence of the hold-up problem in the presence of process specificity which operates similarly to asset specificity.

Construction researchers have recognized the significance of inter-firm dependency and the resultant hold-up problem in a single contractual agreement. However the dependency and the potential of the hold-up in a long-term collaboration where repetitive transactions occur are largely ignored. By long-term collaboration we refer to the quasi-firm governance structure defined by Eccles (1981) where the buyer purchases the service from a limited pool of suppliers as opposed to the committed partnership where the competition between suppliers is minimized.

Continuous collaboration between firms will minimize transaction costs and maximize inter-organizational learning benefits. Firms prefer to work with a subcontractor with which they have experience not only because of the reputation effect but also because it will be less costly and risky (Miozzo and Dewick 2004). However, the potential rent that the client can receive if they contract with the same subcontractor in the next project is also the opportunity cost of not working with the same subcontractor if they decide to hire another subcontractor. This implies the existence of a switching cost from one subcontractor to another in between two transactions. By working with the same subcontractor for several projects, the client can inadvertently give the subcontractor bargaining power during the bidding process. Therefore another form of asset specificity, relational specificity, can exist.

If there is a benefit to continuous, relational collaboration, the subcontractor might realize the switching cost of the contractor and adjust their profit margin accordingly. Previous agent-based simulation has provided algebraic proof of the existence of relational hold-up in an oligopolistic market (Unsal and Taylor 2009). However in order to argue its existence and impact on the market, a further experimental study is needed. The first reason is that the actual behaviors of individuals usually differ from those predicted by game theory due to the rationality assumption. Secondly, unless the technical specification or geographical constraints of the companies limits the number of bidders in a contract, the bidding process in construction market resembles perfect competition. The pool of the bidders might be limited but there are usually numerous potential qualified bidders in the market. In this paper we replicate a market to show that opportunistic behavior exists in repetitive transactions under perfect competition if there is an incentive for continuous collaboration. We further investigate how opportunistic behavior, if it

exists, will impact the market efficiency and structure over time.

Methodology

We developed an interactive bidding game to create an artificial market. From the vast behavioral game theory literature it is known that decisions of individuals deviate from what Nash Equilibrium suggests (Nash 1951). Therefore an experimental study with human subjects has stronger validity than a simulation of individuals where each agent is assumed to be identical, behave rationally and have unlimited computational capacity. In fact, analytical game theory is often criticized because people do not think with equations and are not capable of making too many iterations (Camerer 2003). When people do limited iteration in a single game, they approach the Nash equilibrium when the game is repeated. So we designed the experiment as a repeated game in which the behavior of a large group impacts the decision of an individual. For this reason, we also encouraged participants to participate in several bidding games. This not only compensated for the limited iterative thinking but also allowed us to observe how the market evolved over time as participants became more experienced. Having participants receive feedback from the market over time, we expected to reach the Nash equilibrium that was identified by the earlier simulation work of Unsal and Taylor (2009).

Experimental design

Each participant was assigned one of the two roles: contractor (bid-taker) or subcontractor (bid-submitter.) Each bidding game was comprised of 10 successive projects. Each project was considered as a period. In each period, there were three stages. In the first stage the contractor requested bids from their pool of subcontractors. In the second, the subcontractors responded to the bid request by submitting a bid price. In the third stage, the contractors decided to which subcontractor they would award the bid. Each role had a unique objective function and cost structure. To ensure the motivation of the participants, the participants were compensated based on their relative financial success in the game compared to the other participants.

In each period, contractors completed projects and earned $200,000 in revenue. The 10 projects were assumed to be identical so revenue was constant for each project in the game. The contractors' objective was to maximize their profit by minimizing their cost. The following equation is the objective function of contractor:

$$Max\ \pi = \sum_{i=1}^{10} 200{,}000 - TCc_i - p_i$$

Where; π = total profit, TCc_i = total transaction costs for the contractor in period i, and p_i = the winning bid price of the period i.

The total transaction cost (TC) is the sum of three different types of transaction costs. One of the reasons why firms do not keep their pool of potential subcontractors infinitely large is that there is a cost associated with collecting and evaluating bids. There are also long term costs of working with a large pool of suppliers. Every time a contractor requests a bid and every time they evaluate a bid, the transaction costs of "bid request cost" and "bid evaluation cost" apply respectively. We assumed the cost

of a single bid request to be $1,000 and the cost of a single bid evaluation to be $3,000. A third type of transaction cost for the contractor represents the inter-organizational learning benefits. Firms decrease transaction costs that are associated with collaboration significantly as they gain experience working with each other. They create more effective solution methods to problems by developing inter-organizational routines, resolving conflicts more efficiently and decreasing monitoring costs. Also, as the partners become more familiar with each other the potential risk goes down. In the Unsal and Taylor (2009) simulation study this cost was referred to as the boundary cost. However for the participants to understand it better we referred to it as collaboration cost. The collaboration cost follows the learning curve that was defined by Wright (1936). The equation is as follows:

$$CC_{c,s} = CC_0 \times (n_{c,s})^{\log_2 \lambda}$$

Where; CC_0 = coll. cost of working with any firm for the first time, $n_{c,s}$ = number of projects that contractor c worked on with subcontractor s, and λ=learning rate.

Contractors are expected to employ the best subcontractor selection strategy in order to maximize their profits. A screenshot of a typical contractor user interface in the bidding game is included in Figure 1-1.

Subcontractors compete with each other by submitting bids to contractors. Their objective function is to maximize their profit by both minimizing costs and maximizing revenue. For any subcontractor s the objective function is:

$$Max\ \pi = \sum_{i=1}^{10} \left[\sum_{c=1}^{C} \left(p_{c,i} - c_{c,i}\right) \times I_c(winning) \right] - TCs_i$$

Where; $p_{c,i}$ = price that the subcontractor sent to contractor c in i^{th}period, $c_{c,i}$ = cost of the subcontractor if they get the project from contractor c in i^{th}period, $I_c(winning)$ = indicator that shows whether the contractor c awarded the bid to subcontractor, and TCs_i = the transaction cost of the subcontractor in period i.

The transaction cost for the subcontractor is the cost they spend on preparing the bid. Subcontractors will send bids as long as they think their bids are considered seriously. For this, if a contractor does not hire a subcontractor for several projects, the subcontractor will often stop sending bids. This is what can eliminate the price mechanism in industry. A buyer cannot get price information by requesting bids from every subcontractor. The transaction cost that represents this factor in the game is "bid preparation cost" which is applied if the subcontractor decides to submit bid to a contractor. The subcontractors can submit a bid even if one is not requested from them but then they have to compensate the contractor for their bid request and bid evaluation costs.

Assuming the contract is lump-sum, the subcontractors' profit is the difference between the revenue and the cost of the project to them. The cost is estimated internally based on the material and labor the subcontractor will spend on the tasks. To represent the changes in cost estimation between subcontractors the cost

of the work for subcontractor is determined randomly between $80,000 and $100,000. The subcontractors took into account their own cost values and the uncertainty about the opponent subcontractors' cost values when bidding. Subcontractors were allowed to bid below cost. However, they start with a set amount of money in their bank account and if the bank account goes below zero during the game they go bankrupt and are not allowed to continue. A screenshot of the subcontractor user interface is included in Figure 1-2. Information on the previous winners of each project and the collaboration costs are shared with all subcontractors and contractors.

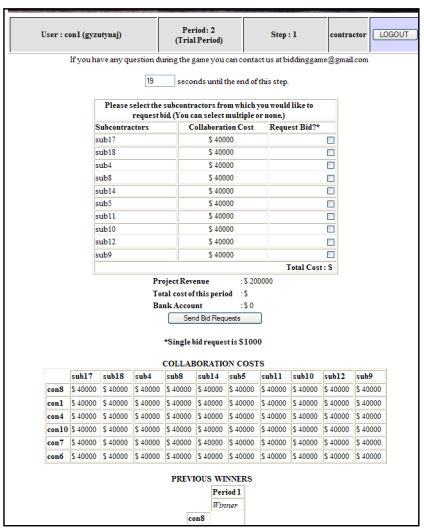


Figure 1-1 Contractor User Interface

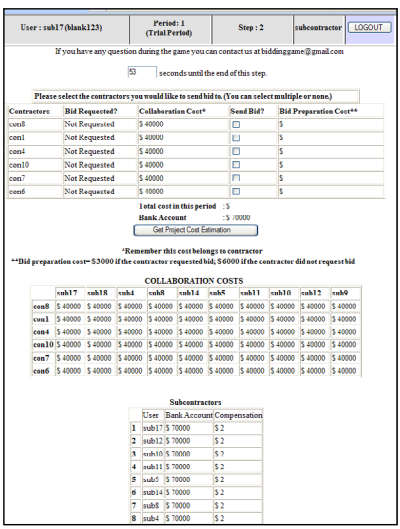


Figure 1-2 Subcontractor User Interface

Data Collection

The participants were recruited in the online workplace website Amazon Mechanical Turk (AMT). AMT has registered users all over world completing tasks that employers submit. The assignments, or as they refer them "Human Interface Tasks," usually consist of subtasks that require human intelligence that computer programs are unable to complete. The users interested in participating were directed to the game website and were asked to enter the bidding game virtual room and wait until the game started. The applicants were required to reside in U.S. in order to be able to participate. There was no prequalification criterion other than location. Each game had the capacity to hold 25 participants, 15 of which were subcontractors and the remaining of which were contractors. After participants joined the game 40-50% of them stayed and successfully participated in the game. The rest either changed their mind after joining the game or they had technical problems such as the browser not loading the game. Each participant was compensated with a minimum of $2 compensation plus a bonus based on their earnings in the game. This strategy was employed to increase the motivation of the players to succeed in the game. At the end

of each game the participants were asked to respond to a short questionnaire describing their strategy. The following section presents the data that was collected in 18 bidding game experiments.

Results

As contractors gain experience working with specific subcontractors their collaboration costs decrease. This makes the subcontractors who have experience with the contractor comparatively favorable to others. The first objective was to examine whether opportunistic behavior emerged as one or a few subcontractors gain a comparative productivity advantage compared to their rivals. Figure 2 includes the winning bid price of 18 games for each of the 10 projects. The solid line represents the average of the 18 games for each project. In the beginning of the collaboration, the average winning bid was very close to the expected cost of the subcontractors. However, as subcontractors won bids and realized they have a significant advantage over their rivals they began to submit higher bids that take more of the economic rents created by the inter-organizational learning. As a result the average winning bid in the 10th project was 22% higher than the average winning bid in the 1st project.

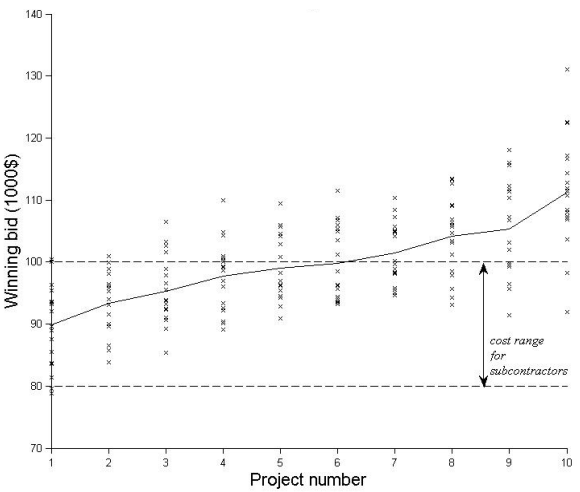


Figure 2 Average Winning Bid in Each Period

We found that opportunistic behavior did exist in the case where there were costs for contractors to switch to another subcontractor. However the discussion of how it emerges and how it impacts the efficiency of the market has further value. In the initial games when players were not as experienced, the common approach by the contractors was to request bids from several subcontractors and try to pick the one that provided the highest profit. Players on average soon realized that the strategy of sticking with one subcontractor minimizes the transaction costs, therefore maximizes profit. At this stage the subcontractors followed a cost-plus strategy so subcontractors who were fortunate enough to get low bids in the initial few rounds ended up as

winners of the game. However as the subcontractors got more experienced they realized that a loss in the first few rounds can be compensated by future earnings if they can lock in a contractor. As a consequence, the bids in the first rounds got abnormally low with the expectation of future benefits. This is similar to the case in the industry when subcontractors bid low to become a qualified supplier and earn future work. But when all participants in the game (or subcontractors in the industry) realize that this is the best strategy it becomes commonplace in the market. As opportunistic behavior becomes the only way to survive by subcontractors, the contractors begin to protect themselves by switching subcontractors from project to project in order to have an additional option or to make the subcontractor they are dominantly relying on aware that they can select other subcontractors for the work. Then the market is back to where it started with contractors selecting from a pool of 2-3 subcontractors. This is an example of how the market does the iteration on behalf of individuals for whom computational capacity is limited. If a group of inexperienced people can respond to a market and develop survival strategies in 18 games, it is reasonable to assume that industry professionals with years of experience will respond similarly in the existence of opportunism threat.

We were also interested in examining how opportunistic behavior, if it exists, would impact market efficiency. Drawing upon Williamson's work in transaction cost economics (1975), we represented the efficiency of the market with the amount of transaction costs spent on each project. Figure 3 shows how transaction costs in the market changed over time as participants became more experienced. The evolution of the market explains the change in the total transaction costs. The market reached an optimum point where all players realized the benefits of collaboration. However this was before the subcontractors realized that they can have an advantage by following an opportunistic strategy. Once the benefits of opportunism became common knowledge, the contractors' self-protection strategies led to their desire to increase competition by working with more subcontractors. The result is an inefficient market with a more fierce competition and higher bankruptcy rate.

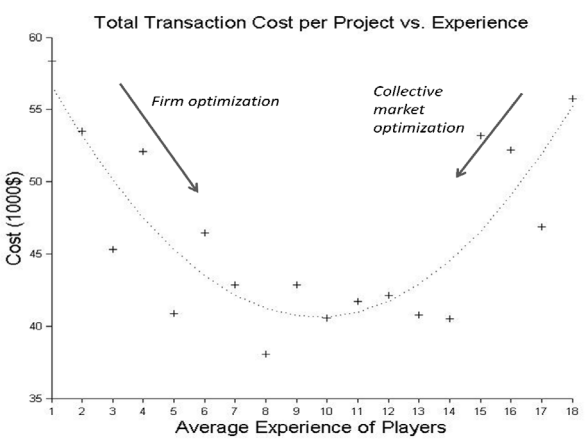


Figure 3 Evolution of Market Efficiency over Time

Discussion and Conclusion

Preventing opportunism is a more challenging problem than defining it. For a single project, the natural reaction for self-protection is to attempt to write more powerful contracts and facilitate conflict resolution processes. However, not only is this practically infeasible due to the complexity of construction projects but also, according to some researchers, limits the flexibility of the project (Chang and Ive 2007a). Boukendour (2007) proposed an innovative method of procurement where the clients are given the option to switch from lump-sum contract to cost-plus contract which alters the incentive system and limits the opportunistic behavior of the contractor. The case for repetitive projects is a bit more complicated. Writing contracts that will limit opportunistic behavior in repetitive transactions is extremely difficult if not impossible. While academicians and experts propose companies seek long-term partnerships the underlying assumption is that industry is at the left-most point of the curve in Figure 3. However the industry is more likely to have evolved to the right-most point of the same curve. Although it is true that the optimum efficiency of the market is where there are long-term partnerships, the methodology to reach the middle of the curve is different for those two points. The optimization by individual firms moves the market toward the right. This makes the left-most point an unstable one and therefore the shift of the market to the right is a natural consequence.

By simulating a bidding market where there are financial benefits for close collaboration, we showed that the opportunistic behavior does exist. We also showed that through many transactions the market iteratively evolves towards the Nash Equilibrium point. Near the equilibrium point, the contractors follow a self-protection strategy which increases the total transaction costs therefore decreases the efficiency of the market. Although it is not visible at the equilibrium point, the opportunistic behavior is the driving force behind the inefficient subcontracting behavior. We hope that the findings of this paper can shift some of the focus of subcontractor selection strategy literature from individual partnering cases to market level analyses. We can then explore the underlying dynamics in the market and demonstrate its effect in overall efficiency. We do not suggest firms become paranoid due to the threat of opportunistic behavior. However, we do suggest that the impact of the potential for opportunistic behavior on the overall market should be acknowledged and included in the discussions of collaboration and partnering in project networks.

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A Tool for Improving Construction Organizations' Innovation Capabilities

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ABSTRACT

Nearly 200 interviews and surveys collected by a Construction Industry Institute research indicate that innovation is valued within large engineering-procurement-construction (EPC) organizations but is hindered by organizational factors such as lack of resources allocated to innovation efforts; low risk tolerance; and a failure to establish innovation-enhancing processes. To enable EPC organizations to evaluate and improve their innovation capabilities, the team created an Innovation Maturity Model (IMM) that evaluates an organization in each of 61 innovation-related attributes. The IMM, which is based on the data collected and a review of relevant innovation literature, includes a macro-enabled spreadsheet that aggregates the individual survey data, identifies the ten attributes offering the greatest opportunity for improvement, and provides the recommendations for improving these ten attributes. The IMM was pilot tested using six large EPC organizations and will be available through the Web.

INTRODUCTION

Although the ability to innovate is considered to be a fundamental requirement for long-term business success in nearly all industries, the need for innovation has been undervalued within the industry that provides engineering and architectural design, construction procurement and construction services in the industrial, infrastructure and building construction markets (hereafter referred to as the "EPC industry"). In response to the need to enhance innovation, the Construction Industry Institute (CII) established a research team (RT 243) to "Explore and document the current levels of innovation in the E&C industry, identify opportunities for enhanced levels of

innovation; and best practices for E&C companies individually (and the industry collectively) to become more innovative." The research was co-sponsored and guided by the Charles Pankow Foundation (CPF). The joint CII/CPF research team actively performed research between November 2006 and August 2009. This paper summarizes the research team's methodology, findings and the tool it developed to enhance innovation within EPC organizations.

It is important that the reader keep in mind that every aspect of the research reflected the unique context underlying the research team. One key aspect of the research was the composition of the research team: four academics and eight industry professionals with between two and twenty years of industry experience, including two senior managers who were appointed as Co-Chairs. In other words, the research was a joint academic-industry effort, as is the expectation for all CII-funded research projects. Another key aspect was the objectives of the research: rather than contributing to the theoretical understanding of innovation held by academics, the research was directed to providing practitioners with knowledge and tools that offered immediate and practical value.

LITERATURE REVIEW

The team elected to begin the research process by reviewing the relevant literature on innovation and establishing seven specific research questions. The following paragraphs present the seven research questions and a very brief summary of the literature related to each question.

1. Is innovation perceived to lead to higher profit margins? Although researchers and practitioners have found that innovation is required for organizations to prosper or survive in competitive markets (Damanpour and Schneider 2006; Howell and Higgins 1990), one of the key findings of the literature search was that there has been no published research analyzing the relationship between EPC firms' investment in innovation and their financial performance. Findings establish an indirect link between investment in innovation and enhanced business performance. For example, LePatner (2007) found that construction's low investment in innovation has contributed to the EPC's very low growth in productivity since 1964 (25% compared to 250% for other industries).

2. How is innovation measured? Metrics for assessing the success and impact of an innovation have been identified and discussed in literature but practical application of these metrics is limited. Egbu (2001) and Tucker (2004) suggest tracking innovation success by measuring lagging indicators such as the percentage of profit/sale derived from the innovation. Dikmen et al. (2005) built upon these studies by identifying trailing indicators of innovation such as technological advancements, improvements in schedule, budget, and quality, and increased effectiveness of the firm.

3. What are the key perceived drivers of innovation? Toole (1998) suggests that the adoption of innovative products and processes can directly improve the

achievement of product and firm goals because they can decrease project cost and duration and increase the performance of the final structure or system. Dikmen et al. (2005) also points out that that innovation should be evaluated in terms of the overall value that results, which transcends products and service metrics. For example, innovation can lead to competitive advantage through improved firm reputation, easier work processes and improved ability to attract new employees (Slaughter 1998).

4. What are the key perceived barriers to innovation? Unfortunately, many organizations focus on optimizing the current value system rather than pursuing more radical, systemic improvements (Hamel 2006). Sawhney and Wolcott (2004) suggest the lack of innovation in EPC is not due to employees lacking innovative ideas but to a lack of mechanisms for implementing these ideas. According to LePatner (2007) EPC organizations' lack of economies of scale, lack of financial cushion and the process interdependency of many separate firms each trying to maximize individual profits hinder innovation.

5. What are the management characteristics that promote innovation? A recent study of innovation within homebuilding organizations identified management strategies that differentiate successful firms including: (1) motivated leaders, (2) a technology advocate within the firm, (3) stressing the importance of being creative and the first to use new products, and (4) using technology transfer programs (Koebel et al. 2004). One of the most impactful factors on innovation within organizations is the specific characteristics of project managers and supervisors themselves. Researchers have found that senior managers' tenure in position (Hambrick and Mason 1984; Huber et al. 1993), industry experience (Damanpour and Schneider 2006), age (Damanpour and Schneider 2006; Huber et al. 1993), gender (Sonfield et al. 2001; Stelter 2002), education (Hausman 2005; Lee et al. 2005), willingness and ability to manage conflicts (Hausman 2005) willingness to share control (Scott and Bruce 1994; Timmons and Spinelli 2004) highly influence the innovative capacity of an organization.

6. What are the project related characteristics that promote innovation? Success in the construction industry requires effective inter-organizational management. That is, construction projects often require collaboration among and management of diverse firms in order to achieve a common goal. Gambatese and Hallowell (In Press) identified specific project-related factors that promote co-innovation including Owner vision; funding from the Owner; contractor input during the design phase; overlap of the different project development phases; an innovation "champion" and entrepreneur; and co-location of the project team.

7. What are the elements of a successful innovation process? In the 1990's there were significant efforts to create process models for successful achievement of innovation within organizations (e.g., Abd El Halim and Haas 2004; Kangari and Miyatake 1997; Bernstein et al. 1998; Rogers 1995; Subramanian and Nilakanta 1996; Schroeder et al. 2000). Bernstein et al. (1998) identify four key steps: (1)

generalization or conceptualization of an idea; (2) development and production of the new technology; (3) transfer of knowledge; and (4) subsequent application to solving problems. These steps are similar to those identified by Kangari and Miyatake (1997) who found that the innovation process incorporates three major activities in the progression from new idea to implementation: envisioning new work strategies, designing the process, and implementing change.

METHODOLOGY

Another aspect of the research that reflected the unique context of the research team was the research methodology, which was pragmatic and designed by the team based on preliminary findings. The team planned, coordinated and analyzed much of its work through a dozen face to face meetings, approximately 50 conference calls, and hundreds of email conversations. Based on the findings from the literature review the team drafted an interview script and performed approximately twenty-five semi-structured interviews of EPC professionals using a convenience sample. This script was modified based on the feedback obtained through the interviews and converted to a survey. The written survey was initially completed by 46 members of the CII Board of Advisors at their Spring 2007 meeting.

The survey was subsequently converted into an online version and made available on www.surveymonkey.com. The approximately 110 EPC practitioners who completed the anonymous survey represented a convenience survey of CII members, CPF members, and a few alumni from the academic research team members' universities. Univariate and multivariate analysis was performed using SPSS and Excel. Analysis of the demographic data on the survey indicated the sample was fairly well stratified by market sector (commercial, process or infrastructure), geographic location across the U.S., and number of years in the EPC industry.

The results of the survey provided clear evidence that innovation was valued in most EPC organizations but attributes needed to effectively innovate was frequently missing. The research team found the attributes can be appropriate grouped into eight areas: Culture, Resources, Risk perspective, Customer focus, Learning, Collaboration, Leadership and Processes. It was clear from the interviews, surveys and team members' analysis of their own organizations that with regards to innovation, EPC managers don't know what they don't know—that is, they do not realize that weakness in two to three of the above areas can outweigh strengths in other areas. As such, the team decided to create a tool that could be used to evaluate an organization's innovation capabilities, identify weak areas, and suggest ways to strengthen weak areas. This tool was named the Innovation Maturity Model (IMM).

The IMM evaluation survey consisted of 61 Likert scale items, each associated with an important organizational attribute that facilitates innovation. The IMM also contained a brief set of recommendations on how to improve the attribute associated with one of the 61 statements. (See Table 1 for an example.) These recommendations reflected a synthesis of the literature the research team had reviewed as well as the

survey and interview data. The IMM evaluation survey and a macro-enabled spreadsheet that allows managers to aggregate their surveys and identify recommendations to improve their organizational attributes most hindering innovation can be downloaded from www.facstaff.bucknell.edu/ttoole/innovation.

Table 1: Example of an IMM Evaluation statement and the associated recommendation

Our organization expects individuals to share ideas through formal forums.	Continuous learning is essential for highly innovative organizations. One of the best ways to really learn about a subject is to prepare to explain or teach it. Companies can stimulate the participation of their employees in learning activities by engaging as many employees as possible in defining and optimizing processes and sub-processes. Tracking the new techniques and processes learned by employees during the annual performance review and encouraging employees to prepare and deliver presentations on new ideas and approaches in non-threatening environments can be highly effective. Firms may also want to establish a "process improvement suggestion" program and track the number of suggestions generated by various employee groups.

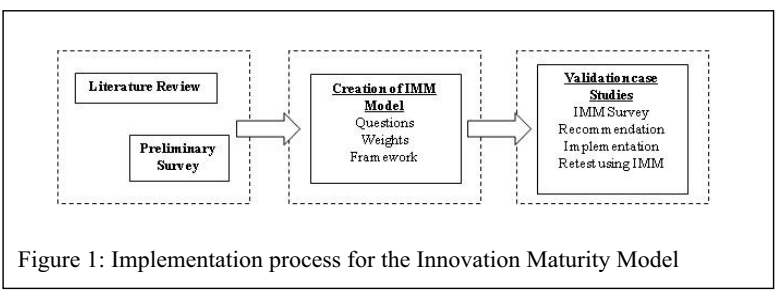


Figure 1: Implementation process for the Innovation Maturity Model

Figure 1 summarizes the process used to create and validate the IMM. The IMM was presented at the 2008 CII annual conference with a call for volunteer organizations to help validate and refine of the tool by pilot testing it. Five of the approximately twenty firms who volunteered were requested to participate as case study firms. In addition, one CPF member company identified by the CPF Board was requested to participate. The identities of the six organizations that participated in the case study process are being kept confidential due to the sensitive nature of the data recorded for each firm. Each case study firm was asked to perform the following actions:

1. have a small set of employees review the format and overall content of the IMM evaluation questions and the specific wording of each question and provide the team with constructive criticism;
2. have a larger set of employees (25-100) complete the IMM evaluation tool, adding demographic questions as appropriate to allow the organization to identify statistically significant differences in data from different groups within the organization (such as supervisory versus non-supervisory personnel, geographic locations, etc.);
3. allow the research team to analyze the results and provide the organization with recommendations for improving the organizational characteristics that

offered the most potential for improving the organization's innovation potential;
4. implement the recommendations within at least one portion of the organization and share the outcomes with the research team; and
5. provide any feedback regarding the effectiveness of the IMM.

The number of completed evaluation surveys in each organization ranged from 20 to 90 responses. The selection of the respondents was left up to the organization. In each case, the organizations selected a segment of the organization to focus upon, although this focus was different in each organization. Once the surveys were completed, the following four-step process was utilized for each organization:

1. The results were analyzed to determine the top ten attributes with the highest potential for innovation improvement within the organization. RT 243 determined an individual weighting factor for each of the 61 IMM questions that reflected the relative importance of each item based on the literature review and surveys. The Innovation Potential is calculated for each question by subtracting the average score (e.g., 3.6) for the organization from the maximum potential (5) and then multiplying this result by the weighting factor.
2. The detailed findings and specific recommendations for improvement in the ten areas with greatest innovation potential were reported to the case study liaisons.
3. After agreeing on the specific recommendations to adopt, the implementation process was placed under the direction of the individual companies. The RT 243 team provided advice when requested but ensured the implementation remained independent.
4. The case study liaisons were contacted several months later to determine what progress had been made on the suggested implementations. In one case, the same group of respondents as well as a new group of employees were asked to complete the IMM survey several months later to measure innovation-related changes in the organization since the implementation.

FINDINGS

The survey data combined with interview notes provided strong empirical support for the overall finding alluded to in the previous section and to the general finding that typical EPC organizations value innovation but lack key organizational attributes necessary for sustained, organization-wide innovation. The key attributes for successful innovation are summarized below. The eight areas that underlie the IMM are underlined. A very small portion of the data analysis is presented to illustrate the points due to space limitations but the full analysis can be downloaded from www.facstaff.bucknell.edu/ttoole/innovation/innovationsurveyresults.docx.

Risk Perspective. While typical EPC firms have a culture that generally affirms the importance of innovation, managers apparently enable innovation only on a project basis. They do not adopt a long-term, appropriate risk perspective that

enables innovation on an organization-wide basis. Most firms reported low agreement with survey statements related to risk perspective, such as, "My firm encourages risk taking and trying new approaches" and the differences in means between innovative and non-innovative firms was statistically significant (p=0.001). EPC managers must allow the costs and risks of an innovation to be spread across multiple projects, such that the risks of using an innovation is not unacceptably high for one project or one set of project leaders. 70% of survey respondents agreed with the statement "Schedules and budgets are too tight to take a chance on something new."

Resources. Innovation-related resources include expense budgets as well as staff time. The majority (61%) of survey respondents indicated their companies lack the resources necessary to identify, nurture, track and apply innovations. The majority of innovations (60%) proposed on projects are funded from the original project budget. Only 33% of respondents agreed with the statement "My firm has personnel explicitly tasked with promoting and facilitating innovation within the firm" and only 9% of respondents agreed that "Workloads are managed to ensure staff have sufficient time to pursue innovation." Especially as a result of the global economic downturn over the past few years, EPC organizations are now "lean, mean design and construction machines," with little slack resources. Austere staffing promotes short-term earnings but not long-term success through innovation.

Processes and Structure. The innovation literature makes it clear that innovation will rarely happen when there is not an organizational structure and formalized processes for methodically identifying and evaluating potential innovations and effectively adopting them on appropriate projects. Organizations must also have structure and processes to enable organizational learning to occur which will allow innovations to be effectively implemented on subsequent projects. The survey data showed that firms that viewed themselves as innovative were more apt to have innovation occurring through departmental or organizational practices, rather than on individual projects (p=0.003). The survey also showed that innovative firms are more likely to have methodical or rigorous innovation decision processes (p=0.000).

Changed Project Environments. Successful innovation requires real and sustained commitment by all project entities. Organizations with a genuine customer focus will not hesitate to collaborate with other entities serving the same customer yet nearly one-third of survey respondents agreed that "Lack of communication between project participants" and "Too many players in the process" were critical barriers to innovation. Project delivery and contract methods that inhibit collaboration between entities during design and construction and prevent risk taking are not conducive to the creative integration needed to innovate. Nearly half of the respondents indicated that the design-bid-build delivery method hinders innovation.

Leadership and Culture. All of the organizational traits that enable innovation mentioned above cannot occur without the appropriate leadership and organizational culture. They are the cornerstones that must underlie all innovation initiatives.

The results of the six case studies provided two valuable sets of empirical information. First, the pilot tests of the IMM provided confirmation that the content and wording of the IMM questions and recommendations were appropriate and useful. The organization who had employees retake the IMM several months after IMM recommendations were implemented experienced statistically significant improvement in the scores for the attributes that were targeted for improvement. Second, the pilot tests supported the overall findings from the survey, namely that the organizational culture and leadership may support innovation, but resources, processes and risk perspective do not.

CONCLUSIONS

EPC organizations focus on bringing capital projects in on time, under budget and without injury. They believe the best way of achieving these goals are by implementing best practices, that is, by adopting what has worked on past projects and eliminating all unnecessary sources of risk to achieving project goals. EPC organizations are rightfully proud of their strategic abilities to manage successful capital projects and of their lean organizations that facilitates positive financial performance even during market downturns.

The trouble is that EPC organization's project management strengths are exactly what keep them from being innovative, despite the value attached to innovation by managers. EPC organizations like the idea of being innovative but most are poor at identifying, trying, nurturing, and managing knowledge regarding innovations within their organizations. New methods, processes, products and systems may sound exciting, but the reality is that they are treated as too costly and too risky to pursue even on the smallest projects. Project and corporate budgets are too lean to allow personnel from pursuing innovation-related activities.

This paper has summarized the research that led to the development of a tool to allow EPC managers to identify the attributes of their organization that are hampering their ability to innovate. Although the research process reflected a pragmatic approach that best suited the strong industry composition of the research team, the positive feedback received from the six organizations who pilot tested the IMM indicates the tool has promise for helping EPC organizations identify and implement the changes needed to enhance innovation within their organization.

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Conflict Management in Concurrent Engineering, a Case Study

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Abstract:

Despite increasing industrial interest in Concurrent Design, little empirical research has been undertaken on design conflicts that occur during such concurrent engineering design efforts. To overcome this gap, this paper presents results from a case study we conducted at the Chinese office of a worldwide operating design consultancy firm. This paper presents the sources of conflicts that practitioners of this design office encountered during concurrent design activities on a number of historical and ongoing projects. The paper also presents a number of strategies to effectively detect and manage conflicts on concurrent engineering projects that we derived together with practitioners of the design consultancy company. These strategies include processes for effective change management, communication management, quality management, and risk management.

Introduction

Conflict in design is not a novel principle and has plagued projects throughout construction history. Design conflicts occur because of interfering designs between different parties. These interferences can be either physical or conceptual in nature. Possible parties include various disciplines within a team of engineers as well as external parties such as the client and contractor involved in the engineering process.

Managers continually face the challenge of managing design conflicts within their design teams to achieve the prerequisite deadlines. With the application of concurrent engineering (CE) in the construction industry and the growing complexity of building requirements, conflict in design is increasing in occurrence and severity. Additionally, the increasing complexity of the industry requires larger design teams, so that conflicts become increasingly difficult to resolve.

To overcome this gap, this papers presents the results of an empirical case study with the aim to increase understanding about how to manage design conflicts that occur during CE efforts. We analyzed the causes of design

conflicts that occurred on a number of historical projects carried out by the Shanghai China office of an internationally operating design firm. We identified four major reasons why design conflicts occurred: Discipline fragmentation, missing heritage relationships, insufficient client integration, and the introduction of new design innovations. Based on these four root causes, we then developed a number of strategies to improve design management procedures together with the design office's practitioners.

This paper is structured as follows: We start with a short introduction to CE. Afterwards, we describe our research methodology. We then continue with describing the research results. We close with a short discussion of the findings that result in a number of practical recommendations.

Concurrent Engineering

CE as defined by Evbuomwan and Anumba (1998) attempts to optimize the design of the project and its construction process to achieve reduced lead times, and improved quality and cost by the integration of design, fabrication, construction and erection activities and by maximizing concurrency and collaboration in working practices.

Evbuomwan and Anumba (1998) see CE as a method to avoid the pitfalls that traditional 'sequential' engineering deals with:

- The fragmentation of the different participants in the construction project,
- The fragmentation of design and construction data,
- The occurrence of costly design changes and unnecessary liability claims,
- The lack of true life-cycle analysis efforts, and
- The frequently occurring miscommunication of design rationale and intent.

In this way, CE theoretically can lead to a number of benefits (Anumba, Baugh, & Khalfan, 2002), such as:

- Getting the job right the first time around,
- Increased Client satisfaction,
- Reduced product development time and costs, without compromising quality,
- Eliminating waste, and costly and time consuming downstream changes, and
- The reduction or elimination of non-value-adding activities.

Because CE organizes work so that different parties work concurrently on tasks, effective knowledge transfer between the various disciplines and team members is a cornerstone to prevent problems from occurring. CE design teams require specific communication methods to ensure minimal ambiguity and rework (Loch & Terwiesch, 1998)and function best if they are able to:

- Invest in signature relationship practices,
- Model collaborative behavior,
- Create a 'gift' culture,
- Ensure the requisite skills,
- Support a strong sense of community,
- Assign team leaders that are both task- and relationship-oriented,
- Build on heritage relationships, and
- Understand role clarity and task ambiguity (Gratton and Erickson 2007).

Even if CE teams promote co-design and intend to achieve the same goals (Kleinsmann & Valkenburg 2008), tensions have been frequently reported in practice between the various disciplines (Lu, Cai, Burkett, & Udwadia, 2000, Cicimil & Marshall, 2005, Erkamp, 2009). For example, Cicmil and Marshall (2005), analyzing a case study, found that there is a lack of trust between various parties which prevents team members from communicating about mistakes, design decisions, and possible areas of improvements. Cicmil and Marshall (2005) show that CE has an extremely high risk of communication failure. This high communication risk can lead to significant rework and long decision times, and subsequently to long delays in projects. Next to communication, political issues also cause problems during CE efforts. External parties such as the contractor or the client have their own agenda's and, thus, parties frequently have conflicting views of the design project.

Overall, despite a number of mainly theoretical efforts to overcome barriers between the different disciplines (Détienne, 2005; Evbuomwan & Anumba, 1998; Kleinsmann & Valkenburg, 2008), little empirical research with the potential to deepen our understanding about how conflicts occur in practice exist.

To overcome this gap, we conducted a case study. The aim of the study was to analyze conflict that occurs during CE, to discover the causes of these conflicts, to map out the effects of these conflicts, and to provide practical suggestions which CE team can use to improve conflict management.

Research Methodology

We conducted this case study research with the Chinese division of an international consultancy firm based in Shanghai. Employing a workforce of approximately 60 people, the office fulfills an advisory role on most of its projects, acting as a conduit between the client, the Chinese government, and local companies. In house experts from other company offices across the world support the design capabilities of the Shanghai office. Overall, the company offers a great case to study conflict because it houses many experts in this field that are able to indicate the largest issues encountered over the past few years on the subject of conflict management in CE. Additionally, the company implements CE; which they refer to as "Total Design Management". The company is involved in all phases of the design and construction process and engineers concurrently perform tasks.

	Description	Duration	Main issues
Project I	*The design and construction management of a chemical research and development campus.*	*4 years*	• *Large client with multiple departments each with different demands: Complex and difficult communication* • *Innovation of LEED Gold certification* • *Discrepancies between final building and client vision* • *Lengthy project; difficult integration of new employees into the project team which led to difficult communication.*
Project II	*The Design and construction management of a chemical factory*	*3 years*	• *Discipline engineers had too little time to effectively work as a t* *External designers were frequently used for design reviews leading to a lower quality and increase in conflicts.* • *Client requested 125 design changes throughout the project*
Project III	*The Design and construction management of a factory including warehousing*	*2 years*	• *Project joined at a later phase, company had to resolve issues caused by previous mismanagement.* • *Communication with client was troublesome; poor documentation led to rework for the company* • *Client requested 500 design changes throughout the project*
Project IV	*The design and construction management of a factory specialized in the manufacturing of robotics.*	*2 years*	• *The company was bypassed in important decisions by client and contractor*

During the case study we focused on four different projects[1] the company completed within a year of the interviews. Table 1 summarizes a number of characteristics from these projects.

To learn about these projects we followed a four phase research strategy:

1. First round of interviews with 2 project managers and 5 engineers to learn about the conflicts that occurred on the projects and to learn about processes the project team applied to manage these conflicts.
2. Second round of interviews with 4 project managers and 11 engineers including the interviewees from step 1 to validate and deepen our understanding from research phase 1.
3. Development of an improved conflict management strategy for the company
4. Validation of our strategy by presenting our findings to the interviewees asking for critical feedback.

Research Results

In summary, the data shows four causes of conflicts on the case projects: Discipline fragmentation, missing heritage relationships, insufficient client integration, and the implementation of new design innovations on the project.

Discipline Fragmentation

We observed discipline fragmentation during a number of interviews with company staff. A quote from an architect illustrates this well:

"I am the architect, I focus on the looks of the building and the layout, the rest is up to the other discipline engineers. This is my job; it is not my job to look at what the other discipline engineer is doing."

The above displays exactly the kind of mindset that causes internal fragmentation. This mindset is confirmed by one of the project managers:

"Engineers were very passive during design review meetings. They were not straightforward with each other, didn't listen well to engineers of different disciplines, didn't have much patience with each other and were looking at the project exclusively from their own discipline (perspective)." And, *"The amount of communication between the engineers was very low. The engineers were very reluctant to look over to other disciplines. Everyone is working on their own little island and hoping it will fit in the end. "*

These comments display that engineers are very reluctant to look past their own discipline and are hesitant to try and integrate someone else's field of expertise into their own work. The following statement of an engineer provides an overview of his experiences at the company and claims:

"Design team engineers here are very reluctant to break the discipline 'walls'. Integrated design requires all discipline engineers to participate proactively in the process. It doesn't work if only one person is trying to communicate his discipline to others."

One engineer presented a specific example of how discipline fragmentation hindered the project:

"During project II the structural and HVAC engineer didn't communicate

[1] We removed all project names and all names of informants to ensure the anonymity of the involved parties.

efficiently so when we reached the construction phase of the project we discovered that the design drawings indicated that the air-conditioning ducts passed straight through a horizontal structural beam designed to support a crane system. Of course, we couldn't just move the piping under it because it would prevent the crane from functioning; above the structural beam we also lacked space due to the roof of the building. Eventually we had to redesign the air-conditioning system to split up into two separate, smaller ducts that could pass above the crane beam. This entire process cost us several days to resolve."

Overall, our data clearly shows that despite the application of CE, team members still need to make a complete transition to a more collaborative mindset. Engineers still have difficulty applying collaborative design techniques effectively, which is a very real cause of conflicts. Discipline fragmentation led to several costly design conflicts in the final design such as the following one that an engineer indicated during the interviews:

"The design conflicts didn't come to light until the contractor reviewed the final design and this in turn led to changes in the design during the construction phase and consequently led to an increase in the overall costs and a reduced quality of the final construction."

Missing Heritage Relationships

In addition to discipline fragmentation, missing heritage relationships play a large role in causing conflicts during CE activities. In the case firm, engineers were frequently dealing with new people and this led to a lack of trust between engineers and to problems with the integration of someone into the team who is not familiar with CE methodology. When asking a project manager about project I, she said,

"Almost everyone was replaced in the duration of this project at one point or another; it would be extremely beneficial if we somehow created a procedure to reintegrate the knowledge that is lost with this employee quickly." When questioned about the effects that leaving employees had on the project: "Of course, when an engineer left the team, it took a lot of time to find a new employee and get him up to date on the project, this cost us a lot of time and effort."

Statements from other interviews further confirm the lack of heritage relationships.

"One of the biggest problems is that people here do not stay at the company long enough to reach a level of seniority that is needed for integrated design to work. For integrated design to function, there need to be a few people in the team that are very knowledgeable of not only their own discipline, but also have extensive knowledge of how the other discipline engineers work."

"The problem is that when people leave during a project, much of their knowledge isn't written down and that makes is hard to train a new person to replace the empty position. This is especially a problem on longer projects"

"The discipline engineers were changing throughout the engineering project. The designers were not the same people that were involved with solving the onsite

construction projects. This meant that the discipline engineers had to take a lot of time to study the design drawings when a problem occurred during the construction phase."

Insufficient Client Integration

As indicated earlier, it is essential in the CE process to involve the client into the design at an early phase. In this case study, cooperation between multiple design firms, the contractor, specialists and the client often led to conflicts. The tensions that exist between the different parties are usually related to the field of expertise and the lack of knowledge of other companies and disciplines. These conflicting views often lead to the lack of compatibility between various elements in the design.

The interview results suggest that there were various cases in which the communication between the design team and the client was troublesome and that the client was not involved in several elements of the design. One project manager recalls that during project I

"Electrical engineers designed an electrical system where there were many different electric rooms spread throughout the building. During the construction, however, the client indicated that this was not what he was expecting and that they would much rather have had a single electricity control room. We didn't discuss the electrical system expectations with the client, and in the end we were unable to modify the system to completely satisfy the client requirements. In the future we should communicate these things better."

In addition, the project manager recalled another case during the same project,

"The general contractor wanted to implement a design change: They wanted to increase the concrete thickness of a certain part of the pavement because they believed that it would be insufficient to carry the loads that were required. The design team rejected the change due to the increased costs it would have incurred on the client, but didn't communicate this issue with the client. Now, after the construction has been built the client is stuck with a pavement that doesn't meet the required quality standards. In hindsight, the client indicated that they would much rather have paid a bit of extra money for the durability gain in the concrete."

In project II, an engineer indicated that *"The client made 125 design changes in the duration of the construction period."* When asked about the amount, the engineer claimed*: "This is because the client cannot predict and see everything in the design drawings. It is difficult to read these drawings and although they may look fine on paper, when the building is being constructed this view may change and the client will file a change order."*

This means that the client will generally be unable to understand the design drawings and translate them completely to a finished product. The result is that they will order these design changes to ensure that the final result is still what they envisioned.

Findings from project III reinforce all the above. An engineer, for example, indicated that *"The client only had a very basic Idea of what he wanted. He was*

only able to indicate the type of rooms that he wanted, and nothing else. Our company joined (project III) when the design was already completed, and we discovered that the design was not what the client wanted. During the construction of the building a total of about 500 change orders were filed costing us well over 3 months of extra time. Combined with a severe error on behalf of the contractor, the project was delayed about 8 months!"

Our data shows that, despite the effort to involve the client early in the design phase, the client still changed demands for the building, especially on projects with long durations.

The design changes occurred when the client came to certain realizations during a specific phase of the project, or changing requirements that the company has of the building. These design changes frequently conflict with completed work, and thus force the design team to alter the designs. Consequently, client induced design changes caused unplanned delays depending on the severity of the design change.

Introduction of Design Innovations

Integrating new technological elements into a design has a significant impact on the amount of conflict that occurs in a design team. From our data, it appears that innovation aggregates all the conflict causes presented earlier. Project I was the most innovative of all the projects researched, incorporating new sustainable building technologies as well as specialist R&D requirements for various different departments because the design included highly complex laboratory spaces with which the company had no experience in the past.

'PM A' indicates, *"Integrating the new LEED requirements (An American based Green Building Certificate) into the design (of project I) proved very difficult, it was difficult for the engineers to detail the design to comply with the rules set by the standard."* 'PM E' indicates, *"Despite the presence of a lead engineer specialized in LEED in the team, engineers indicated that they often had difficulty integrating the new requirements into their designs."*

During team meetings for project I the team discovered that the design was frequently not up to the required demands and that the design team had to rework certain areas. Most of the conflicts occurring were between the specialist and the design engineers of all the other disciplines, specifically due to design errors attributed to a lack of experience of the engineers in appropriately integrating the new technology into their designs.

Next to problems with implementing new sustainable design technologies, project I, showed difficulties relating to the development of new laboratory spaces, which was not only affected severely by the client constantly changing their demands for the laboratory spaces, but also by the design team being unfamiliar with the design of laboratory spaces in general. The engineering team invited an expert from the Netherlands to assist in the design work, but similarly to integrating LEED technology into the design work, the team had difficulties integrating the specialist requirements into the designs. One project manager explained a specific example of this problem: *"The (design)-engineers had produced a design for the lab spaces that included the ducts for air filtering. The client, however, wanted to change the locations of several machines in the labs due to changing technologies and keeping*

up with the industry. The locations of the ducts, however, were incompatible with the newly suggested machine locations. Engineers has to change the design to the ducts would be in the right location."

In addition to technical issues, innovation created tough new communication issues between the various involved parties on Project I. Because the design team had very little experience creating the specialist spaces required, this led to numerous conflicts between the clients' representatives and the design team. These issues appeared on a biweekly basis during meetings between the design team and the client. According to interviewees, a significant portion of time was spent on managing the specialist requirements for the laboratories. An engineer claimed:

"There were three different divisions (Client-side) that were going to use the laboratories. Each of these wanted to handle different design elements that often conflicted with each other. A special job was created for me to handle the communication between these different stakeholders and the design team."

Findings and Recommendations

We found effective team cooperation to be the main cause for conflicts to occur within the design team. Ineffective communication between the various parties was pointed out by the engineers and project managers on all four projects as a large cause of conflicts. This led to conflicts causing delays and a significant amount of rework for the team on a number of projects.

Additionally, this research shows that engineers and project managers perceive design conflicts in CE as being overwhelmingly negative in effect. Our data suggests that the conflicts are a major cause for delays and redesign work for the engineering team, and can frequently lead to increased costs for parties involved. It is, therefore, important to reduce the amount of conflict occurring during CE to increase overall project performance for all involved parties.

Such an effective conflict management strategy requires three different elements: prevention, detection, and effective management of detected conflicts.

Our data shows that designers could have avoided many conflicts by involving the client early in the design phase to prevent downstream design changes. To achieve this, it is important to ensure that the design team and the client have the same idea of the building at every stage throughout the design process. Even despite having regular client meetings, our data shows that clients still frequently see discrepancy with their vision and the final design when the building is constructed. The communication and presentation of early designs in a format that is easily understandable by clients is, therefore, of utmost importance. The use of 3D models (Hartmann, Gao, & Fischer, 2008) already in early phases instead of only during final design stages and during the tendering procedure might help the client oversee the design intent more clearly and prevent conflicts in later phases of design.

Designers can avoid conflicts with external design companies through space management methods. Space management allows for a design team to preset areas in a design where the target discipline is given a certain amount of space to use for its design solution.

This space management diagram is created by the entire design team during a design meeting. Based on client and

building requirements, each discipline will be able to predict a reasonable amount of space that will be necessary for each the design works. Once this space division has been agreed upon, engineers will attempt to design within their boundaries. If an engineer has to supersede these boundaries, he has to inform all other engineers immediately and the team will review these areas in detail.

This procedure is initiated once the initial design is approved by the client and design detailing starts. Engineers will determine the required discipline information with regards to space usage (e.g. approximate space needed for plumbing pipes). The internal design team holds a joint team meeting verifying the required information. This information will be condensed into a set of space usage rules for each discipline. These guidelines will be communicated with externals. Our interview results also show that the design team frequently encountered difficulties with integrating design innovations. To prevent conflicts due to the implementation of new innovations, companies should spend more time on training employees. Additionally they can add more experts directly to the design team that can support the other team members with the integration of new technology.

Next to preventing conflicts, companies need to detect conflicts that engineers could not prevent in earlier phases. To do so, companies should perform design reviews of the designers work at certain preset times in the design process. These dates should be agreed upon beforehand and, therefore, involve certain deadlines for external design parties. This form of control will also ensure that the design team is on the right path and understands their job. In addition to serving as a method of schedule control during a design project, the design reviews allow engineers to focus on finding and resolving conflicts whilst designs are still in a relatively fluid state, meaning a cheap solution can be agreed upon before the issue reaches the construction stage.

The design review consists of a single-disciplinary design review and a multidisciplinary design review. Initially internal design review engineers will receive copies of all drawings related to their specific field. With these drawings the internal design review engineers can check whether client requirements are satisfied. After this initial design review, the team can then proceed to a multidisciplinary analysis where the team will use tools such as the space management method we suggest earlier. If needed the internal design review engineers can invite external designers to these discipline specific or multi-disciplinary meetings.

Conclusion

This paper presents a case study to identify causes of conflicts during CE activities. Overall, the findings from the case study show four areas of conflict: Discipline fragmentation, missing heritage relationships, insufficient client integration, and the introduction of new design innovations. Based on these four conflict sources the paper represents a number of recommendations of how to avoid conflicts altogether and how to resolve unavoidable conflicts during CE activities.

With its empirical focus, this paper complements the mainly theoretical CE research work by providing in depth insights in “real world” CE design activities. We suggest that other researchers provide similar empirical work in the future to provide more

generality for the paper's findings and to develop more in depth insights in CE activities. We believe that only such empirical work will have the potential to enable practitioners and researchers to gain the understanding that is necessary to truly move design practice forward.

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Establishing a Collaborative Environment among Project Stakeholders

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Abstract

Three key aspects necessary to ensure a successful project environment are communication, coordination and cooperation (3Cs) between stakeholders. Incorporating these aspects into implementation strategies is paramount to facilitate project delivery and relationships among stakeholders. This paper reports results from a study on collaborative efforts between transportation agencies and tribal nations within the United States. Several methods were used in this study, including qualitative content analysis, workshops, interviews and a Delphi study. Findings include a list of issues that are encountered on projects affecting tribal communities, and a set of 3Cs strategies, which have been utilized to establish a collaborative environment. The study has implications for the architecture-engineering-construction industry because the singularity of the relationship between owners and stakeholders significantly affects several aspects of a project delivery, including planning, design, construction, and operations. These implications are summarized in the final section of this paper.

Introduction

Project success relies heavily on the establishment of a collaborative environment among project stakeholders (Schaufelberger 2000; Drexler and Larson 2000). The implementation of strategies utilizing communication, coordination and cooperation (3Cs) can assist in creating a collaborative environment on construction projects of high complexity. In surface transportation projects, the introduction of many project stakeholders leads to higher complexity on projects. A previous study captured the essence of collaboration in the following excerpt:

> *Most importantly, the team members on the project are enjoying the job and getting things done in a relatively harmonious atmosphere, one in which people can openly disagree because they know their position will be heard. […] A comment made by [an external party attending some of the meetings] probably summed it up best when he said, "I honestly could not tell who in the room worked for who"* (Ernzen et al 2000; pp. 211).

Likewise, the literature offers several studies on factors affecting collaboration and best practices on surface projects. However, these studies usually focus on contractually-regulated relationships. Conversely, surface transportation projects usually involve stakeholders who have a vested interest in the project, and often have decisional authority over its fate, but are not contractually related to all or any of the other parties. This is especially true on surface transportation projects affecting tribal communities.

Over recent years, the transportation sector has been receptive to the need of facilitating collaboration among all stakeholders. These efforts may be grouped under the umbrella of practices named context sensitive solutions (CSS) and defined as:

> *Context sensitive solutions […] can be defined as a collaborative, interdisciplinary approach that involves all stakeholders to develop a facility that*

> *fits its physical setting and preserves scenic, aesthetic, historic, and environmental resources"* (Schexnayder 2003; pp. 10-11).

While CSS practices seem successful in establishing a collaborative environment (Olszak et al. 2008), they rely on certain assumptions that not hold when tribal nations are among the stakeholders.

Executive Order 13175 issued by President Bill Clinton describes and recognizes the unique relationships that are present between the federal government and tribal governments. This executive order requires that the federal government consult with tribes on "the development of Federal policies that have tribal implications" (Clinton 2000). It also recognizes the relationship between the federal government and sovereign tribal governments as a government-to-government relationship. In addition, the National Historic Preservation Act requires the investigation of historical sites and cultural properties of concern to tribes (National Historic Preservation Act 2006).

As a result, transportation projects in which tribes are stakeholders reach a higher level of complexity as additional institutional processes and governmental protocols are introduced. Government-to-government relationships between local, state, federal and tribal governments require special considerations in transportation planning and project delivery, as consultation with tribal governments is unique, leading to special issues that arise during the project life cycle. Many of these issues, like tribal sovereignty, can be unique to the tribal transportation context, however, other issues, such as land ownership or project funding can be encountered on non-tribal projects.

Additional issues contribute to the complexity of delivering projects affecting tribes. Each tribe has its own culture. This cultural diversity challenges the communication process. To overcome this challenge, project teams are required to be culturally competent (Lum 2003). The concept of cultural competency explains why most of the collaboration practices developed for traditional contractually-regulated relationships is not adaptable to this context. Successful collaboration with tribes cannot be achieved by a loss of identity as the one described in the previously-quoted statement "*I honestly could not tell who in the room worked for who"* (Ernzen et al 2000; pp. 211) because communication with tribal representatives must follow specific protocols and it is specific to the tribe(s) involved.

Several initiatives have been used for bridging this information gap and establishing collaboration (Arizona Department of Transportation). While these efforts have served to establish formal relationships among stakeholders and initiated a collaborative process, no comprehensive efforts or tools have been developed to truly capture the elements of the collaborative environment on infrastructure projects when federal, state, local and tribal governments are project stakeholders. Similarly, there is a total lack of information on the implications for AEC firms when they decide to operate in these projects. The purpose of this paper is to describe collaborative processes and governmental policies on this type of projects, and finally to discuss ramifications for the AEC industry.

Methodology

The research team utilized a three-step approach to the research methodology. First, using a literature review, the research team identified issues commonly encountered on transportation projects affecting tribal communities, as well as

strategies implemented by project stakeholders to alleviate the identified issues. A content analysis of selected literature sources was conducted to capture the complexity of the issues and develop 3Cs categories. Second, the research team refined the issues and strategies identified by organizing workshops and performing interviews with individuals experienced in the specific project. Finally, the research team validated the effectiveness of each of the identified strategies for treating the identified issues through the use of a Delphi Questionnaire.

In the initial identification phase, the research team identified the literature pertaining to: (a) initiatives undertaken to create a collaborative environment on tribal transportation projects; (b) governmental policy regarding consultation on such projects; and (c) specific case studies of strategy implementation. The literature provided the research team with an overview on the state of the practice of tribal transportation programs, including information on state's departments of transportation programs, federal and state executive orders, and regional tribal transportation partnerships. During this initial review of the literature, the authors identified and reviewed more than 140 sources. A complete annotated bibliography was developed for these sources (Migliaccio et al 2008). A summary of literature statistics, with respect to the transportation project planning and construction process is included in Table 1.

Following the initial literature review, information sources were sampled for significance to 3Cs strategies that have been implemented to enable collaboration among project stakeholders. A qualitative content analysis was performed on this sample, which included representative information sources and all case studies of tribal transportation initiatives. This method of sampling is used in qualitative content analysis in order to answer research questions posed by the researcher (White & Marsh 2006). The research questions focused on identifying issues affecting success of transportation projects of interest to and affecting Tribes and 3Cs strategies adopted by parties to facilitate communication between transportation agencies and tribal communities. While the identification of the issues followed a bottom-up approach, initiative were coded as significant to any of the 3Cs using a set of operational definitions, which is included in Table 2.

At the end of this initial research phase, a set of issues and strategies was identified. At this time, the research team conducted workshops and interviews in order to gain feedback from experienced transportation and tribal officials, so that the identified issues and strategies could be refined. Workshops were conducted at venues across the nation with participants from both transportation agencies and tribal communities. These participants also shared their experience in strategy implementation and issue identification. The research team also conducted telephone interviews with 30 individuals representing local, state, federal and tribal governments. Feedback from this phase assisted the research team in finalizing a list of commonly encountered issues on tribal transportation projects and 3Cs strategies that have been utilized to treat such issues.

The perceived effectiveness of each of these strategies in treating each of the issues was assessed through a Delphi study. Invitations to participate in the Delphi round of the research study were sent to representatives from local, state, federal, and tribal governments and consultants, all with experience in the transportation project

process. Forty-seven individuals participated in the first round of the Delphi study. Results were analyzed to determine if respondents broadly agreed on the effectiveness on a given strategy when a specific issue was present (first criterion), and if there was internal consensus on the rating of the strategy (second criterion). Delphi panelists also provided qualitative feedback that was organized into lessons learned and recommendations. Strategies that passed both criteria were determined to be effective, while those that only met one criterion were reformulated using the qualitative comments and retested in a second round of the Delphi Questionnaire.

A Ladder to Collaboration: Identification of Issues and 3Cs Strategies

To build a foundation for success, communication, coordination and cooperation strategies (3Cs) must be implemented to allow project stakeholders to collaborate on complex projects. With the assumption that the strategies are utilized in conjunction with one another, project stakeholders can build a ladder that leads to a collaborative environment and project success.

To differentiate 3Cs collaborative strategies, a definition was identified for each of the 3Cs reflective of the idea that, by escalating the approach for collaboration, the effort in implementing a collaborative strategy would also increase from communication to coordination and from coordination to cooperation. Three operational definitions for the 3Cs were developed and are included in Table 2. These operational definitions were contextualized in the tribe-transportation agency context, but they can be generalized into any entity-to-entity communication within the construction industry.

The ladder approach is proposed to assist in the complex process of establishing a collaborative environment when multiple governmental entities are project stakeholders, often with differing interests. These differing interests can add to the difficulty of collaboration and requires extensive negotiations among stakeholders (O'Mahony & Bechky, 2008). However, negotiation can be difficult when differences among stakeholders extend beyond their governmental structure to encompass fundamental culture and operations. In the first step of the ladder, "communication" requires that project stakeholders share a base knowledge in order to share entity specific knowledge across agencies (Carlile, 2004). While work has been done to examine the collaborative environment in different fields like the performing arts (Bechky, 2002) and software implementation (Elliot & Scacchi, 2008), little has been done to capture elements of the collaborative environment on infrastructure projects when multiple government entities are stakeholders.

Communication is the first step in creating a collaborative environment among project stakeholders. The fundamental process of communication is sharing and receiving of information between parties. The second step for creating a collaborative project environment is coordination. Coordination efforts go beyond the first step of communication as parties begin the process of coordinating work on a program or project. Cooperation is the final step identified for enabling collaboration on projects. Cooperation goes beyond coordination as parties work in conjunction with one another to achieve success rather than working interdependently for success. Parties work together, often as one unit, creating the collaborative environment.

Findings

Results of the initial two research phases included an extensive list of issues and 3Cs strategies implemented for creating a collaborative environment. A summary of these findings list is provided in the "Issues" and "Strategies' sections. As the review and analysis of the literature simply identified the state-of-the-practice, the effectiveness of each of the strategies identified could not be determined. A Delphi study was conducted to establish relationships and assess success of 3Cs strategies. Results of the Delphi study are summarized in the "Delphi Study" section.

Issues

The project team identified commonly encountered issues on projects affecting or of concern to tribal communities. This approach reflected the idea that factors affecting success must first be identified and understood before strategies for achieving success are investigated. Issues identified as being commonly encountered on tribal transportation projects were categorized organized into six major categories. Major issue categories and their descriptions in the tribal context are provided in Table 3.

Strategies

The content analysis also provided the researchers with a comprehensive list and descriptions of 3C strategies that have been implemented to establish a collaborative environment. Each of these strategies was classified as being a communication, coordination or cooperation strategy. Table 4 lists the identified 3Cs strategies. Some of these strategies are contextualized in the examples provided in the final section.

Delphi Study

In order to determine the effectiveness of each of the strategies in being used when a specific issue is present, a Delphi study was conducted. Forty-seven individuals representing local, state, federal and tribal governments and consultants with experience in transportation projects affecting tribes participated in the Delphi study. Each panelist scored individual strategies and whether the strategy being tested is effective when treating each of the six major issues. The results were compiled and analyzed based on the perceived success of each of the strategies. Results were based on the evaluation of the strategies based on the two criteria. Strategies were considered to be successful if respondents broadly agreed on the effectiveness of a strategy when treating a specific issue and if there was an internal consensus on the median value score of the respondents. Broad agreement was considered achieved if at least 75% of respondents showed at least moderate agreement with the effectiveness of the strategy. Internal consensus was achieved if the Average Deviation Index (Burke & Dunlap, 2002) from the median value was less than 1.

After the first Delphi round, sixty-one strategy/issue pairs met both of the criteria and were considered effective. Fifteen strategy/issue pairs met one of the two criteria and were identified in need of a retest after reformulation of strategy description based upon feedback from Delphi respondents. Fifteen strategies showed significant agreement among panelists with at least 60% of respondents showing some level of agreement, but only five of these strategy/issue pairs were categorized for retesting because panelist comments indicated that strategy reformulation could improve the perceived effective of the strategies. Finally twenty-seven strategy/issue pairs passed

neither criteria and showed no significant agreement amongst respondents. These strategy/issue pairs were considered to be ineffective. These results are summarized in Figure 1.

In second round of the Delphi study, panelists were asked to reassess twenty strategy/issue pairs that were reformulated according to their comments. In addition, the authors decided to assess an additional strategy (i.e., Training) that was captured after the first Delphi distribution. Thirty-four panelists responded to the second round. Results of this additional assessment were positive with only one out of twenty-six pairs missing the criterion for internal consensus.

Conclusions and Implications for the Construction Industry

The singularity of the relationship between owners and tribal stakeholders significantly affects several aspects of a project delivery, including planning, design, construction, and operations. While the described research project has focused on surface transportation projects affecting or of concern to tribal communities, it has allowed the authors to capture ramifications for the AEC industry. Some examples is provided in the following paragraphs.

Differences in selecting 3Cs strategies begin in the project planning phase. Planners usually use publicly available databases to collect data on resources to be preserved. However, information on the existence and/or the position of tribal-sensitive resources is often not available. This information gap triggers the necessity of extracting this information out of the community tacit knowledge. Elderly tribal member are often the ones retaining this knowledge, but planners usually do not have access to this tacit knowledge. Another challenge is offered by the confidentiality of this information. All these challenges need to be taken into consideration when organizing planning activities. For instance, a collaborative approach to deal with these issues is to involve the tribe in the process of selecting planning consultants. This would avoid later problems deriving by tribal members refusing to interact with these consultants.

Similarly, design professionals are usually unprepared to communicate and participate successfully in the outreach to tribal communities. The way to convey information needs to be radically modified as well as the way to interact with the audience and to organize the venue for the meetings. As a result, both the owner and the design firm are required to address these issues. Owners should evaluate if the potential consultant is culturally competent while making sure that the agency's own personnel meet the same requirement. Design firms desiring to work on these projects should include in their staff individuals who meet the requirements to be culturally competent. These requirements go beyond skills and knowledge to encompass personal characteristics of the individual (Lum 2003).

On a roadway project, the design firm kept encountering an unjustified and strong resistance on the proposed alignment. No reasons were provided for this resistance. After employing a tribal mediator, the reason for the resistance emerged: the proposed alignment was opposed because it affected a tribal-sensitive natural resource. The position of that specific resource was protected by confidentiality. As a result, the information was not transmitted to the designer because he was not a tribal member. In this case, the use of a tribal mediator allows design firm to pre-screen design alternatives.

Finally, if a contractor is interested in bidding on a transportation project that affects tribes, he will need to assess how this situation may affect the project delivery. Issues, such as preferred employment, jurisdiction and tribal taxation may be evident. However, other issues, such as tribal traditional practices may have a significant effect on the project delivery. On a project, construction activities were disrupted because the construction site was adjacent to an area used for seasonal ceremonials. The problem was solved by fencing the area making it inaccessible to the view of the construction workers. Owners should be proactive in identifying this type of issues and to share them with contractors.

While this study has produced several findings, working tools and a collection of case studies, the authors included in this paper only a summary of the findings and research activities. It should be noted that a considerable list of comments, lessons learned and recommendation has been collected. These qualitative information will be analyzed by the research team with the goal of outlining a set of research propositions to be carried out beyond the conclusion of the current research contract that is funded by the Transportation Research Board of the National Academies of Sciences.

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Table 1: Literature Statistics by Project Category

Category	*Subcategory*	*Count*
Overall	Tribal Summit/Meeting	32
	Tribal Liaison	7
	Reference Guide	28
	Research and Study	19
	Other	33
Project	Finance and Planning	42
	Pre-Construction: Design	5
	Pre-Construction: Environmental Evaluation	17
	Pre-Construction: Right-of-Way	8
	Construction	11
	Operation and Maintenance	5

Table 2: Definitions of the 3Cs

3Cs	*Definition*
Communication between Tribes and transportation agencies	process by which information, data or knowledge regarding issues and projects is exchanged through methods, such as speech, writing, or graphics by the transmitting party, so that it is satisfactorily received or understood from the receiving parties.
Coordination between Tribes and transportation agencies	process by which representatives of these entities communicate information on how and when each party must act in order to harmoniously work interdependently for the purpose of achieving effective common results.
Cooperation between Tribes and transportation agencies	process by which representatives of these entities work together to achieve a common goal or objective in carrying out transportation planning, programming and delivery processes.

Table 3: Typical Issues on Projects Affecting or of Concern to Tribal Communities

Major Category Issue	*Issue in the Tribal Context*
Cultural Competency	Cultural differences between tribes and transportation agencies can make the implementation of strategies, like communication, difficult as agency and individual interaction protocols can differ between parties
Protection/Preservation of Tribal-Sensitive Resources	For cultural and historical reasons, tribes often consider resources, otherwise not considered sensitive, as needing to be reserved regardless of the need for transportation facilities.
Confidentiality of Tribal-Sensitive Matters	Cultural practices and historical considerations often limit tribes on the extent of information that they can share with other project stakeholders. It may be that a tribe has knowledge of a historic or cultural property that needs to be protected, but the location of the site is confidential.
Sovereignty	The federal government recognizes tribes across the nation as separate, sovereign nations, whose jurisdictions and institutional relationships and protocols must be recognized.
Land Ownership	Common land ownership issues like right-of-way can lead to difficulties to project completion. In addition to common issues, consideration must be given to unique land ownership situations in the tribal context, like the management of trust lands by tribes.
Funding	While project funding issues are also common to all transportation projects, the tribal transportation context lead to new levels of funding issues, as funding on such projects can be provided by multiple sources. Project funding can be provided by the tribe, state or Bureau of Indian affairs to complete tribal-needs projects.

Table 4: 3Cs Strategies

Communication	*Coordination*	*Cooperation*
Presentations	Meetings, Seminars, Summits and Workshops	Planning Organizations
Data Collection, Analysis and Distributions	Tribal Liaison or Coordinator	Resource Sharing
Newsletters and Bulletins	Public Involvement	Regional Transportation/Transit District or Coalition
Mailings with Response Forms	Formal Agreements	Investigation of Alternatives
Tribal Mediator	Loans and/or Grants for Funding	Planning for Disaster Preparedness
Standards and Handbooks	Regional or State-Level Conferences	
Training	Tribal Consortium	

		MC1: Cultural Competency	MC2: Protection/ Preservation	MC3: Confidentiality	MC4: Sovereignty	MC5: Land Ownership	MC6: Monetary Issues
Section B) Communication Strategies							
B.1	Presentations						
B.2	Data Collection/Analysis						
B.3	Standards and Handbooks						
B.4	Newsletters/Bulletins						
B.5	Mailings/ Response Forms						
B.6	Tribal Mediator						
B.7	Training						
Section C) Coordination Strategies							
C.1	Meetings/Seminars						
C.2	Public Involvement						
C.3	Tribal Consortium						
C.4	Loans for Funding						
C.5	State Tribal Liaisons						
C.6	Formal Agreements						
C.7	Regional/State Conferences						
Section D) Cooperation Strategies							
D.1	Planning Organizations						
D.2	Regional Transportation / Transit Districts						
D.3	Resource Sharing						
D.4	Investigating Alternatives						
D.5	Planning for Disaster Preparedness						

	LEGEND (with count)	N
	Green = Strategy effective	61
	Yellow = Strategy effective but requiring a follow-up	15
	Red/Yellow = Strategy potentially effective that requires a follow-up	5
	Red = Strategy potentially effective but comments do not justify a follow-up	10
	Black = Strategy ineffective or findings inconclusive	17
	White = New Strategy to be assessed in the second questionnaire	6

Figure 1: Results of Delphi Round 1

Governance Challenges of Infrastructure Delivery: The Case for Socio-Economic Governance Approaches

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Abstract

Research on governance of infrastructure projects has explored who should optimally own and operate these assets. Instead, we focus on a set of governance challenges that arise systematically during the project shaping, design, construction and operation phases of infrastructure projects. Importantly, project decisions at one stage can limit choice options and compromise financial, environmental and socio-political sustainability in subsequent stages. This paper discusses how these challenges arise within different phases of the infrastructure project lifecycle and propagate across phases; it shows how poorly traditional financing and governance approaches have addressed these challenges on past infrastructure projects; and it proposes socio-economic approaches that have the potential to address the governance requirements of future infrastructure projects more fully.

Keywords: Infrastructure; contract management; arbitration; dispute resolution; partnerships; privatization.

Introduction

Civil infrastructure (roads, railroads, ports, airports, bridges, telecommunications, power supply, water supply and treatment) and social infrastructure (schools, hospitals, civic buildings prisons, etc.) are critical in sustaining public health, economic growth and quality of life. At the same time many of these infrastructure assets have the attributes of public goods and constitute natural monopolies because of the last mile of water pipe or copper wire required to deliver services to end-users that is prohibitively costly to duplicate. As a result of these attributes, the conception,

development, delivery and operation of infrastructure has been subject to several kinds of failures. (Figure 1: [10,11,12,13,14,15,16 and 17])[1]

Efficiency challenges arise when government representatives, managers and employees are not adequately incentivized to select, contract for, build or operate infrastructure assets in the most efficient and sustainable manner [6,15]. Public works projects are some of the largest capital outlays made by governments, comparable only to large defense acquisitions. This makes them an attractive target for corruption in the award and administration of contracts [3,12]. Secondly, over the last several decades—and probably for centuries before that—government representatives and employees have systematically overemphasized the demand for and benefits of infrastructure that benefits their constituents, while underestimating its costs and time of construction (Flyvbjerg 2003). At the same time, there has been little public demand and government enthusiasm for adequately maintaining infrastructure projects, relative to building new ones [3,6,8,14,15]. As a result infrastructure in developed countries like the US is crumbling. Witness the recent collapse of the bridge in Minneapolis and the repeated structural integrity problems of the San Francisco-Oakland Bay Bridge, including one as recently as October of 2009.

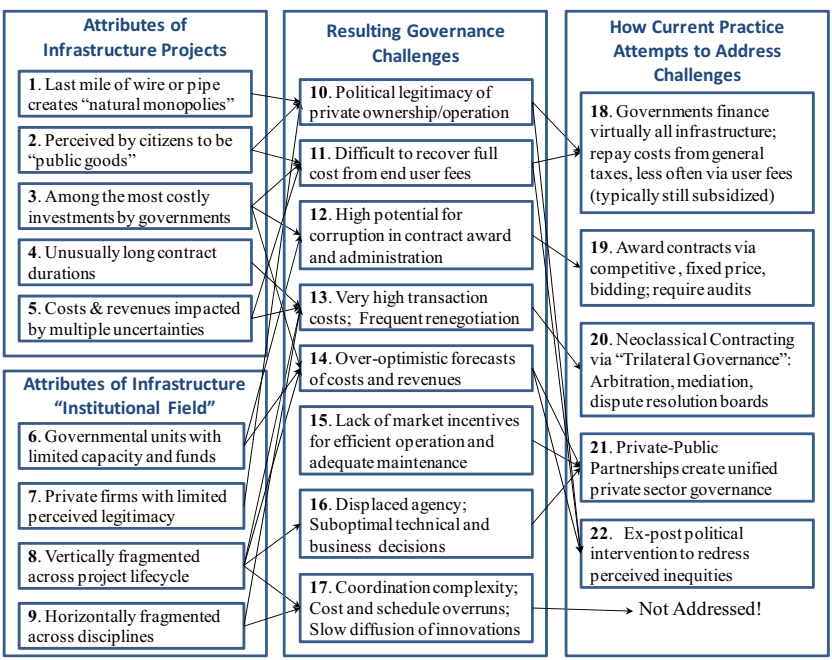


Figure 1. How Current Practice Attempts to Address Key Governance Challenges of Delivering Infrastructure Projects

[3] In the remainder of this paper, we use numbers in square brackets to refer to boxes in Figure 1.

Legitimacy challenges arise when infrastructure projects are managed by private firms, especially ones foreign to the host country, and the tolls or other user fees that they are allowed to charge are viewed as excessive by end users of the facility [2,5,11]. This frequently results in demands for *ex-post* political interventions by governments, in violation of existing agreements between the government and the Special Purpose Vehicle (SPV)[2] that owns and operates the infrastructure asset [22]. These typically take the form of coercive downward renegotiation of tariffs or license agreements, which is tantamount to partial or complete expropriation of the income stream from the public works project. In extreme cases the asset may be completely nationalized, as in the case of the Cochabamba Water Project in Bolivia. Or it may be repurchased by a government agency under duress, as in the case of the SR-91 toll road in Orange County, California, which was sold back to a local public transportation agency by its SPV to in the face of severe consumer backlash against time-of-day congestion pricing by the private operator and a lawsuit that the SPV filed against the state for upgrading an adjacent freeway based on the strict non-compete clause in its concession agreement. Clearly, ex-post political intervention in infrastructure projects is not confined to developing countries [2,4,5,13,22]!

Displaced agency challenges result from the vertical fragmentation of the construction supply-chain by lifecycle phase. Decisions over the lifecycle of an infrastructure or other constructed facility almost always divide and separate considerations about alternative kinds and levels of capital investment from considerations of operating costs and sustainability. Infrastructure projects are often paid for by grants from provincial, state or federal governments and represent an inflow of money and jobs to the local area, while operating costs are almost always born locally. From lifecycle cost and sustainability viewpoints, this can lead to overinvestment (gold-plated facilities when broader jurisdictions pay most of the capital costs) or it can drive underinvestment (inadequate up-front investment in features that enhance maintainability, durability, energy efficiency, etc.) when locals bear all or most capital costs. This "displaced agency" arises in almost every kind of constructed facility, including infrastructure and it has spawned a legacy of buildings and infrastructure that consume much more energy than they should —even considering only investments with positive net present values (Enkvist et al 2007)— use non-recyclable materials that contribute to about half of the volume of most landfills, use water inefficiently and so on.

Previous Research on Governance of Construction

Researchers have focused on who should own and operate infrastructure assets at each phase of their lifecycle, often using the transaction cost economics (TCE) framework of Oliver Williamson (1979). This theory sums production costs and "transaction costs"—all of the cost required to locate transaction partners, enter into and consummate a transaction, including costs of arbitration or litigation related to the transaction—to determine whether the production of goods and services covered by the transaction should be performed by employees of the organization's

[2] Special Purpose Vehicles are corporations formed to finance and deliver a project such as an infrastructure asset with limited liability for its investors.

"hierarchy" or outsourced via the "market." For infrastructure projects, TCE has been used to determine whether governments should plan, finance, design, build and or operate infrastructure assets or outsource these functions via the market.

Scholars have long expressed dissatisfaction with the "sharp delineation of markets vs. hierarchies" especially in networked, project-based industries like construction (Gunnarsson & Levitt 1982; Stinchcombe 1985; Bradach and Eccles 1989:97) and have offered myriad calls to pay more attention to hybrid forms of organization in which relational contracting governed by trust complements or dominates price or authority mechanisms. This paper frames the challenges of governance for infrastructure projects and lays out the theoretical points of departure and empirical evidence to demonstrate that previous, narrow governance frameworks inadequately address this problem. The paper poses a challenge to researchers in this field to consider adopting a broader governance framework that integrates psychological, sociological and economic/legal perspectives. We begin by elaborating how opportunism can intrude into each phase of the project lifecycle, creating the kinds of failures we have described above.

High Transaction Costs across Phases of the Project Life-Cycle

The transaction cost economics framework for which Williamson received the 2009 Nobel Prize in economics makes a set of assumptions both about individuals and their behavior in the face of complex and uncertain transactions. It assumes that individuals have "bounded rationality"—i.e. they cannot know and comprehend all of the details and uncertainties associated with a complex transaction; and they will be opportunistic in exploiting all opportunities that they encounter to "pursue their self-interest with guile." Thus, when transactions involve high degrees of uncertainty and require one or both parties to make "asset specific" investments —i.e., investments that have little or no value outside of the given transaction—"hold-up" problems will inevitably arise in which one of the parties to the transaction can be opportunistic. High transaction costs arising from opportunism impact construction projects at every phase of the project lifecycle [2,3,4,5,6,7,8,9,13]. We illustrate this with examples.

Project Shaping Phase. In the project shaping phase, planning consultants are typically paid a fixed fee or reimbursable fee with fixed profit for their services by the project sponsors—the government agency acting as the owner-developer or the private consortium providing the equity investment and management of the project. If the projects go ahead based on planning stage estimates, these consultants are well placed to receive much larger contracts for detailed design and construction supervision on these projects, as well as future planning contracts from these and other sponsors. In the public sector, half-completed infrastructure projects become such a source of public embarrassment that governments—typically future governments—tend to find funds to complete them, blaming the cost overruns on their predecessors and taking credit for rescuing the failed projects. In the private sector, equity holders can often renegotiate terms with lenders to help them recover at least some of their potential losses from costs over-runs and demand under-runs—as was done in the case of the Channel Tunnel. So there are typically strong incentives for infrastructure planning consultants to align their behavior to serve the interests of politicized public and opportunistic private sector promoters, tending systematically to overestimate demand and underestimate construction cost. As a result, estimates of

demand for public works projects are notoriously optimistic; and estimates of construction costs tend to be even more so, resulting in "Bridges to Nowhere" that exceed their estimated costs by many times (Flyvbjerg et al. 2003) [8,14,16].

The true costs for these projects are deferred to future users or taxpayers whereas the political benefit from potential future counterparties and stakeholders for their announcement is received in the present. Thus, the local or regional development agencies or private sponsors and their agents (i.e., the planning consultants) opportunistically collude—explicitly or implicitly—to initiate the development of myriad projects whose long-run economic and political feasibility is sometimes dubious at best. Countries like Japan have clearly overinvested in infrastructure with many "bridges to nowhere" created by an extremely robust "iron triangle" of elected officials, government bureaucrats and engineering construction companies who all support each other (Sakakibara 2003). The Channel Tunnel between England and France is a sad example of a common pattern in infrastructure projects. This project exceeded its cost estimate of £2.6 Billion by almost 80%; its financing costs were 140% of estimated costs; and its passenger trip demand in the first year of operation was just 18% of the forecasted demand (Flyvbjerg et al, 2003). As a result, the Channel Tunnel has gone through multiple rounds of refinancing, and was just beginning to show a profit in 2009—15 years after commencement of operations—when it was hit with a shutdown that stranded 60,000 pre-Christmas passengers in the dark, cold tunnel for up to 16 hours!

Design Phase. When the up-front capital costs are borne largely by grants from a regional or national infrastructure agency (e.g., the UMTA rapid transit grants of the 1970s and 1980s to cities like Boston, Atlanta, Washington DC etc. or the EPA wastewater treatment plant grants of the 1980s and 90s which provided 90% federal funding), local governments working with their design consultants during the detailed design phase frequently "gold plate" (i.e., overdesign) the proposed facilities in order to create even miniscule savings in operating costs that will be borne exclusively or largely by the local communities that they represent. For example, a study of design decision-making on a major urban transit project, found that the local transit agency sought to eliminate the operational cost of pumping water out of a tunnel by specifying that the tunnel should have zero leakage. The engineers on this project, facing liability in the event of any leakage, specified a 12-inch thick concrete lining for tunnels, far beyond what was needed for structural support, at a cost of millions of dollars per mile (Levitt et al 1980). Private design consultants, or government professional engineers have strong incentives to go along with such overdesign, and design conservatively in order to avoid potential professional liability suits for failures of any kind (Levitt et al 1980; 1984). They have few incentives to design aggressively to limit construction costs: They work on reimbursable fee contracts; they are selected for future work based on consultant selection boards convened by the same public agencies; and any overdesign tends to be imperceptible to taxpayers within or outside the project service area [3,6,8,16].

Construction Phase. Construction under typical firm-fixed-price or fixed unit price contracts necessarily creates an adversarial relationship between the client, often represented by the engineer as its agent, and the contractor. Any ambiguity or discrepancy among the multiple sets of plans and specifications produced by multiple,

fragmented, specialist designers creates an opportunity for honest or opportunistic "change order" negotiation by the contractor to increase payments and allowable completion time. Negotiations about the legitimacy and magnitude of change orders can then further escalate into arbitration or litigation ("Claims") if not settled to the contractor's satisfaction. Thus, when contractors spot inconsistencies in bidding documents, they are motivated not to raise questions about any perceived errors or omissions prior to the bid, but rather use this asymmetric information to bid low, capture the project, and then seek additional compensation via change orders after work has commenced and they "discover" the discrepancies [4,5,8,13].

Operations Phase. Unified governance across the lifecycle is an obvious solution to displaced agency. Governments in almost all jurisdictions lack capacity to perform some tasks associated with the lifecycle of infrastructure, so one approach to unified governance has been the creation of private public partnerships that design, build, operate, maintain and finance infrastructure, recovering their investment through either user fees or periodic government "availability payments." Economic models clearly highlight the efficiency of market-based pricing for infrastructure services; however, the political and social sustainability of such pricing models is an open question, even in countries where the sanctity of contracts is a widely supported norm. When prices or shareholder returns for private operators of infrastructure are perceived to be "too high" relative to the ability or willingness to pay of consumers, direct or indirect political pressure to renegotiate the terms of the deal is likely to follow, irrespective of the formal independence of the regulatory authority, or sophistication of the contractual guarantees. It is simply impossible for governments to credibly commit themselves and future governments to contracts with private infrastructure concessionaires that remove these political elements of market risk.

An infrastructure owner's or operator's foreign identity can further aggravate perceptions of unfairness or illegitimacy by local stakeholders (Gomez-Ibanez et al. 2004). Consider the case of the water supply project in Cochabamba, Bolivia where the government granted a concession to a consortium of foreign companies for the city's water services. As soon as the private concessionaire began operations in November 1999, protests arose over the project. Tariffs had increased substantially by the new operators to cover the full capital costs of supply improvements. Additionally, the concession granted the consortium exclusive rights to all water resources in the city. As a result, well-established alternative water sources including privately-owned wells and storage tanks and tanker-based vendors were to be phased out over time. After six months of road blocks, strikes, and public demonstrations, the Bolivian government cancelled the concession contract. Nickson and Vargas (2002) suggest that, for the Bolivian population, the project represented "a preference for foreign capital over the national interest…" in a country with "…a long tradition of anti-imperialist rhetoric." Foreign firms delivering, treating and selling water for profit and imposing limits on groundwater pumping by local farmers flew in the face of local cognitive-cultural institutions (Scott 2001) that "…water is a basic, natural right of citizens." The public opposition generated by this project helped to feed a popular uprising that removed the entrenched government in 2006 [2,3,5,10,11].

These examples of displaced agency and lack of political legitimacy illustrate the flow of causality that generates the unique governance challenges of infrastructure

projects presented in Figure 1. Next, we identify some limitations of conventional governance approaches developed in response to these challenges [18,19,20,21,22].

Limitations of Conventional Governance

The construction management literature has followed the logic of transaction cost economics in arguing that a typical construction project, with its delayered system architecture and fragmented supply-chain, has some of the characteristics of both markets and hierarchies (Eccles 1981; Gunnarson and Levitt 1982; Stinchcombe 1985). Opportunistic behavior can, it has been argued, be mitigated through unified governance structures in which all of the lifecycle project costs and benefits of a project are born by a single entity—i.e. the local government agency [18,19], or a private entity that will finance, design, build, operate, maintain and collect revenues to pay back the costs of the facility over an extended period [21]. Alternatively, the opportunistic behavior can be mitigated through carefully specified contractual incentives with appeal to neoclassical contracting [20]. We argue that all of these governance mechanisms are partial solutions that fail to fully address the underlying hazard of opportunistic behavior by direct contractual counterparties, as well as stakeholders distant from the immediate transaction.

Unified Governance [18,21]. A design-build construction contractor unifies design and construction services and tenders a proposal to the client to maximize the value that can be delivered for a given budget. The client then picks the design-build tender —typically from a joint venture of one or more construction firms and design firms— that appears to offer it the greatest value for its fixed budget. In addition Design-Build contracting allows construction to begin before design is complete, and can thus save considerable time compared to a traditional Design-Bid-Build approach. However, only relatively sophisticated construction buyers can specify their requirements well enough at the conceptual design stage to pick a "Design-Build" or "Engineer, Procure and Construct" (EPC) contractor that will optimally satisfy its needs and wants for the project. As a result, this approach tends to be used for relatively well specified facilities. Large manufacturing services companies or large governmental agencies that develop a series of similar facilities over time can develop the in-house expertise to specify their requirements clearly and unambiguously enough to exploit this mode of contracting successfully. For other buyers, the subsequent buyer's remorse at what they have bought, or the *ex post* renegotiation costs incurred with a Design-Build contractor can outweigh the savings in time and the increases in value from using this approach.

In the case of infrastructure, several countries have decided to extend the scope of the Design-Build construction organization further, both upstream and downstream, I contracting with a single, private entity to finance, design, build, own and operate the facility for an extended period— typically 25 to 50 years. This further internalization, however, can generate yet another conflict in which the ultimate costs of the project are passed onto third parties—end users—who are unable to assess the risks that they are bearing accurately, or have no choice but to accept them. In addition, when a contractor or contractors that will design and build the project also take on the role of part owners of a private infrastructure development consortium, they have two ways to make profits: payment for their design-construction services, and income from their share of the investment returns for the operation of the facilities. The English

Channel Tunnel ("Chunnel") project described above is an egregious example of this conflict of interest problem. California's SR-91 project described below demonstrates a similar conflict of interest of builders versus owners.

Neoclassical Contracting [20]. Few if any public or private organizations are capable or willing to internalize the full set of transactions involved in infrastructure provision. Thus, some form of market exchange in which opportunistic behavior can arise seems inevitable. The traditional way to mitigate opportunism in such transactions is through the use of external commitment or bonding mechanisms, such as an appeal to the judicial system, financial guarantors such as surety bonding companies, or credible, third party alternative dispute resolution of detailed contractual commitments [20]. While in theory, the reliance on independent and impartial third party rulings could resolve the inherent uncertainty in complex and always incomplete contingent contracts, one or both parties may face incentives to tilt the playing field in its favor by directly or indirectly stimulating political intervention in the dispute. The aim of such influence tactics is typically to avoid the uncertainty of the dispute resolution process and use political or regulatory intervention to secure a more favorable and potentially expeditious outcome.

The history of the State Route 91 (SR-91) express lanes in Orange County, California highlights the implicit hazards of neoclassical governance of infrastructure projects, even in countries with well developed legal systems and property rights. The bondholders of the project demanded a strong non-compete clause in the PPP contract, which blocked the California State Transportation Department (Caltrans) from making any improvements to the SR-91 free lanes that could increase their capacity, and thereby undermine the revenue received by the toll road operator. The clause was invoked when Caltrans proposed a number of improvements to the free lanes in order to "alleviate safety concerns." In response to this proposal by Caltrans, CPTC filed a lawsuit against Caltrans in March 1999, claiming that the improvements were actually disguised efforts to increase capacity and, therefore, constituted a violation of the non-compete clause. Caltrans' actual intentions remain unclear and, in practice, it is often difficult to separate safety improvements from capacity increases. Although Caltrans and CPTC were able to reach a settlement, the combination of the lawsuit and a steep increase in tolls for the use of the road at peak commute times led to growing protests, and the labeling of the toll lanes as the "Lexus lanes". In the face of this upwelling of political opposition, the PPP consortium "voluntarily" exited the PPP agreement by selling the project to a regional transportation agency. The PPP concession agreement had failed to provide adequate means to renegotiate terms of the partnership as traffic conditions evolved [21].

Discussion

The examples described above illustrate a series of severe and recurring challenges to traditional and PPP forms of project governance for infrastructure development and delivery projects, arising from several underlying attributes of these projects and the industry that develops and delivers infrastructure assets. Displaced agency problems arise from the cycling in and out across successive project phases of the "project" of multiple horizontally and vertically fragmented supply chain participants playing different roles, and whose interests can be in direct conflict both within a project phase and across project phases. The broad scope of the potential counterparties

makes it extremely difficult to balance interests via contracts even at a single point in time; and it makes it especially difficult to continually realign contractual terms to sustain the balance of interests among parties over the decades-long lifecycle of such projects as global, regional and local technologies, economies and politics change in material ways. Finally, the strategic impact of large infrastructure assets on communities and whole countries invokes the intervening or moderating presence of governments in infrastructure disputes such as those described above. The always present specter of governmental intervention—even in liberal market economies like the US—overwhelms the power of contracts, whether backed by domestic courts or international arbitration and dispute resolution. Individuals or groups can appeal to political rather than legal resolution of perceived inequities that may arise over time. Clearly a richer set of mechanisms than contracts or unified governance is needed to make such projects predictably sustainable.

W. Richard Scott's (2001) "Three pillars of institutions" framework asserts that legal "regulative" institutions are, in practice, augmented by "normative" institutions in which social exchange among parties to a contract, and social sanctions for behaving opportunistically can temper opportunism. In addition, we argue that a large party of psychological research on "fair processes" that embody principles of procedural justice, and efforts such as "partnering" to build a shared identity for all project team members can harness the third pillar of institutions—"cognitive-cultural" institutions—to further mitigate economic incentives for opportunism.

Investors and host governments grappling with the risks posed by these socio-political governance challenges need to complement legal, financial and organizational mechanisms of governance with broader socio-political governance instruments. These instruments can facilitate adaptation not only by explicit economic counterparties but also by implicit economic, political and social counterparties. In addition to the power of legal fiat enjoyed by hierarchy and the economic incentives enjoyed by market, we seek to draw attention to the power of common identity and social ties in shaping the behavior of all parties in a manner that highlights collective interest, develops real trust and attenuates opportunistic behavior, without incurring the administrative costs and lost incentive intensity of full-scale vertical integration or the high transaction costs and ultimate failure of complex contingent contracts with cross-national trilateral governance.

Retail drinking water distribution has historically been one of the most challenging of all infrastructure sectors to govern both efficiently and sustainably. Cooperatives are an example of hybrid market-hierarchy-economic-socio-political governance frameworks that have been used successfully in several countries, including Argentina and the Philippines, to govern the operation of retail water distribution infrastructure, in the face of failures of both traditional governmental or Private-Public Partnership (PPP) governance approaches for this sector.

Conclusion: Toward Socio-Political Governance

We argue that future research on governance of infrastructure projects should draw upon complementary insights from multiple disciplines to develop enhanced governance frameworks that include regulative, normative and cognitive-cultural institutions. Our own future work will explore ideas from: social exchange theory, which focuses on the relationship versus the transaction as the unit of analysis; and

social control and sanctioning mechanisms, such as the construction of a collective identity (Dutton et al. 1994), restricted access to outsiders, socialization, sanctions and reputation (Jones et al. 1997), norms of reciprocity (Adams 1965; Gouldner 1960), and adherence to principles of distributive justice (Blau 1964; Homans 1958) and procedural justice (Lind and Tyler 1988; Thibaut and Walker 1975).

Our hope is that the ideas framed in this paper will encourage our fellow construction management researchers interested in contracting and governance to begin exploring the use of broader governance frameworks for infrastructure and other construction projects.

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KNOWLEDGE SYSTEM CONFLICTS IN GLOBAL PROJECT NETWORKS

Melissa Di Marco[1] and J. E. Taylor[2]

ABSTRACT

As the design and construction industry globalizes, firms are increasingly engaged in cross-cultural project networks that must share complex knowledge efficiently for projects to succeed. When complex design work is outsourced to international firms, researchers have shown that boundaries are created due to national cultural differences which can hinder effective knowledge transfer and reduce collaboration effectiveness. It is across these boundaries that knowledge system conflicts can occur. In this paper we longitudinally observe three complex engineering projects each involving a design firm in North America outsourcing a significant portion of the design work to an international engineering firm. Analyzing empirical interview data, collaboration meetings and project documentation we develop a model of knowledge system conflict emergence. We find these conflicts to arise in the initial stages of design collaboration. We classify the knowledge system conflicts into four categories; (1) linguistic, (2) scope of work, (3) work process, and (4) local knowledge. Understanding the emergence and typology of knowledge system conflicts that can occur on global projects can enable project managers to improve collaboration effectiveness on global projects.

INTRODUCTION

The increase in globalization influences how multinational architecture, engineering and construction (AEC) firms strategize to remain competitive. One strategic approach is to acquire engineering talent globally. As global firms establish ties with engineering firms in low-cost regions, the trend is now towards locating more complex and critical work in regions such as India, China, Eastern Europe, the Philippines and South America (Couto et al. 2006). The reality of offshoring services to remote countries is slowly evolving from low-cost call centers to sophisticated tasks that require professional judgment. Industries such as information technology have also

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begun to offshore high-caliber work to locations where talent is abundant and labor arbitrage is expected (Carmel and Tjia 2005).

Global project networks often invest time and money in order to keep up with the most up-to-date and emerging technologies to facilitate knowledge transfer. These include: establishing user friendly net meetings, chat services for faster communication, voice-over IP phone for call-ins, VPN networks for shared documentations, etc. They often overlook the challenges that exist at the beginning stages of design projects that can either make or break the collaboration effectiveness of the team (Levina and Vaast 2008). Not only can these challenges impede the project, but they can also result in poor performance within the network, making firms suspicious of future global collaborations.

Offshoring requires collaboration across time and distance that involves intricate coordination which is frequently met with even greater challenges (Hinds and Bailey 2003) often due to inexperience with collaborating in a cross-cultural environment. Nayak and Taylor (2009) identified the concerns between clients and vendors in global project networks and found a number of mutual concerns such as: cultural barriers, design practice norms, and role redundancy as well as unique individual concerns. When more than two parties are communicating within global project networks, these concerns identified by the client and vendors may become amplified. Knowledge systems envelop the combination of both national culture and organizational culture to define the individuals' experiences and set of values they bring with them when working in a global environment. In this paper we examine how knowledge systems evolve in global project networks by focusing on how networks address knowledge system conflicts that emerge.

BACKGROUND

In a study conducted by Couto and colleagues (2006) they found that some companies were choosing not to offshore due to internal organizational issues such as operational efficiency, loss of managerial control and lack of acceptance from internal clients. What this demonstrated is that companies are not necessarily opposed to offshoring strictly due to the cultural implications. Rather they believe that the internal structure of their own organization is not prepared for such exchanges. Companies that do not have a strategy in place to offshore complex work will quickly realize organizational boundaries within their global project networks (Chan and Tse 2003). As trends in offshoring mature, firms need to develop and understand their own strategies to cope with the dynamics of cross-cultural and inter-organizational settings. Ozorhon at al. (2008) investigated the impact of organizational and national cultural in international joint ventures and concluded that differences in organizational cultural created more conflict than differences in national culture. Many researchers focusing on cross-cultural collaborations might argue the latter, that conflicts and challenges are generated within global project networks due to the existing cultural differences (Mahalingam and Levitt 2007). However it is still important to also consider the impact of organizational culture within global project networks.

In Maloney and Federley's (1991) framework of organizational culture they identified that the effectiveness of organizations was highly dependent on whether their culture involved an open system that included room for adaptability, readiness

and growth. These are firms that focus on external issues and therefore are likely most effective at transforming and expanding over time. In a survey conducted by Dikmen and colleagues (2005) aimed at developing an analytical model for organizational effectiveness, of the 22 input parameters some of the most significant within organizations were found to be: frequency of joint venturing (JV); the strength of culture; level of organizational learning; adaptability/flexibility; and effectiveness of information flow. However, the most important parameter identified by respondents was the organization's ability to monitor changes in the markets and adapt to those changes. Recently, those changes would include developing strong relationships within global project networks.

There are a number of existing definitions for 'culture' established by researchers over the last century, particularly that of national culture. Kroeber and Kluckhohn (1952) examined definitions of culture over time and established that:

> *"patterns, explicit and implicit, of and for behavior acquired and transmitted by symbols, constituting the distinctive achievements of human groups, including their embodiments in artifacts; the essential core of culture consists of traditional (i.e. historically derived and selected) ideas and especially their attached values; culture systems may, on the one hand, be considered as products of action, and on the other as conditioning elements of further action." (p.47).*

Existing definitions posit that culture is significantly different across the boundaries of space and time. As firms from distinct cultures collaborate within global project networks, differences in national culture will create boundaries that lead to conflicts unique to global collaborations (Levina and Vaast 2008). Chen and colleagues (2009) compared cultural dimensions to distinguish any differences in managerial values of construction managers from China and the UK. Of the five key differences in cultural dimension found between the two nations, three of them were directly due to differences in culture: Chinese attention to relationships, Chinese concern for their company and the UK attention to utilization of the contract. These differences may explain why many western organizations have had difficulty penetrating the Chinese construction market and collaborating effectively within global project networks (NAE 2008). Past research has also supported these findings, determining similar differences in Eastern and Western cultural dimensions particularly between the individualistic cultures of the west versus the collectivistic cultures of the east (Bigoness and Blakely 1996). These cultural dimensions become a part of the organization's knowledge system and define work practices. Other qualities necessary to adapt to national cultural diversity in global project networks include: exercising good politics (Porter 1995) and the development of cross-cultural communication skills at the university level (Gilleard and Gilleard 2002). Though failures in communication may occur in regular project networks, linguistic barriers pose a greater problem within international collaborations. AEC disciplines have a standard technical language; nevertheless linguistic boundaries often emerge as problematic and difficult to penetrate in global collaboration.

The conflicts that exist within global project networks have been observed by researchers. Mahalingam and Levitt (2007) utilized institutional theory to determine the conflicts from a case. Their findings identified problems occurring during particular phases (i.e. planning, design and construction). Researchers of IT offshore outsourcing have identified conflicts occurring as a result of boundaries being created due to differences in national culture (Levina and Vaast 2008). More recently, research conducted by the investigators (Di Marco et al. 2009) isolated the categories of knowledge system conflicts that arose when American and Indian engineers collaborated on interdependent scheduling and modeling tasks. In this paper we extend these earlier findings by defining the categories of knowledge system conflicts and developing a notional model on how knowledge system conflicts emerge within large-scale engineering design and construction projects that involve globally dispersed team members. Past research has done an adequate job at identifying the various cultural 'clashes' from both an organizational and national cultural perspective along with the challenges that exist. All of which contribute to the knowledge system of the engineers in the global project network. However, little is known about the emergence of the conflicts that surface at the boundaries of diverging knowledge systems collaborating within a complex global project network.

METHODOLOGY

There are many emerging forms of global collaboration in the AEC sectors due to the increase in popularity of offshore outsourcing (NAE 2008). Due to shortages of engineers in western nations, many engineering and construction firms are outsourcing their work to low-cost regions such as China, India, Easter Europe and South America (Coutu et al. 2006). In this paper we discuss ethnographic data collected from three large engineering firms based in North America, offshore outsourcing a significant portion of design to globally dispersed teams of designers in India and Eastern Europe. From each of the participating global firms we chose one project to observe longitudinally, over the span of up to two years. In order to maintain consistency, we chose all three of the projects to have somewhat similar scopes.

The purpose of this research was to explore and reveal the unique types of conflicts that emerged due to the diverse knowledge systems in global project networks. In order to understand the circumstances in which conflicts arose and between which participants, it was important to study this phenomenon longitudinally. Thus, we are first conducting a series of semi-structured face-to-face interviews, over the course of each of the projects, in order to obtain the views of key members and regular project personnel (Spradley 1979) from both the onshore and offshore locations. The basis of the interviews was to discuss the main challenges faced within their global project networks and, in particular, the projects at hand (see Table 1 for a breakdown of all 75 interviews by country and global project network, GPN, as well as the type of project being observed). We presently have completed 37 interviews with onshore project personal and 38 interviews with offshore project personnel. As part of the data collection process we were also present at a series of general and milestone project meetings that occurred both virtually, via Internet and phone, and face-to-face, most of which were also recorded and transcribed. Lastly, we were given

access to project documentation in order to gain a greater understanding of the context of the work processes carried out.

Table 1. Data Collected from Case Projects

	Interviews Onshore	**Interviews Offshore**	**Meetings**
GPN #1 (Gas Plant)	5	(Romania) – 7	18
GPN #2 (Gas and Coker Plant)	11	(Kolkata, India) – 22	23
GPN #3 (Power Plant)	21	(Mumbai, India) – 9 (Warsaw, Poland) – 2	3
Total:	**37**	**38**	**44**

The interviews and team meetings were transcribed and compared across projects and firms to reveal knowledge system conflicts. Data was analyzed using the grounded theory method outlined by Glazer and Strauss (1967) to deductively develop an answer to the question of how knowledge system conflicts emerge within global project networks. In order to synthesize our findings from existing literature, our approach to data analysis could be described "middle-zone theorizing" in which initial examples are chosen systematically (Eden and Huxham 1996). We are imported and coded the transcriptions into qualitative coding software (Atlas.ti) for analysis and comparison.

PRELIMINARY FINDINGS

The following section is a discussion of our preliminary findings from the ongoing data collection and analyses of the three design projects we are studying. We extracted from our observations the specific instances of knowledge system conflicts. While we mainly found that these specific conflicts were somewhat distributed throughout the length of the project, the majority of KSC's were present at the earlier stages of collaboration and most salient in the less experienced global project networks. In the words of one of the more experiences onshore managers: *"It really is a matter of growing pains, in the beginning you think, 'what did we get ourselves into' and then after sometime you get into a routine so the work just flows as it should and then you find it's worth it."*

Linguistic Conflicts

As global project networks often involve collaborating with firms that work in a different first language, linguistics is often a source of miscommunication. Linguistics however, is far more complex than language itself, it involves heterogeneous interpretations from both people and organizations; where boundaries are created and conflicts emerge. As explained from GPN#2's offshore manager:

> *"Technical language is technical language. [The company has previously] had communication training for Texas English. One problem is in their [Indians] own head. They don't speak up freely and speaking up is important to Americans.*

There are plans for more training. The best way to participate and improve is by practice, [we try to give everyone] the incentive to push to cross the language barrier. When a manger from the US first came here he said to me "no one understands me." I said speak slower. He said I never thought of that."

By and large, despite the common engineering language that design offices across the globe share, linguistic miscommunication, either it is language or interpretation was still identified by many study participants as a main source of conflict. These were more present in global project networks with less offshore outsourcing experience.

Proposition 1a): If language and interpretation differences in Global Project Networks are inadequately mitigated at the initial stages of collaboration; linguistic conflicts emerge.

Proposition 1b): If language and interpretation differences in Global Project Networks are adequately mitigated at the initial stages of collaboration; linguistic conflicts are reduced.

Scope of Work

Conflicts due to scope of work existed within all three design projects we studied. Most of the offshore firms claimed to work from a relatively well defined scope of work. The onshore managers felt they adequately represented the work on their part; however the detail within these scopes of work was often misinterpreted. Sub-tasks were delegated to the offshore party by the U.S. counterparts either through e-mail or phone, which might have been fine for a U.S. firm, but, was misinterpreted by the offshore collaborators. This was often a cause for frustration from both parties. Scope of work conflicts emerged when tasks were being completed incorrectly by the offshore designers and U.S. partners were not making themselves available for adequate questioning as they felt they had delivered sufficient information. From the offshore perspective, they often felt as though they were not being properly guided within the scope of work and this therefore left them susceptible to making incorrect judgments from their own interpretations. When discussing the lessons learned so far with the offshore project manager of GPN #3 he emphasized:

"*Definition of work, if that has been done properly then we are very fast to execute that work. At one point in time they kept on sending us many changes and they kept on sending changes to us in pieces and some documents you would see 17 to 18 revisions. They had us stop working in ordering to finally decide what to do."*

This is often seen as a problem in offshore outsourcing of design work as onshore personnel can think due to the low cost of labor, this empowers them to ask for changes liberally without consequences. When large-scope AEC projects have many decision makers, these changes (and insufficient team assignment definition) can often add up and incur greater costs to the project. Frequently the offshore design group is held responsible for not maintaining their agreed to scope of work hours as initially agreed upon because of this.

Proposition 2a): If partnering firms in Global Project Networks lack adequate scope definition and do not enable scope clarification; conflicts emerge due to scope of work.

Proposition 2b): If partnering firms in Global Project Networks dynamically maintain and enable a well-defined scope of work; conflicts due to scope of work are reduced.

Work Process

Work processes also have difficulty transferring through both organizations and cultural boundaries. In engineering design the QA/QC phases often represent an important component to the continuation of work. Within global project networks, the checking and accepting of documentation is often also misinterpreted. Particularly with design work that involves vertical splitting of the project between global partners as the interface portions often are causes for conflict when two organizations carry out their work differently. A designer from GPN#1's offshore team expresses his frustration with this:

"Sometimes the Americans, they don't think, they send us back work that they say is wrong, and when I ask them why they say 'that is not the way we do it here'. They see it as wrong but it is not wrong, it works just fine but it's not how they would do it. That does not make it wrong."

A vertical split of design work is when one entire portion (vertically), including all disciplines, is allocated to one team. Despite these differences in work process, through our observations we found that often what works best is to allow the global partner to continue utilizing their organization's work process. By not enforcing too many onshore, and unfamiliar, means and methods the offshore partners feel less pressured to meet the onshore expectations. This acceptance of differences does not necessarily reduce the quality of work but can reduce the number and magnitude of knowledge system conflicts that emerge from diverse work processes.

Proposition 3: When partnering firms in Global Project Networks meet at an interface portion of the engineering and design work; conflicts due to differences in work process emerge.

Local Knowledge

When it comes to the local knowledge and the awareness of differences in design work that can exist in remote locations, it is often the lack of exposure the offshore offices face that leads to knowledge system conflicts. As the exposure within the global project networks increase, the local knowledge of both onshore and offshore offices are expanded to achieve a more thorough mutual understanding as is described in the following quote from an offshore structural engineer in GPN#3:

"When we did work with another office in Australia, it was a heavy civil project. We had someone stationed here for fifteen days. So basically when we started to do the design work, the designing aspects and the requirements were understood very clearly. Because he was here, and he was talking to the vendors also and

asking them the required information of which we were asking of him. That coordination moves things much faster."

In engineering design and construction adaptability is imperative in less developed nations as they are often forced to comply with what is available to them. In western cultures the approaches are much different as efficiency is emphasized and designers and contractors work to optimize their work while reducing their costs. An onshore structural lead from GPN#2 confirmed this observation:

"We started off using CMU [concrete masonry unit] walls and then we switched it over to concrete. We eventually found out that for them it was easier to do the concrete because they are more familiar with it. Their way of doing CMU is very different from us... Their way of construction is that they form the cast-in-place columns and beams and fill it in with CMU and it's not actually structural, so changing these drawing took up quite some time."

These tasks can often be completed quickly as unlimited resources are also available to them. When working in a global setting the lack of this type of local knowledge can often lead to misunderstandings and rework.

Proposition 4a): If partnering firms in Global Project Networks lack adequate exposure to one another's working environment and expectations, local knowledge conflicts will emerge.

Proposition 4b): If partnering firms in Global Project Networks consistently expose one another to their work expectations, local knowledge conflicts are reduced.

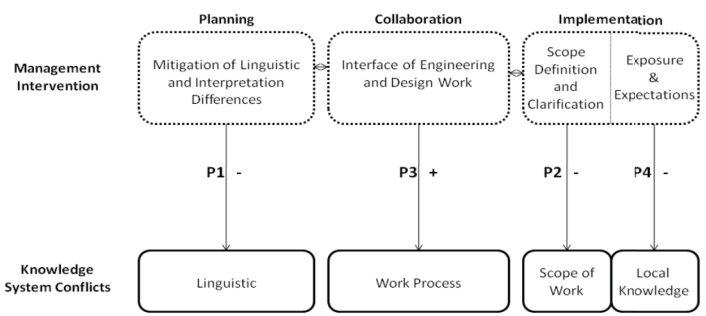


Figure 1. Emergence of Knowledge System Conflicts in Global Project Networks

Knowledge System Conflict Framework

The data presented above is specific to networks that are globally distributed, however the possibility remains that knowledge system conflicts can also be present in firms that are collocated. We observed that during project execution, the differences between the individual firms' knowledge systems created boundaries that in turn led to the emergence of knowledge system conflicts. We propose that merging of organizational and national culture within a global project network's knowledge system, results in greater conflicts at these boundaries. Figure 1 includes a

propositional model of the emergence and categorization of knowledge system conflicts. We observe that the conflicts emerge during three stages of project execution which include: planning, collaboration and implementation. It is how the individual stages are managed by the onshore and offshore project managers that determine the degree of knowledge system conflicts that will emerge in Global Project Network collaborations.

CONCLUSIONS AND NEXT STEPS

This study summarizes one aspect of a current investigative research aiming to observe, dissect and explain the practicing dynamics within engineering global project networks, particularly the offshore outsourcing of engineering and construction services to remote locations. Through the use of longitudinal observations, participating in meetings, and semi-structured interviews we were able to preliminarily interpret the knowledge system conflicts within global project networks. Conceptualizing these knowledge system conflicts has important implications for the study of differences across organizational cultures and national cultures in global collaborations. By applying this approach we extend the existing literature on the implications of differences and subsequent conflicts that materialize within inter-organizational and inter-cultural project network collaboration. Both onshore and offshore managers can benefit from this study by understanding how knowledge systems can reduce collaboration effectiveness of global collaborations. In the next stages of this research we aim to further validate these findings in order to develop a framework of the emergence and patterns of knowledge system evolution in global project networks.

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Theoretical Categories of Successful Collaboration and BIM Implementation within the AEC Industry

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Abstract

Researchers have found successful collaboration that spans organizational boundaries enhances the productivity of the design and construction process. Researchers and practitioners alike argue using Building Information Modeling (BIM) should lead to tighter collaboration and closer communication among project participants working in cross-organizational environments. Using data from observations over fifteen months of the integrated design process of a laboratory building project, we build a typology of the strategies of successful collaboration within the AEC industry. Then, using interview data from 70 architects, engineers and general contractors from across the U.S., we test our proposed typology to suggest how the collaboration process is implicated in inter-organizational BIM integration.

We find that inter-organizational BIM-enabled projects and successful inter-organizational collaboration have shared theoretical categories: fostering integrated teams; implementing tools and strategies to encourage clear communication across the team; and developing transparent technology use. We argue that attempts at either will not be successful without first establishing the right social and organizational foundation that supports both collaboration and successful technology implementation.

Introduction: The Relationship between Collaboration and BIM

In industry and academia alike, discussions about Building Information Modeling (BIM) often include arguments for collaboration across organizational boundaries

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(CURT 2004; American Institute of Architects 2006; Taylor 2007; Eastman, Teicholz et al. 2008). Common approaches for facilitating collaboration involve some combination of risk sharing, obtaining access to new technologies and markets, co-location and pooling complementary skills (Hagedoorn 1983; Kogut 1989; Kleinknecht and Reijnen 1992; Eisenhardt and Schoonhoven 1996; Harty 2005). However, when new technologies are introduced within organizations, regardless of the setting, people have often resisted change (Barley 1986; Orlikowski 2000; Bechky 2003). Furthermore, in the ACE industry, cultural and organizational boundaries tend to stifle collaborative work and joint problem solving even with contractual agreements meant to foster a team environment (Cicmil and Marshall 2005). In previous research we found that organizational cultures and the norms of organization on construction projects play important roles in how practices contribute to successful projects (Dossick, Neff et al. 2009). Although researchers have found that when digital tools are introduced to help coordination, teams may be more satisfied with results (Orlikowski 2000; Liston, Fischer et al. 2007), in inter-organizational collaborations, "considerable mutual adjustment" is often required to make technology adoption successful for collaboration (Taylor 2007).

According to the vision established by the National BIM Standard (NBIMS), taking full advantage of BIM technology requires an industry paradigm shift where information is exchanged, shared and coordinated electronically across organizational boundaries (Smith and Tardif 2009). In this paper, we address what we call inter-organizational BIM or *I-BIM*. With I-BIM we refer to the use of these tools across organizational boundaries including interdisciplinary scope coordination (e.g., structural and architectural models, or building systems models), and vertical integration of information exchange (such as steel design and fabrication). This is in contrast to some existing definitions of BIM that are used to refer to a *single* organization's adoption of object-oriented modeling tools such as Revit or ArchiCAD. When referring to collaboration across organizational boundaries—with or without shared technology adoption—we use the term *collaborative project environment* or CPE. When comparing the findings from a case with a successful collaborative project environment to qualitative data on successful I-BIM, we find that the two share "theoretical categories" (Strauss and Corbin 1990). That is, following established qualitative research methods we find many of the same underlying themes in the data from a "non BIM" case and in BIM projects. Our research implies that successful I-BIM and successful CPE should be tandem goals for the same array of cultural and organizational changes within integrated design build teams.

Our paper proceeds as follows. First, we describe the methods used in our case study and interviews. Then we outline the three theoretical categories of strategies for success that emerged from our qualitative data: 1) fostering integrated teams, 2) implementing tools for clear communication, and 3) developing transparent technology use. We discuss the implications of these similarities for successful BIM adoption and the limitations of our research. Finally, we suggest avenues for future work to tease apart the effects of adoption of BIM technology from the organizational and social environments that support collaboration.

Methods & Setting

We observed over a fifteen-month period in 2008 and 2009 the social, organizational, and technological strategies that a multidisciplinary Integrated Design team used to collaborate on the design and pre-construction process for a scientific research lab project in a U.S. city. This project, while highly collaborative, did not utilize I-BIM. We chose a qualitative research design to build theory based on observed practices—not reported responses—of people implementing change within the AEC industry. The "grounded theory" method that we describe below is well-suited for generating theory that builds on observed practices and is applicable to settings outside of the particular one observed. This allows researchers to develop a rich picture of social practices and is ideally suited for observing culture, communication, and values, especially in workplace settings where these may be in conflict.

We participated in weekly schematic design meetings, weekly consultant meetings between the architect and engineering and other consultants, weekly preconstruction meetings led by the general contractor, and occasional stakeholder meetings. We also observed members of architectural, engineering and construction teams in their offices as they collaborated on these phases of the project. We wrote detailed field notes as soon as feasible after each observation and meeting for over a total of 300 field hours of work. These were then compared using an iterative coding scheme based on the methods of "grounded theory" development (Glaser and Strauss 1967; Strauss and Corbin 1990). We analyzed our field notes for strategies that were observed during meetings and workplace participation. We then combined similar strategies into theoretical categories that we, in turn, compared back to the field notes and to our observed experience, adjusting our categories in response to the evidence from the field data confirming and extending our theoretical categories until reaching the point of "theoretical saturation," (Strauss and Corbin 1990) when no new theoretical categories emerged from our data and our existing theoretical categories were stable in continued comparison. These results form the typology of CPE theoretical categories.

Similarly, we constructed theoretical categories from the analysis of a purposive subsample of interview data on experiences with Building Information Modeling. We interviewed 70 architects, engineers, and builders (none of whom worked on our observed project) for 60-90 minutes using a semi-structured interview tool on collaboration, communication, organizational culture, and BIM. Using a similar iterative, open coding process, we first identified the strategies that our respondents associated with the successful implementation of BIM and then combined these into theoretical categories. These theoretical categories were then compared back to the interview data in general, adjusting our theoretical categories to confirm our theoretical categories from our subsample of interview data through iterative comparison.

Findings: CPE and I-BIM Theoretical Categories

Based on observation data of a non-I-BIM project, we developed a framework for studying the strategies used in the AEC industry to achieve a collaborative project environment. Within this framework, we identified three key overarching theoretical categories: 1) fostering integrated teams, 2) implementing tools and strategies to encourage clear communication, and 3) developing transparent technology use. We used this framework to analyze our interview data and found that these three theoretical categories also emerge as essential for implementation of I-BIM in our qualitative interview data. Below we discuss each theoretical category, how it supports the collaborative project environment, and how BIM technologies may be integrated into this process.

Fostering Integrated Teams

The first and largest CPE theoretical category is fostering integrated teams. Integration requires a strong organizational foundation to remediate the preexisting cultural and organizational divisions that can stifle collaborative work. Integrated teams fostered by strategic behaviors of the team members as well as procedural and managerial strategies can help dissolve the cultural divisions that impede joint problem solving. Within teams enabled by I-BIM, information may be digitally integrated but there may remain organizational barriers that prevent the open information sharing (Dossick & Neff forthcoming). As an architect we interviewed stated, "It never is just about the tool. And we need the tool to support what human beings are doing together, but it's very much a human thing, very much a human thing... [B]ad technology can make it harder to do things, but if you've got a good set of human relationships, you can overcome any of the technology obstacles" (A080125).Below we present organizational– and individual-level strategies to foster integrated teams, in order to show the complex relationships among individual attitudes, procedural structures, standards of practice, technology applications, and business contracts.

Organizational-level Strategies. We identified several organizational-level strategies that foster integrated teams to achieve CPE, a majority of which also support implementation of I-BIM. Together, social and procedural strategies in this theoretical category account for approximately 63% and technical and contractual strategies about 25% of the total number of strategies we identified.

Building relationships among individuals on a team requires some social engineering. Examples of social strategies include building trust, training collaborators, building on prior relationships, developing issue-logging processes, and pairing experienced staff with technically trained personnel. These strategies appear both in the data on the CPE case study and implementation of I-BIM. For example, talking about effective collaboration, one architect we interviewed mentioned the importance of "…working in a trust-built, incentive-based environment to produce collective values" (A071121). In prior case studies of I-BIM, we also found trust among the project participants to be significant, and we argue that maintaining trust in

leadership, information technology, skills of others and organizational processes are success elements in achieving a higher level of collaboration when using BIM technologies (Dossick et al. 2008).

The paradigm shift required for collaborative project environments is more explicit within I-BIM environments and challenges the standard procedures used in the industry to conduct work. Some of the procedural strategies identified to be effective in fostering integrated teams include timing of specialists in design process, allowing direct communication between first, second and third tier parties; developing issue logging processes; pairing people experienced in the field with people who are experienced with the technology; co-location; and conducting integration sessions. We found that most of these strategies were present in the I-BIM implementation data as well. For example, procedures to allow direct communication and information exchange between first–, second–, and third-tier parties, such as among fabricators, subcontractors, and designers can lead to better collaboration. New ways of organizing communication among these teams should also accompany I-BIM adoption or any other technological integration for joint problem solving.

Technical procedures and standards of practice such as use of reliable ways of mutually sharing documents and using interoperable programs are also applied in the AEC industry to foster integrated teams. These techniques and procedures, found to be fundamental in implementation of I-BIM technologies, are also seen to be important in facilitating CPE with or without I-BIM technologies. Development of standards and procedures to use I-BIM or other communication means and methods, results in having a less problematic and more authentic collaborative environment.

Interviewees often mentioned contractual issues as barriers to achieve integrated teams. Inter-organizational collaboration requires participants to consider what is best for the project coordination or design. Contract clauses can be used to foster a sense of shared risk and responsibility for the overall project outcome from the individual players who have a specific scope contribution and who do not traditionally benefit from the project's success. All of these organizational strategies take part in maximizing the benefits of using I-BIM technologies where project participants need to openly share their data and avoid duplicating documents, data entry, and modeling. However, beyond the organizational-level strategies to help fostering integrated teams, group- and individual-level strategies also provide a better environment for fostering integrated teams. We address these strategies in two major types: 1)Teamwork and 2)Inter-organizational meetings.

Teamwork Strategies. We identified several strategies for developing leaders' and team members' skills that build towards an integrated team environment. Approximately 80 % of these strategies are social and 20% are procedural. These strategies include improving the interpersonal skills and attitudes to support team integration. For example, architects have a critical role in the design phase to establish and maintain an integrated team. Architects and General Contractors need to build strategic team relationships to help them lead the group. They, furthermore, face the challenge of gaining knowledge of other disciplines to be able to understand the

scopes and oversee construction. As one of the architects we interviewed stated: “So for a young architect I’d be saying—build something, be involved in building and be involved with people who build, because then you’re connecting concept and execution” (A071121).

Alternatively, all team members should know more about other scopes to obtain a holistic understanding of the project and their role within that context. According to our interviewees, gaining inter-disciplinary knowledge is also crucial for implementation of I-BIM. As one of our interviewees said, “[I]t is important for [engineers] to be working in the same medium as everyone else, which is the whole point of BIM—making sure that everyone is working in a shared medium, shared space, and that requires them to rethink the way that they work because their specific way of looking at something might be great on its own but needs to be kind of tweaked a little bit to fit into a comprehensive view of the project” (A071217).

Team members should be willing to learn from each other and educate others about their scopes. Understanding the project as a whole appears to help team members be more flexible and innovative. When individual interests conflict, such understanding can lead to equitable compromises between scopes and the project as a whole. For example, a structural engineer whom we interviewed agreed to use a less efficient structural system to accommodate a basement that the project needed for security. Working with the architect and other consultants, the engineer optimized for the project constraints, rather than just the structural system.

Another teamwork-specific strategy entails project participants realizing their own strengths and weaknesses as well as other team members’ strengths and weaknesses. This can be challenging in a fast paced ego-driven environment were professional expertise is the calling card. As the team forms, they can focus on respecting others’ ideas and be sympathetic with other team players technical issues and constraints. Even in problematic situations, team members can choose to problem solve and work together or get defensive and blame others for the issues at hand. In this way, team members set the tone for their interactions. Our interview data show that developing these personal skills and teamwork strategies not only helps to support a collaborative project environment, but they also provide an ideal social context for implementing inter-organizational BIM.

Inter-organizational Meeting Strategies. The strategies that we identified for inter-organizational meetings split evenly between social and procedural strategies and standards of practice. Face-to-face meetings play an essential role in fostering integrated teams as they provide the opportunity to brainstorm on the issues that are related to multiple disciplines. However, conducting efficient meetings in which all the team members actively participate is a challenge. Procedural strategies have critical influence on the quality, effectiveness, and productivity of meetings. Some of these include starting and ending the meetings on-time, clearly stating meeting goals and agendas, having a scribe for general meetings, and insuring that no single scope or issue dominates general meetings. Social strategies relate to leadership and teamwork. For example, the role of the meeting facilitator is to encourage

participation and to include all the ideas in the conclusion so that everybody feels invested. Participants should follow several basic ground rules such as respecting others' ideas, being active listeners, relying on dialog, and avoiding the use of disciplinary jargon.

There is a balance that must be struck between structuring meetings to handle detailed scopes of work versus exploring a wider range of solutions and involving team members in the decision-making process. In integrated practice, such meetings cannot cover the requirements for all scopes and situations. According to our observations, general coordination meetings would break into smaller scope meetings, or "pocket meetings," where architects and engineers would work on specific issues in smaller groups during a general meeting. These informal pocket meetings often occurred spontaneously as small groups of 3-5 people would break out for twenty minutes for a more detailed discussion after general group discussions. If needed, the group would draw someone into their conversation with a question or join another huddle with a comment, clarification, or question. Architects often circulated among these pockets to keep the issues moving.

Implementing Tools and Strategies to Encourage Clear Communication

The second theoretical category for CPE and implementation of I-BIM is applying proper tools and strategies to encourage clear communication. Within the context of the integrated teams discussed above, the team members followed certain strategies to ease the process of information exchange and minimize misunderstandings, information loss, and time for communication. We identified several strategies in this category ranging from social and procedural to technical and contractual, with more emphasis on procedural and standards of practice (56%). While these strategies are effective for inter-organizational collaboration, some are not seen as important for implementation of I-BIM, as they are mostly embedded in the I-BIM technology. For instance, one of the significant ways of encouraging clear communication on non-I-BIM projects is to have updated documents and models in the coordination meetings to reduce any ambiguity in critical situations. Within an I-BIM project, the model can be shared in real-time from a central server such that all project participants work from a shared database and always work with current information.

There are also strategies to encourage clear communication in collaborative environments that do not have a direct effect on the implementation of I-BIM, but could be used to supplement the tools. One example is sketching. In general, BIM-enabled projects may have less need for sketching, but we found that sketching by hand was an important way to communicate during meetings. In the words of one of our respondents, sketching is part of "a visual language, and there is just a lot of subtle information in that visual language which is lost when the information is coming off of high speed plotters" (A080125).

Communication strategies are at the heart of our industry's work and there are many practices in collaborative environments as well as I-BIM enabled environments that support clear communication. Examples from our case include strategic

documentation. Collaborative project environments were fostered when designers made an effort to tailor the presentation of information to their audience. We observed examples of both positive communication where the concepts were easily understood, fostering constructive dialog and negative communication where the time was spent in explaining or re-explaining misunderstandings about the design decisions or issues at hand, from which project participants left frustrated and antagonized. To have a clear communication, it is important for the design team to present their work to the construction team by compiling documents and models that are meaningful for builders—combining information and representations differently for execution than for design. In one of our case study observations, there was a discussion about how to efficiently model a ventilation system for the building. One of the main concerns was how to find the right tool that can integrate certain variables and flows without needing extra modeling effort that does not serve the project interest. After all, once the right tool is agreed upon, it is important to "model for a purpose" (081203) to eliminate extra modeling cost and help to clearly communicate the required information. Within BIM-enabled environments, strategic modeling is seen as effective in encouraging clear communication. As an architect explained, "[Consider] how would the reader of these documents receive them. . . . [I]t's important to talk to those people as you shape your design, but also as you formulate the way that you communicate it, because you want it to be in a language that they understand, that's kind of native to the way they work" (A071217).

Developing Transparent Technology Use

The last theoretical category of achieving CPE and implementing I-BIM is developing transparent technology use. Effective strategies in this category are mostly procedures and standards of practice (76%) while there are some technical and contractual considerations as well (24%). Although CPE and I-BIM share many strategies for developing transparent technology use, not every strategy in this category is applicable for achieving CPE as the strategies depend on the level and type of the technology used in the project.

Procedural strategies that support transparent technology development include staged delivery of the model, improved intelligibility of models and documents, and accurate use of the programs. Accurate use of the programs refers to using software programs according to their standards and procedures. For example, using a 3D drafting tool, it might seem simple to sketch a wall as a generic rectangle, or to use two parallel lines in a 2D representation. However, as the project advances and more modifications are applied to the documents, the walls drawn with generic objects or parallel lines might not support downstream usage such as "hosting" a door or ventilation system. For the projects that are using I-BIM, this could be more problematic, because it is nearly impossible to anticipate the variety of ways the model will be used by others on the team. For instance, if the same model drafted by the design team, is passed to the construction team for cost estimating, the program will not recognize the walls as they are not drawn by the right function, and they need to be re-modeled.

Developing transparent technology use is also contingent to using defined standards of practice, which includes developing standards of interaction and finding common parameters to work on the models/documents. This is especially important within collaborative projects where the team members are using different modeling or drafting programs. However, even within I-BIM-enabled projects where the team is working within the same digital environment, it is important to define all the parameters of the software according to the project needs (e.g., the dimension tolerances and shared reference lines) and provide team members with those settings.

Technical considerations such as addressing interoperability issues and contractual strategies such as addressing issues of liability in the contracts are also important elements in achieving transparent technology use. However important these issues are, they are not sufficient to overcome the barriers to transparent technology use. If architects and engineers openly share their models with the construction team, the project participants still need to understand the contractual risk allocation, explicitly address technological barriers, redefine standards of practice, and develop collaboration procedures to support transparent technology use.

Discussion and Conclusion: Implications for BIM Adoption

We created a theoretical framework to describe the implementation of collaborative project environments and inter-organizational BIM. The three main theoretical categories in this framework, fostering integrated teams, creating tools and strategies to encourage clear communication, and developing transparent technology use are interrelated in that they influence each other. Social and organizational dynamics of a project can positively or negatively reinforce each theme. If technical standards, exchanges, and issues are addressed, this positively supports the development of a team environment. However, if team meets regular technical challenges, this has a negative impact and erodes the trust in the process and the team formation. Likewise, with clear communication and transparent technology comes more team member confidence in technology integration. Integrated teams also support clear communication and transparent technology strategies. Our analysis implies that if a team succeeds in one area, they are more likely to succeed in the other two as well. Thus, these three large categories of strategies that we identified are tightly coupled and interdependent with success in one area supporting success in the others.

The fundamental categories of the collaborative project environments are also fundamental for inter-organizational BIM implementation. Although I-BIM implementation requires the refinement of standards of practice, procedures, and contractual processes, many of the strategies were at the team and interpersonal levels of the organization for both I-BIM and CPE. Thus, our research shows that the social environment and organizational foundation used on projects that exhibit successful collaboration is also found in instances of successful I-BIM implementation. As a result, implementing inter-organizational BIM and establishing collaborative project environments should be pursued in tandem; one cannot cause or lead to the other. This finding contradicts some arguments in the research literature that the implementation of BIM itself can push for change in the social and organizational

context. Our research implies that failure to implement I-BIM successfully could, in part, be due to pre-existing ineffective collaboration strategies.

Future work

Our findings imply that current scholarship on I-BIM needs to tease apart the effects of adoption of BIM technology from the organizational and social environments that support collaboration. This will enable scholars to identify causal variables and associated effects. One future step could be to quantitatively test the impact of each of these strategies on the overall success of the project. This would allow the field to better predict which projects have a greater likelihood for success based the strategies that teams pursue. It could also potentially lead to findings that suggest to the industry how investments in particular strategies should be prioritized.

While our framework can be used to assess the relationship between CPEs and I-BIM, it could be expanded and tested in other situations, such as evaluating the outcomes of green building projects based on design and construction teams' collaboration and technology practices. This could, in theory, allow researchers to better understand how the adoption of technological and social changes within the process of design and construction could improve buildings themselves.

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THE EVOLUTION OF COLLABORATION WITHIN INTER-ORGANIZATIONAL NETWORKS OF TEMPORARY PROJECT TEAMS

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ABSTRACT

This paper introduces an agent-based simulation (ABS) of "*the evolution of collaboration*" within inter-organizational networks of construction project teams from a game theory and social network point of views. Our simulation shows that as individuals are less familiar with others in the network and thereby less aware of networks they are involved in, it is more likely to take a longer time for networks to reach stable states. It was also found that the stronger tendency of cohesion arises, as the effort that individuals have to make for forming a relation with outside partner increases. Furthermore, the results indicate that the more efforts individuals need to make to form relations with those from other organizations, the less efficient networks are formed.

KEY WORDS: Project Management, Organizations, Networks, Simulation

INTRODUCTION

As construction projects have been getting larger and more complex (Chan et al. 2004), close collaborations among project stakeholders are more importantly emphasized in order to accomplish project objectives. However, project teams in large-scale construction projects have not been very successful at being flexible and

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thus it is not unusual for them to fail. According to Morris and Hough (1987), unique organizational features of construction project teams have resulted in project failure such as cost overruns or schedule slippages which are becoming pandemic in large-scale projects (Flyvbjerg et al. 2003). Nevertheless, current construction management practice does not reflect the organizational aspects of projects and there have been only a few investigations on the impact of organizational processes on quality of project teams' outcomes and overall project performance. Based on these considerations, this paper proposes a game-theory model to explain the evolution of collaboration within inter-organizational networks in temporary teams of large-scale construction projects and an ABS on the basis of the developed model.

THEORETICAL BACKGROUND

Collaboration in Construction

Collaboration is vital to accomplish project objectives in the building process (Shohet and Frydman 2003). However, often times, the crux of communication and coordination called *social dilemma* (Hanaki et al. 2007) takes effect. Particularly, the problem of social dilemma arises when individuals' interest and their collective outcome are at odds. Even though cooperative and altruistic actions could produce a higher outcome, individuals end up with selfish actions by with which they can be better off. The other considerable issue regarding collaboration is the *embeddedness* in networks (Granovetter 1985). Individuals essentially reside in several layers of networks such as institutional networks, knowledge networks, and social networks. The collaborative behaviors of individuals and resulting outcomes therefore cannot but be affected by the aggregate network configurations and the attributes of personal relations.

Game Theory

Game theory is multi-personal interdependent decision theory in which strategic interactions among rational players determine their payoffs. In general, a game is specified by the set of players, the set of possible strategies for each player and payoffs as the result of their choosing strategy. When a game plays, it is assumed that all players are rational maximizing their payoffs and reasoning strategically to take into account other players' behaviors. However, conventional game theory has several limitations to be successfully applied in dynamic conditions. Several efforts have been undertaken to complement the limitations of conventional game theory; for instance, evolutionary game theory.

A MODEL OF THE EVOLUTION OF COLLABORATION

On the extension of existing studies (Jackson and Watts 2002), we have developed a game theory model of the evolution of collaboration within team networks of large-scale projects and implemented it using agent-based modeling and simulation.

Behavioral Dynamics

(1) Strategy and Payoff: There are *n* individuals playing in the game. In each time step *t*, individuals meet a candidate partner and choose either to cooperate or to defect. Whether individuals cooperate or defect is determined by comparing the current payoff they are attaining from the combination of existing partners and the potential payoff they could achieve by forming a new relation with a candidate partner, while severing a least efficient relation. The resulting payoffs of individuals are determined by Equation 1.

(2) Collaboration: As individuals have a between-group partner (*between relations*), the possibility for them to access necessary task-related information and resources increase. Such synergistic effect is maximized when individuals has within-group partners (*within relations*) and between-groups partners at the same time. In particular, individuals who have *ω within relations* and *β between relations* are expected to achieve higher payoff than players with either (*ω* + *β*) *within relations* or (*ω* + *β*) *between relations*. This idea is manifested in the value of the elasticity for *within relations* and *between relations,* which measure the responsiveness of payoff to a change in *within relations* and *between relations*. The synergistic effect arises when $\beta_{i,t}$ is greater than zero. The effect of $\beta_{i,t}$ exponentially increases the effect of $\omega_{i,t}$ (Equation1).

(3) Maintenance Cost: Sustaining relations have a cost proportional to the number of relations. Maintenance cost in this study does not refer to a payment in monetary value, but rather can be interpreted as a composite measure of the sacrifice for everything that one is consuming to sustain relations. Or, when there is an interchange barrier between two individuals or organizations, maintenance cost of a relation between them is considered higher than the others. Maintenance cost for *within relations* (*within cost)* is assumed to be less than that for *between relations* (*between cost*).

$$\text{Payoff: } u_i(g_t) = ((\omega_{i,t}+1)^a)^{(\beta_{i,t}+1)^b} \times (\beta_{i,t}+1)^b - \sum_{j:ij\in g} c_{ij}, \qquad (1)$$

where g_t : network at time t — $\omega_{i,t}$: the number of within relations
$\beta_{i,t}$: the number of between relations — a : the elasticity of $\omega_{i,t}$ to payoff
b : the elasticity of $\beta_{i,t}$ to payoff — c : cost to maintain a relation

In consequence, individuals have a different set of partners that gives them greatest payoff (Figure 1). When *between cost* is low (0.2), an individual, in most cases, prefer to make a *between relation* that enhance her payoff rather than to have a *within relation* as specified. However, it is fundamental to have a base *within relation* to fully exploit the benefit of *between relations*. Therefore, having both *within relations* and *between relations* together produces higher payoff than either all three *within relations* or all three *between relations*. In this case, having a *within relation* and two *between relations* generates the highest payoff and having pure *within relations* or *between relations* returns a modest payoff. On the contrary, it is not favorable to have pure *between relations* when *between cost* is moderate (0.6). This is because individuals have to spend more maintenance cost than the extra payoff they earn from the relations. Individuals still want to have *between relations* together with *within relations* in order to benefit from the synergistic effect. Having two *within relation* and a *between relations* results in the highest payoff. However, individuals like to work only with within-group partners when *between cost* is high (1.0). They even prefer to work alone rather than to collaborate with between-group partners in most cases. Having three *within relations* produces the highest payoff in this case.

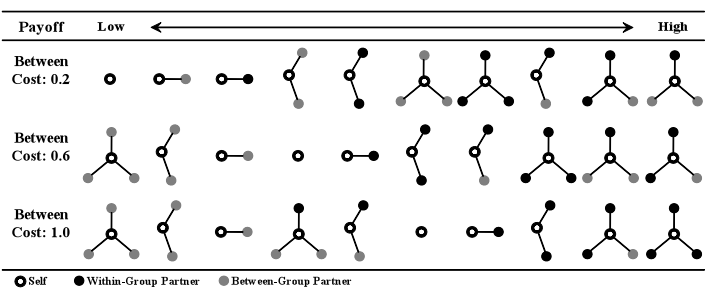


Figure 1. Payoff Comparison with Different Between Cost

Network Dynamics

(1) Personality: The personal characteristics of individuals are portrayed in the different value of *sociability* and *familiarity*. *Sociability* refers to the extent that individuals are outgoing so they have a chance to meet a new candidate partner. *Familiarity* refers to the extent that individuals are close with other individuals in the network. This can be thought of as the level of network awareness of individuals. It relates to how likely an individual to have a contact with another.

(2) Social Contact: At each time step, individuals participate in social interactions with a probability of *sociability*. If individuals are not social enough to meet a new

individual, they seldom have an opportunity to improve their payoff through forming a new relation or replacing an unproductive partner with a promising one. In the social interaction they are involved, they make a new contact with an individual who is not currently in ther relations. The likelihood of who individuals meet is decided by the probability distribution of *familiarity* to others (Equation 2). It is supposed that individuals keep higher *familiarity* to those belonging to the same organization than an outsider. Meanwhile, when two individuals meet, each individual's *familiarity* for the other increases, following Equation 3. This equation is conceived to reflect the fact that the *familiarity* increase rate gradually diminishes, while converging to a maximum.

Probability of i meeting j: $P(i,k)_{g_t} = \eta_{ik,g_t} \Big/ \sum_{k:i\neq k,g_t} \eta_{ik}$, (2)

where η_{ij,g_t}: familiarity of i with j at time t

When i meets j, i's familiarity to j increased by $\rho \times (\lambda)^{-\eta_{ij,g_t}}$ (3)

(3) Memory Attenuation: Individuals' *familiarity* values are depreciated at a rate of σ at each time step.

(4) Goal-Seeking Behavior: As mentioned above, when meeting a new individual k, individuals compare payoffs of all possible combinations of relations at g_{t+1}. In this study, the maximum number of partners that individuals concurrently collaborate with is limited to three and they change only one relation at a time step. Hence, individuals are able to add a new relation or replace an existing relation with a new relation. Particularly, if they have less than three partners now and expect a candidate partner to contribute to achieve greater payoff than the previous time step, they form a new relation with him, or even though they have currently three partners, they form a new relation with a promising partner, severing an existing ineffective relation.

(5) Mutation: After the goal-seeking behavior in each time step, mutational partner changes occur with the probability of *mutation rate* (ε) and thus a relation is deleted if it is present and formed if it is absent. Stochastic mutations in the network formation process may arise for a variety of reasons (Jackson and Watts 2002). Individuals may make a mistake in evaluating payoffs; they may fail to sustain current partners due to the limit of time and cost; they may have only partial information and thus they may experimentally change a partner. Or such mutations could be exogenous effects that are beyond the individuals' control.

Co-evolution of Behavioral Dynamics and Network Dynamics

Behavioral dynamics of individuals and overall network dynamics co-evolve, while interacting with each other. Particularly, the properties of the whole network emerge

from the goal-seeking behaviors of distributed individuals in order to accomplish maximum payoff (*emergence*) while the individuals' behaviors are constrained by structural configurations of the network (*embeddedness*).

RESULTS

For brevity, it is assumed that there are two types of agents and model parameters are specified as shown in Table 1.

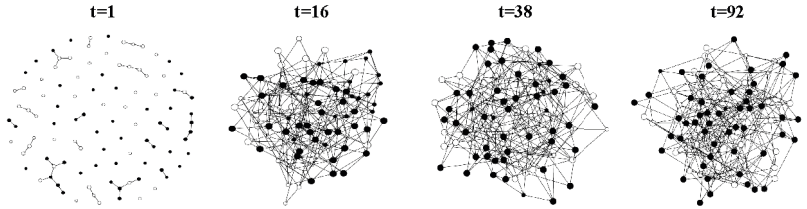
Table 1. Summary of Model Parameters

Number of agents	100	Length of simulations	200
Sociability	Normal(0.3, 0.05)	Attenuation rate (σ)	0.01
Within Familiarity (wf)*	50, 100, 150	Between Familiarity (bf)	10
Initial Within Familiarity	wf × (1+0.2 × Uniform(0,1))	Initial Between Familiarity	bf × (1+0.2 × Uniform(0,1))
ρ (in equation 3)	15	λ (in equation 3)	1.04
Elasticity of $\omega_{i,t}$ (a)	0.4	Elasticity of $\beta_{i,t}$ (b)	0.5
Within Cost	0.1	Between Cost*	0.2, 0.6, 1.0
Mutation rate (ε)	0.2		

* Value varies with different settings
** Normal (μ, σ) denotes a normal distribution with mean is "μ" and standard deviation is "σ"
*** Uniform (a, b) denotes a uniform distribution with a low value of "a" and a high value of "b"

Stable State

As the simulation proceeds, agents start looking for partners and thereby relations among agents are created. While sociable agents quickly and more frequently join the partner searching process, less sociable agents are reluctant to participate. Accordingly, sociable agents begin to receive higher payoff right after a simulation gets started. For instance, in a simulation with the *within familiarity* of 50 and *between cost* of 0.2, the network unfolds as shown in the sociograms shown in Figure 2. At time 1, only 37 agents who are mostly sociable get a partner and thus they achieve higher payoff [1.2182] than those who do not have a partner [1.0]. Among them, agents who maintain higher *between familiarity* show higher payoffs by forming a *between relation* [1.2195] than those who have a *within relation* [1.2142]. Beyond time 16 where agents have the highest number of *within relations* [1.8603], a tendency that they replace *within relations* with more beneficial *between relations* through random social contact arises. Consequently, agents have the number of *between relations* equivalent of that of *between relations* at time 38. Then, the network reaches a stable state at around time 92 where all agents attain the maximum payoff.



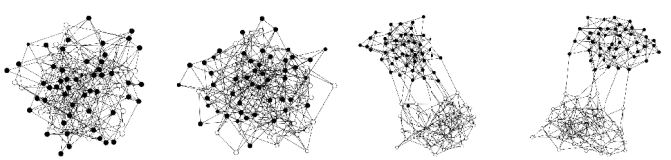
# of Within Relations*: 0.2438	1.8603	1.4971	1.2591
# of Between Relations*: 0.0829	0.9429	1.5009	1.7409
Payoff*: 1.0712	1.9292	2.166	2.2319

* The average value of 100 simulations ** The color of nodes symbolize the types of nodes
*** The size of nodes represent the payoff they earn

Figure 2. The Evolution of Network (Within Familiarity: 50, Between Cost: 0.2)

Occurrence of Cohesive Subgroups

Figure 3 shows stable state networks reached by different conditions. Low *between cost* enables an agent to have *between relations* that are more profitable than *within relations*, so that an agent realizes higher payoff. Networks with *between cost* 0.2, 0.6, and 1.0 in turn result in less *between relations* - respectively 1.7879, 0.9797, and 0.1386. Those lead to different payoffs of 2.2340, 1.7646, and 1.4385.



Within Familiarity	50	50	50	150
Between Cost	0.2	0.6	1.0	1.0
Density	0.03	0.03	0.03	0.03
Diameter	8	8	11	13
# of Within Relations*	1.2121	2.0203	2.8574	2.8894
# of Between Relations*	1.7879	0.9797	0.1326	0.1106
Ave. Distance	3.988	3.889	4.648	4.95
Clustering Coef.	0.019	0.025	0.045	0.053
Average Payoff*	2.2340	1.7646	1.4385	1.4395

* The average value of 100 simulations ** The color of nodes symbolize the types of nodes
*** The size of nodes represent the payoff they earn

Figure 3. Sociograms and Statistics of Typical Stable State Networks

Due to the effect of different *between cost*, the networks come to have remarkably different characteristics. It is most noteworthy that the higher *between cost*, the stronger tendency of cohesion. Particularly, the clustering coefficient increases as between cost gets higher, which implies that local neighborhoods in networks with higher *between cost* are denser than others and thus there seems to be a stronger tendency to form local cohesive subgroups. Also, networks differ in diameter and average distance; while those values in networks with *between cost* 0.2 and 0.6 are almost equivalent, networks with *between cost* 1.0 exhibit bigger diameter [11] and longer distance [4.648]. The outcomes represent the fact that overly high *between cost* prevents agents from having *between relations* by fully offsetting the advantage of having *between relations* whereas moderate *between cost* cancels the advantage only partially. The resulting subgroups are visually illustrated in the third sociogram in Figure 3. It is also worth noting that different levels of *within familiarity* have an effect on the frequency of *between relation* formation by constraining agents' chance to meet heterogeneous partners and ultimately average payoff. When *between cost* is 0.2 or 0.6, as *within familiarity* increases, the average payoff decreases due to the constraints by *within familiarity* (Figure 4). However, interestingly, those constraints generate counterintuitive outcomes that agents with overly high *within familiarity* make higher payoff than others, when between cost is overly high, for example 1.0. In particular, agents with *within familiarity* 50, 100, and 150 achieve payoff of 1.4385, 1.4391, and 1.4395, which are in the reverse order from when *between cost* is 0.2 or 0.6. These results can be explained as low *within familiarity* inhibits agents from escaping from the unprofitable set of partners and thus the network sticks to the inefficient state. In contrast, agents with high *within familiarity* attain higher payoff by swiftly substituting a productive partner for unproductive one.

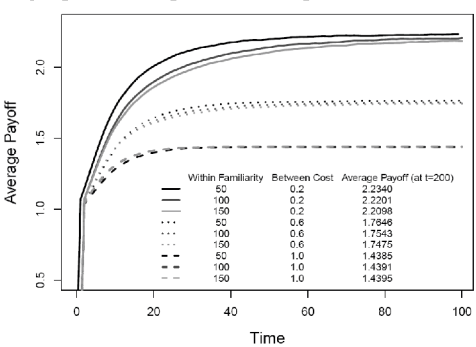


Figure 4. Average Payoff Dynamics

Delayed Network Development

Within familiarity affects the pace of network development as well as average payoff. As mentioned, high *within familiarity* keeps agents from contacting between-group partners. When *between cost* is 0.2 or 0.6, agents can improve their payoffs by making *between relations* along with *within relations*. The impediment due to high *within familiarity* makes agents stay in an inefficient state for a long time. However, when *between cost* is 1.0 which is considered overly high, networks with different *within familiarity* values reach an stable state after nearly same durations: 40, 38 and 41. The reason seems to be that the set of three within-group partners gives agents the greatest payoff and thereby the strong inward preference overwhelms the delay caused by difference in *within familiarity* (Figure 5).

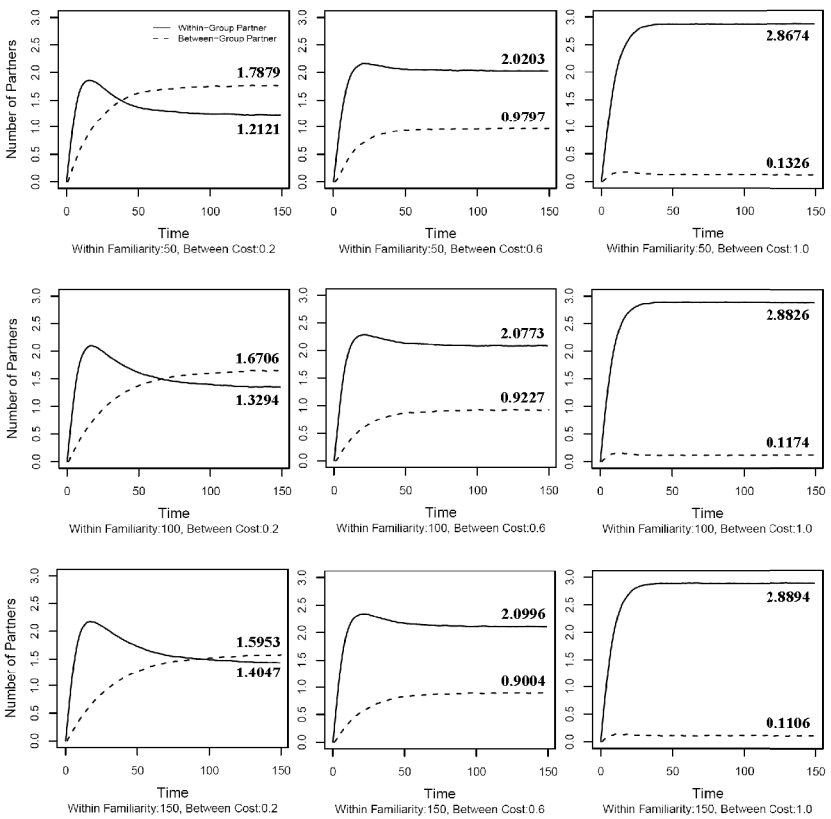


Figure 5. Average Number of Within-Group Partners and Between-Group Partners

CONCLUSIONS

This paper introduces a theoretical framework regarding the evolution of collaboration within inter-organization networks in large-scale construction projects and a simulation model. The main contribution of this paper is twofold. First, it presents an explicit and realistic approach to examining organizational issues in large-scale construction projects. Second, it extends the existing computational organization and network studies by integrating individual behavior models and network models. The research will be continued not only to improve the adequacy and integrity of the organizational simulation model but also to integrate it with construction production process models. In particular, further research will expand this effort by incorporating (1) more realistic representation of agent behavior and interaction rules, (2) more sophisticated model of structural embeddedness and relational embeddedness, and (3) unique characteristics of construction projects and temporary teams.

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The Leadership Flexibility Space

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ABSTRACT

Leadership styles of engineers were studied in a state organization, with the objective of making recommendations for improvement in decision making. A model was synthesized from a critical review of relevant literature, the underlying principles of which have found wide acceptance. Five styles were modeled in an outcome space – complete autocrat, impoverished manager, consensus manager, active manager, and consultative autocrat. The data collection process consisted of a questionnaire plus qualitative interviews. The research method included t-tests for the distance from the active manager's zone, and recording of trends and frequencies of qualitative data. Effects on styles were measured by variables such as years of experience and number of projects handled. Among the results, only one in twelve was an active manager, while more than 50% fell in the impoverished manager's region. The contributions contained ten recommendations that would take the organization to the next level by adopting a cross-section of motivational strategies.

INTRODUCTION

It is a fact that top management provides vital leadership, but leadership exists and exercises itself at all levels of the organization; every performer is a leader in his or her own sphere. The responsibility of innovation, initiative, quality improvement, and productivity improvement, falls on every responsible organizational person, who thus has a duty to champion new developments to help the organization grow. Leadership relates to how decisions are made, and whether decisions are made largely by the group or individually by the decision maker. Teamwork relates to how individuals participate in the decision taking process and gather information for their tasks. This article studies the issues of teamwork and leadership style, where it surveys a large public engineering organization.

DECISION MAKING AND INFORMATION

Active engineers must possess acumen for taking initiatives, independent thinking, and decision-making. The ability to make wise decisions independently implies that decisions can be made quicker without excessive and heated group discussions. Laufer et al. (2008) write that managers need to be "successful in quickly and frequently sharing a large and diverse volume of information with a large number of people, thereby underscoring the vital role of communication in the management of construction projects in a dynamic environment." Thus, too much emphasis on group decision-making can negatively affect initiative and independence, as well as result in potential delays in important decision-making processes that ultimately affect work progress. However, without adequate group input, errors can possibly be made. Thus, a balance between the two modes of group information and decision making is essential. It was with a view to understanding this balance at the State Department of Engineering Construction (SDEC) (an organization with a $1.5 billion a year construction budget), the characteristics of that balance, and how the balance is affected by varying demographics, and what recommendations for improvement in the organization for decision making are advised, that this applied study was undertaken for the construction branch.

PURPOSE

The objective was to study the leadership style of construction engineers at SDEC, and evaluate that style using an adapted version of the Jerrel/Slevin management instrument for various demographics. Differences are to be made between Resident Engineers/Area Engineers (REs/AEs) on the one side and Project Engineers (PEs) on the other with regard to own and team input to decision making. Recommendations for implementation were desired.

THE LEADERSHIP FLEXIBILITY SPACE MODEL

Decision Making (D) and Information Gathering (I) can be plotted on the X and Y axes of a graph, since each respondent is characterized by his or her D-I percentile scores (Figure 1, adapted from Jerrel/Slevin). The D-axis signifies decisions making – ranging from being made solely by the leader to solely by the group. Similarly, the I-axis ranges from all information input taken from the group to none at all. This graph is herein called the "Flexibility Space." Distinct areas of the flexibility space denote distinct leadership and teamwork styles that are briefly explained below.

Consultative Autocrat: The engineer takes information input from all, but does not share decision making.

Complete Autocrat: The engineer will neither take anybody's input, nor will share decision making with anybody.

Impoverished Manager/Shareholder: The engineer will not take any information from the group and will not make any decision by himself/herself.

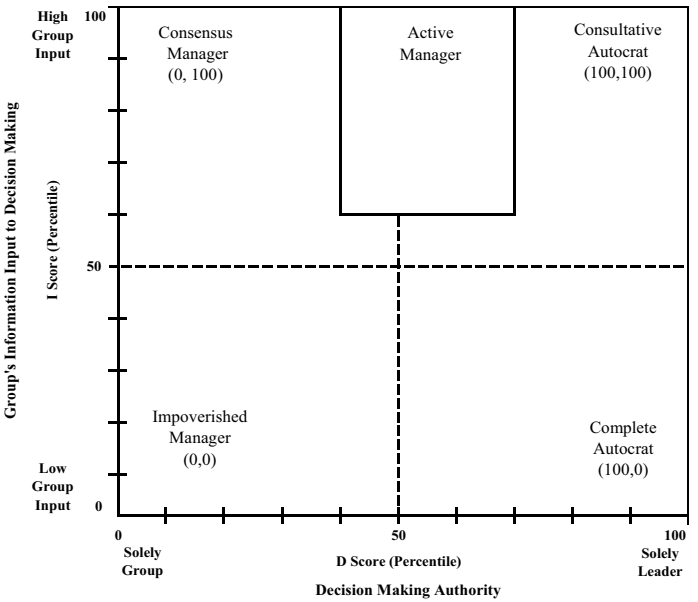


Figure 1: Leadership-Teamwork Flexibility Space

Consensus Manager: The engineer will involve the group in complete decision making and will then let the group decide by consensus.

Active Manager: The active manager avoids complete autocratic behavior but uses high group input. This engineer holds a concern for production and people (refer managerial grid of Blake and Mouton, 1964). The flexibility space of the active manager is soundly bounded between $60 < I < 100$ and $40 < D < 70$.

CONTRAST TO OTHER MODELS

The Leadership Flexibility Space has its roots in management science but still stands apart. Contrasts with two other 2-D graphic models in management literature are discussed in short below for want of space.

Contrast to Managerial Grid

The *Managerial Grid* (Blake and Mouton, 1964) has two major axes representing concern for people and concern for production, respectively. The Flexibility Space is different to the Managerial Grid as follows:

1. The Decision making axis (in the Flexibility Space) and Concern for Production axis (in the Managerial Grid) are different variables.
2. There is no Compromise Management style in the Flexibility Space, while there is a Consultative Autocrat style.
3. The Active Management (in the Flexibility Space) has a possible counterpart in Team Management (in the Managerial Grid), but the positioning is different.

Contrast to Joint Outcome Space

The *Joint Outcome Space* (Thomas, 1976) is a conflict management grid that uses the same axes of the managerial grid, but then evaluates five conflict resolution styles. The problem solving style is considered the most suitable for successful resolutions. Differences between the Flexibility Space and Joint Outcome Space are:

1. There is no Compromise style in the Flexibility Space.
2. The Problem Solving zone on the conflict grid has not been referred to in literature as a Consultative Autocrat zone.

SURVEY SAMPLE

The questionnaire, given in Appendix I, was distributed to a total of 65 engineers at SDEC. Responses came from 36 engineers, divided between 26 Project Engineers and 10 Area Engineers. This is a large and statistically valid sample size.

INSTRUMENT AND SCORING CRITERIA

The model developed here asked questions through a questionnaire that solicited responses for the two variables of (i) Decision making style, D, and (ii) Group involvement (i.e., Information sharing), I. This questionnaire is adapted from the Jerrell/Slevin Management Instrument, which has been applied in research before (Slevin and Pinto, 1988), and can be applied to any organization. Each question is prepared on a scale ranging from 1 to 5. The D and I raw scores of individuals are converted after modifications, to account for the increased size of the questionnaire, to percentiles recommended by Slevin and Pinto (1988). The D-I percentiles of individuals are plotted in the flexibility space.

FINDINGS FOR ALL ENGINEERS

The overall findings for 26 PEs and 10 REs/AEs are shown in Figure 2. It is seen that 46% of all PEs, and 70% of all REs/AEs, fall in the impoverished manager's region. All engineers fall in the Consensus or Impoverished Manager's zones except for three PEs who fall in the Active Manager's zone. The average of PEs is better than that of AEs and REs for both D and I-scores. This indicates that the younger PEs are more efficient than AEs/REs in exercising leadership at SDEC. T-tests indicate that the D-scores of PEs are significantly different to those of REs/AEs at $\alpha = 10\%$; while I-scores are significantly different at $\alpha = 27\%$. Therefore, the statistical tests demonstrate that PEs have significantly higher leadership capabilities.

DEMOGRAPHIC ANALYSIS

Demographic data was collected with the D-I questionnaire and split into two groups: (i) Years of experience, and (ii) Family condition. Sub-areas under Years of experience were Age group; Projects handled in career; Projects handled at SDEC; Years of experience in career; Years of experience at SDEC; and Years in design. Sub-areas under Family condition were (i) marital status and (ii) family encouragement.

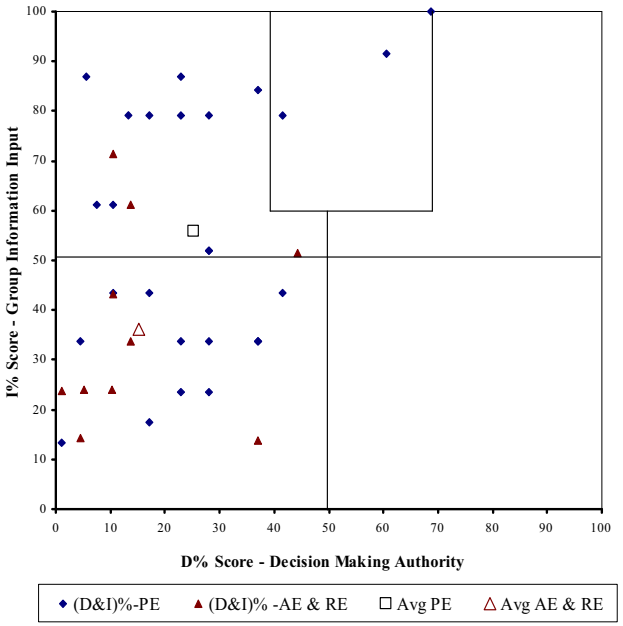


Figure 2: D - I Percentile Chart for PEs, REs & AEs

Age Group

The average D-percentile becomes progressively less for engineers as they become older, implying possibly that they mellow down with age and shift more towards avoiding conflict situations. Similarly, it is found that older engineers have a higher I average, indicating that they are now participating in group dynamics and prefer consensus decision making. On the other hand, the youngest age group (ages 29 to 40) has the highest score in independent decision making, falling closer to the active manager's region.

Number of Projects Handled in Career

Having handled more projects gives the engineer slightly greater confidence, if at all. However, from this analysis, there is no significant difference between the engineers on this score.

Number of Projects Handled at SDEC

The results were not convincing, but rather appeared to be disturbing: the greater the experience at SDEC (> 20 projects), the greater the incidence of impoverishment. It might be the reason that older people feel "beaten down," which implies that SDEC has a stifling atmosphere. Therefore, positive steps must be initiated to overcome this suppressive culture.

Years of Experience
Engineers with experience >20 years fall mostly in the impoverished management region. Decrease in motivation due to age might be a reason for this. However, it is interesting to note that those in the middle level of their careers (having 10-20 years experience) have the highest D-I percentiles with their position closer to the active management region on the flexibility space. On the other hand, the least experienced engineers (< 10 years) fall in between the senior and middle level of engineers.

Years with SDEC
Engineers having more than 20 years experience at SDEC fall in the impoverished management region much like those with over 20 years of experience. Thus, working at SDEC might have a negative cultural impact. Those with 10-20 years with SDEC fall more towards the consensus management region. However, engineers with less than 10 years with SDEC fall closer to the active management position. Overall, the group is characterized by the impoverished and consensus management properties.

Years in Design
Construction managers are usually unable to have conventional design experience. A few years experience, such as from one to five years, helps to improve management styles by taking engineers a step higher to consensus management. The vast majority of engineers surveyed have less than one year of design and 50% of them fall in the impoverished manager's region. Those having more than five years in design are more likely to be consensus managers—a step up in improvement.

Marital Status
Unmarried, or otherwise single engineers, are either in or closest to the active management region. This group is followed by married engineers. Divorced engineers fall convincingly in the impoverished management area.

Why does this trend happen? An attempt at an explanation is bound to be hazardous. But, among many possible perspectives, unmarried people can be imagined to have fewer emotional ties that makes available to them more emotional energy to use in their work place. Divorced people could feel deprived or emotionally saddened, which makes them avoid workplace action. Sociologists and psychologists might have other and better explanations.

Family Encouragement
Those whose families do not share in the stress and travails of their work appear in the active management group. Those whose families are encouraging of their work were found to exhibit increased consensus management, though two were found to belong to the active management space. Family encouragement might be analyzed to have the result of being able to relate to others in a collegial spirit. In other words, those with family encouragement might exhibit greater social maturity. In the organizational context, this implies that such people have greater ability to perform in teams and can be better relied on to provide healthy input to decision making. In any event, there is a definite correlation between family encouragement and decision

making strategy, even if causality can not be shown. Those whose families encouraged them only partially displayed increased amounts of impoverished management.

Discussion

As amazing as some of these findings may be, the authors find it responsible to report them. The analysis is difficult, and sociologists and psychologists could have different explanations for all the findings. Yet, it is important to note that the findings necessarily affect work psychology and work sociology, thus affecting work dynamics and work productivity.

DISTANCE OF PEs FROM ACTIVE MANAGEMENT ZONE

The distance of PE scores from the closest point to the active management zone, with respect to the average of age group, number of projects handled in career, number of projects handled at SDEC, years of experience in career, and years of experience at SDEC, are given in Table 1. The distances are *physically measured* on graphs of each demographic (the graphs are 7.2 cm [on the y-axis] x 14 cm [on the x-axis]).

It is found that, on average, PEs in the middle-aged group fall closest (1.60 cm away) to the active management zone, followed closely (1.66 cm away) by the youngest engineers. However, the oldest PEs are positioned far from the active manager's zone (3.16 cm away), falling more towards the impoverished management zone. The analysis is partially self-evident, but definitely hinges on the motivational level of the engineers, where the motivation decreases as one grows older.

T-tests revealed that there was a significant difference between the average distance of older engineers compared to those of the youngest and middle-aged engineers. For oldest to youngest, significance was remarkable at $\alpha = 1\%$. Likewise, there is a significant difference between the oldest and the middle-aged engineers at $\alpha = 1\%$. However, for distance between youngest to middle, there is no significance at $\alpha = 67\%$, implying that they are quite close to each other.

Table 1: Distance from the Active Zone

Demorgraphic parameters	**Youngest**	**Middle**	**Eldest**
Distance from active zone	**distance in centimeter**		
1. Age group (average)	1.00	2.30	3.00
2. No. of projects handled in career (average)	2.10	1.80	1.90
3. No. of projects handled at SDEC (average)	1.70	1.40	3.70
4. Years of experience in career (average)	2.00	0.50	3.50
5. Years of experience at SDEC (average)	1.50	2.00	3.70
Average distance	**1.66**	**1.60**	**3.16**

Distance (in cm) for average PE with respect to active management zone on the flexibility space	
1. Total Distance for the youngest or least experienced PEs	8.30
2. Total Distance for the middle-aged or middle-experienced PEs	8.00
3. Total Distance for the senior, oldest or maximum-experienced PEs	15.80

QUALITATIVE ANALYSIS

In discussions with engineers, both in groups and in individual capacity, it was discovered that the morale was generally low, and trust in leadership was absent. Engineers complained without exception of departmental shortcomings and ineffective policies. The discontent was pervasive.

CONCLUSIONS

It is seen that there is a considerable degree of non-participatory management at SDEC. There are very few active managers—only three out of thirty-six engineers. And, more than half of all engineers fall in the impoverished management region. This implies that there is a lack of motivation for excellence, leading to a negative impact on the production and efficiency of the organization. The following are some of the findings:

1. Those who had handled greater than 20 projects at SDEC, specifically, were seen to fall in the impoverished management region. This says something about the quality of a career at SDEC.
2. Older engineers were seen to fall prevailingly in the impoverished management and away from individual decision-making.
3. Some design experience helps. Those having one to five years of design experience tend to be closest to the active manager's flexible space.
4. Divorced engineers are likely to perform in the impoverished manager region, while single engineers perform closest to the active management region.
5. Those whose families do not encourage them to work are closer to the active management zone than those whose families encourage them. Those whose families are encouraging of their work, display more of the consensus management style.

Where it is well known that people are the most important assets in any organization, it appears that the people at SDEC are falling far behind in effective leadership performance. There are decision-making and information-sharing weaknesses at SDEC. It is ironic that those to whom we look most for leadership—the more experienced engineers—are the ones who lack the most leadership skills at SDEC. Therefore, investing time and money in training and developing the engineers in leadership capabilities at SDEC should be considered a high priority.

RECOMMENDATIONS

The following recommendations are provided to overcome the present management drawbacks and enhance leadership development at SDEC. These recommendations aim to raise the D-I scores. The recommendations follow from best management practices, and so are stated in general terms. They follow substantively from the qualitative studies and expectations from engineers there. In addition, these recommendation items are validated as being applicable from their sheer absence at SDEC. These recommendations are quite prosaic that would be present in any forward-thinking organization, and therefore impose no onerous responsibilities or

expense on SDEC. These recommendations would be considered the first line of initiative in improving the work culture at SDEC.

1. Increase delegation to AEs/REs
2. Impose trust in all engineers and help them manage their area of responsibility. Create a culture of trust rather than distrust.
3. Provide a nurturing and coaching environment at all times.
4. Provide formal leadership training through workshops and seminars.
5. Encourage the experienced engineers to take part in decision-making processes and recognize the ideas of their teammates.
6. Provide in-depth training in the construction management area and emerging technologies. This will give them more confidence.
7. Invest in people with a sound concept of modern ideas and leadership roles. Thus, the department needs to revise its hiring and promotion criteria and consider revising their pay structure.
8. Provide recognitions to engineers for their achievements to motivate them and increase their morale and self-confidence.
9. Provide growth opportunities through allocating challenging work assignments. This will bring a sense of pride and responsibility to the work culture.
10. Increase the workload of individual engineers to stimulate their productivity and creativity. Simply give them more work to do.

ACKNOWLEDGMENTS

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Appendix 1. Questionnaire

Circle the most appropriate answer in your judgment

#	D - Scale	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	I like quick results	1	2	3	4	5
2	I don't like it when others disagree with me	1	2	3	4	5
3	I enjoy giving orders	1	2	3	4	5
4	I have a strong ego	1	2	3	4	5
5	I find it hard to accept others decisions	1	2	3	4	5
6	The work group should determine its own work schedule	5	4	3	2	1
7	The work group should determine its own vacation schedule	5	4	3	2	1
8	It is fun to work in groups	5	4	3	2	1
9	I feel comfortable when placed in a powerful position	1	2	3	4	5
10	Once I make up my mind, I stick to it	1	2	3	4	5
11	I am open to alternatives once I've made up my mind	5	4	3	2	1
	I - Scale					
12	I often ask for infromation from subordinates and colleagues	1	2	3	4	5
13	It is easier to make decisions in a group	1	2	3	4	5
14	Group discussion takes up more time than they are worth	5	4	3	2	1
15	Group provides a deeper analysis of the problem than what individuals can	1	2	3	4	5
16	The information provided by subordinates/colleagues is useful for my understanding of the work problems	1	2	3	4	5
17	No one else can know as much about the problem as I do	5	4	3	2	1
18	I usually make my decision before the start of a meeting	5	4	3	2	1
19	Group discussion are the best	1	2	3	4	5
20	A group is no better than its best member	5	4	3	2	1
21	Better decisions are made in group situations	1	2	3	4	5
22	I like to make decisions by myself	5	4	3	2	1

Understanding Withdrawal Behavior in the Construction Industry

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Abstract

This paper discusses an innovative approach for studying employee withdrawal behavior (e.g. tardiness, absence, and voluntary turnover). The traditional view is that withdrawal behaviors were caused by characteristics of the individual performing these acts (e.g., job dissatisfaction). While this view has received empirical support, an emerging view is that individual withdrawal behaviors are also governed by social forces within the job or organizational context. In effect, a culture emerges around these behaviors that effectively influence how individuals express themselves. Modelling these informal social dynamics, and understanding how individuals self-regulate within a dynamic social context, can be a great help understand this relationship between the two and further manage this behavior. In this paper we describe how this relationship has been approached in diverse literature and propose a feedback view on its understanding. Also, the implications of this research for management of withdrawal behaviors within the construction industry are discussed.

Introduction

Construction companies contribute more than 10% to Canada's GDP with over $100 Billion annually. The industry itself is labor intensive with workers contributing to production activities that result in the built facilities that are cornerstones for our society and integral to our modern quality of life. Construction projects rely on an interdependent workforce, where crews often work as coordinated teams during the daily production process. Due to this fact, when a worker is late, absent, or quits, it impacts the project. Absenteeism, for example, affects worker morale, forces alterations in planning, increases costs, decreases output, causes onsite stress, reduces workplace satisfaction and consequently overall productivity is significantly reduced

(Business Roundtable 1982). Traditionally studies attempting to understand and solve the issues of withdrawal behaviour in the workplace have focused mainly on ways to reduce the behavior by investigating each individual's causes of withdrawal. This current approach has some limitations. For instance, in case of absenteeism, the main cause is usually indicated by workers' illness, an issue which could likely be a socially acceptable excuse used by some, or if a worker is in fact sick, an issue which cannot be directly solved by such studies. Further, the causes are generalized to the entire workforce, which is often unrealistic so that the findings are leaving it to the company to determine how to make use of them.

It is common for project managers and leaders to view withdrawal behaviors, such as personal absences, as the result of low motivation, poor morale, or a "bad attitude." It shouldn't be surprising to learn that most attendance control policies assume that attendance is caused by factors within the individual, and manage this behaviour accordingly. In this study we propose, as have others, that absence may have as much to do with the individuals' social or cultural environment as it does with the attitudes or motivation of the individual workers (Mathieu and Kohler 1990; Martocchio 1994; Gellatly & Luchak, 1998; Johns 1997). At the heart of this idea is that members of a work crew or other meaningful social unit (including leaders), develop an informal and shared understanding of how much absence is acceptable, tolerable, and legitimate. When the focal behavior is absenteeism, we refer to this concept as an "absence culture." Although not as much work has been devoted to non-absence criteria, the concept of "lateness culture" (Elicker, Foust, O'Malley, & Levy, 2008) and "turnover culture" (Abelson, 1993) has been noted in the literature. (Johns & Nicholson, 1982). Withdrawal cultures are important because they guide day-to-day decisions and ultimately behavior, especially when a high degree of cohesiveness is experienced within the work crew or social unit. Taken together, this emerging literature suggests that individual withdrawal behaviors (i.e., lateness, absence, and turnover) are, in to some degree, under normative control, and that only by understanding how these behaviors are affected by the social context can effective control policies be developed.

A goal of this study is to verify the occurrence of absence cultures, a concept investigated most prominently in the context of social sciences, within the construction industry and gain information concerning the psychological processes and possible solutions prevalent with relation to this process. The study described in this paper will later be deployed in the form of computer simulation models to facilitate further experimentation. System Dynamics will be used to test basic assumptions regarding how informational cues in one's social context affect self-regulation of employee withdrawal behaviors, and the conditions that moderate these dynamics. This study plans to apply knowledge gained from this approach to the construction industry where employee absence, turnover, and lateness are prevalent (e.g. large industrial projects). Furthermore the study can be applied as an innovative way of studying and understanding the determinants of complex, multi-determined job behaviors such as absenteeism with relation to other environments in the future.

Previous Research

Withdrawal Behavior and the Construction Industry

Withdrawal behaviors are important issues to study within the area of social sciences; however it is greatly important to note that this research has also emerged with specific relation to the construction industry. One of the first studies to understand this issue in terms of the construction industry includes a report conducted by the Business Roundtable (1982). This study was inspired by a need to increase productivity in construction, and found that absence and turnover, factors which seem to lead to one another, were among the most significant contributors. In this study, it is found that the reasons for absence and turnover could be divided into controllable absences and uncontrollable absences. The controllable absences involved the environment of the construction site, while the uncontrollable absences involved issues such as travel, illness and overtime on another job. Hinze et al (1985) conducted a similar survey within the same time period, to gain knowledge of the causes of absenteeism. Their findings indicated that other crew members greatly affected absence rates within a crew, and that job satisfaction in fact played a large role in instigating this behavior. A study by Hanna et al (2004) attempted to update this information gathered, concerning absence and the construction industry, acknowledging that this issue has quite a large effect on overall productivity. They created a study to determine individual reasons for absenteeism in electrical construction. This study determined that illness, injury, and medical appointments were the top 3 reasons that workers claimed to be absent. Through this research a best practices for reducing absence was created including suggestions such as using incentive programs, becoming a company of choice, and recording attendance publicly. These studies acknowledge the relationship between productivity and withdrawal behaviors within the construction industry. Despite all of the above work's great contribution to the understanding of withdrawal behavior in construction, there has not been an explicit study on the impact of social context on the withdrawal behavior.

Withdrawal Cultures in the Social Sciences

A variety of methods of studying withdrawal behaviors has been investigated within the social sciences. Particularly, absence has been paid great attention on. Regarding the social influences on individual absence, Martocchio (1994) conducted one of the first empirical studies. In this study, absence culture was defined as "the beliefs about the possible costs and benefits of being voluntarily absent" (based on Nicholson & Johns, 1985). Martocchio found that that absence culture among retail employees consisted of two basic shared beliefs regarding the likely consequences of absence – those that encouraged absence and those that discouraged actual absence. Then, individual-level responses obtained from the survey are retained or aggregated to represent a unit-level measure (i.e., absence culture). Iverson, Buttigieg & Maguire (2003) investigated absence cultures by observing how different members responded to the following questions: "my co-workers discourage others from using up their sick leave;" "my coworkers generally agree that you should use up your sick leave entitlement;" and "my co-workers do not care if others are absent from work."

(Iverson et al, 2003, p. 493). As expected, there was a consensus among employees; evidently, behind the scenes, these informal understandings do appear to be directing attendance decisions. This pattern has been observed for other forms of withdrawal. A study by Abelson (1993) examined turnover cultures. Here, turnover cultures are defined as "the systematic patterns of shared cognitions by organizational or subunit incumbents that influence decisions regarding job movement" (Abelson, 1993, p. 339). Abelson argues that turnover cultures evolve in the same manner as culture, broadly speaking - individuals essentially interpret and share. Finally, the notion of lateness culture (or climate) was investigated by Elicker, Foust, O'Malley & Levy (2008). In short, this study found that shared beliefs around lateness affected actual tardiness, and some of the moderating influences. Collectively, these studies establish that withdrawal cultures seem to exist and should be further investigated. However, despite the evidence of their existence, how these feedback processes between withdrawal behavior and withdrawal culture take place, such as how absence cultures shape and influence individual decisions to miss work, and how such decisions impact the formulation of absence cultures, remain unanswered. In addition, precisely how these feedback processes are moderated by a specific industry context has not been addressed. In other words, the industry itself has unique and different characteristics, which can have a different impact on withdrawal behavior. For example, in Alberta industrial construction, labor characteristics are unique due to greater work mobility, aging workers, and temporary foreign workers. All of these industry context factors can affect workers' withdrawal behavior.

System Dynamics to Analyse Feedback Processes

This study attempts to advance research in the construction industry on individual withdrawal behaviors through the investigations of withdrawal cultures. By taking this perspective, this study could provide a solution which can be utilized by the construction industry to create a reduction in withdrawal behaviors and therefore an increase in productivity. In other words, policies designed to affect withdrawal culture will be complementary to the existing ones that attack specific reasons for withdrawal behavior identified in a specific company. In this way, the effectiveness of the control polices can be maximized.

However, a methodological hurdle for many organizational researchers who study motivation, and self-regulatory processes specifically, has been to model dynamic feedback processes within a research paradigm that tends to be conducted at a single point in time (e.g. cross-sections, survey research). The proposed research introduces a new methodological tool for studying how feedback is used by individuals to self-regulate their behavior by using a computer simulation technique that tests how social context helps individuals align their personal behavior with group norms and the conditions that moderate these dynamics.

To this end, this study uses System Dynamics (SD), integrating it with social science methods (e.g. survey, interview, focus group, and observation). A feedback system can be defined as a system as a closed (i.e. feedback) loop structure that brings back

results from past actions of the system, to control future actions (Forrester, 1971). Most complex dynamic behaviors arise from the feedback among the various components of the system and not from their complexity themselves (Sterman 2000). For example, the fact that real quantity in the system cannot grow permanently due to one or more constraints can be depicted as S-shaped growth, which is a result of the interaction between feedback that strives to grow and feedback that consumes resources (i.e. carrying capacity). As such, feedback is an extremely useful concept for understanding the complex behaviors produced in a system. There are only two types of feedback: self-reinforcing and self-balancing; the former tends to reinforce or amplify whatever is happening in the system, while the latter counteracts and opposes change. Particularly, self-balancing feedback has been widely adopted in cybernetic systems because it can control some variables by acting on differences between an estimate of the variable's current state and its desired state (Vancouver and Day 2005). In other words, when discrepancy between the variable's desired state (i.e. goal) and current state is perceived, this process motivates corrective actions that are geared towards reducing the discrepancy. In this case, self-balancing feedback renders a continually changing perception of the variable of interest. As such, self-balancing feedback identifies the process that will reduce the discrepancy, which eventually explains goal striving and revision processes found in self-regulation. For example, the phenomenon that the discrepancy between group absence rate norm (i.e. desired state) and individual absence rate (i.e. current state) will be reduced through a self-regulating process, can be modelled via such self-balancing feedback in SD, as seen in Figure 1. In other words, individuals try to reduce the discrepancy between their absence rate and absence rate norm (i.e., absence culture), if any, by adjusting their tendency (or willingness) to be absent. Eventually, this will change absence rate norm that aggregates individual absence rate (Martocchio, 1994).

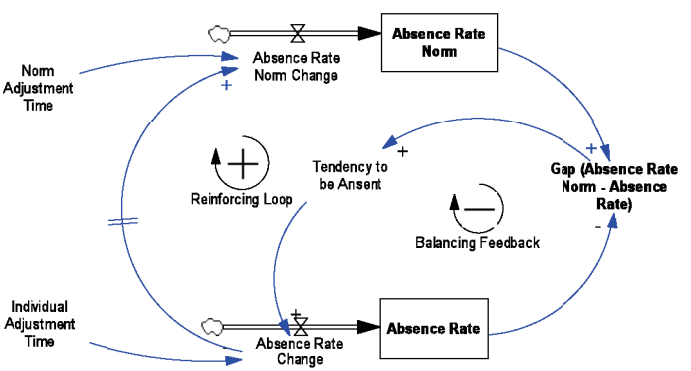


Figure 1. Balancing Feedback between Perceived Absence Rate and Absence Rate Norm

At the same time, SD can also capture feedback between the continually changing perception of individual absence behavior and the group absence norm while identifying the impact of personal or organizational characteristics on these feedback processes. In this way, the processes associated with self-regulation that govern work behavior can be modelled and consequently, tested. This is an example of how the absence behavior can be understood through the feedback process. The same logic can be applied to other withdrawal behaviors.

Focusing on this, SD is utilized to gain a comprehensive understanding of the feedback processes inherent in self-regulation. SD's particular capacity for capturing feedback will be exploited to model complex (multi-determined) processes in the system; this will enable the testing of diverse theoretical hypotheses and will clarify the role of feedback for self-regulation.

Expected Contributions

Over the next 10 years, the development of oil sands projects in Alberta will represent over 50 billion dollars worth of construction. However, increasing rates of absenteeism are a viable threat to time and cost estimates of oil sands development in Alberta (Government of Alberta, 2007), potentially resulting in the loss of billions of dollars. Withdrawal behaviors and withdrawal cultures have been under some investigation in many fields of research, particularly concerning the social sciences. This is the first study which will extend this knowledge to the area of construction quantifying these relationships. As can be seen from the statement above, this research can greatly benefit the construction industry. If withdrawal behaviors such as absenteeism can be reduced, it would likely affect many issues in the workplace. One major area could be cost. If management is able to properly control employee absence, turnover and lateness, productivity could increase and costs could accordingly be reduced. By altering a culture for the better, employees may in turn be happier. When individuals are in a more organized environment, they may find fewer issues exist that deter them from being in attendance. By creating a process that is sensitive to the social dynamics that relate withdrawal the authors advance both theory and management practice within the construction industries. Furthermore, it is expected that this process could be applied to other behaviors of interest, such as safety, engagement, or even productivity. For example, safety behaviors appear to share a similar basis to withdrawal behaviors. If a workplace is quite safety conscious, it would appear that most workers are practicing safe techniques in their everyday work. If a safety culture can be identified, it would be possible to gain knowledge in how to better guard against a hazardous workplace which in return can lead to a more productive environment. In addition, Maloney (1983) discussed the impact of organizational efforts on labor productivity based on field theory. Extension of the idea presented in this paper can be applied to quantify the relationship between individual labor productivity and the organizational efforts in order to support a better productivity improvement. Overall, understanding withdrawal behaviors and cultures could have a great effect on the construction

industry as a whole. The underlying behavioral knowledge gained from this research could be a large contribution to construction productivity and worker satisfaction.

Conclusions

This research project will allow for the analysis of withdrawal cultures such as these, in the area of construction, something which has encountered very little prior investigation. Through the investigation of the feedback processes between social context and individual behavior using System Dynamics, a measure of withdrawal behaviors is enabled. This could produce a solution for many companies where withdrawal behaviors are of concern. The understanding of absence, turnover and lateness ultimately leads to an increase in productivity in a workplace and an ideal working environment for all involved. This understanding goes past the issue of simple cause-effect relationships; it is the investigation of human beliefs and the cultures which derive from these beliefs. By obtaining the information necessary to accomplish this research, we can truly understand the dynamics of the construction environment, and more importantly of the human relations that exist within. From this, knowledge can be expanded to give a new understanding to other similar issues which have not yet had optimal research success. If one cause of withdrawal behaviors is found to be cultural influence, it will mean that such undesirable behaviors can be transformed.

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WHEN ARE PUBLIC-PRIVATE PARTNERSHIPS NOT AN APPROPRIATE GOVERNANCE STRUCTURE? CASE STUDY EVIDENCE

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ABSTRACT

While the higher efficiency due to better pooling of resources is largely emphasized in Public-Private Partnerships (PPPs), the impacts of transaction costs embedded in PPPs are often understated. In fact, excessively high transaction costs could render PPPs an inferior alternative for providing public infrastructures/services. In literature, there are some studies examining the intrinsic types and sources of transaction costs embedded in different governance structures for providing public infrastructures. Specifically, two major sources of transaction costs in PPPs have been suggested, namely, the principal-principal problems and hold-up/renegotiation problems. This paper uses case study method to empirically examine the hypotheses concerning the transaction cost contingencies and whether PPPs are appropriate as a governance structure. The two cases are the Channel Tunnel project and the Taiwan High Speed Rail project, two of the largest and, yet, the most problematic and controversial PPP projects in the world.

1. Introduction

Public-Private Partnerships (PPPs) have developed as one of the most popular governance structures to deliver public infrastructures/services, by which the effectiveness and efficiency are claimed to be achieved more easily than by traditional delivery approaches and governance (Bettignies and Ross 2004). Unfortunately, while the higher efficiency due to better pooling of resources is largely emphasized in PPPs, the impacts of transaction costs embedded in PPPs are often understated. In fact, the high transaction costs could render PPPs an inferior alternative for providing public infrastructures/services. Although an ideal governance structure should improve the production efficiency and, at the same time, economize on the relevant transaction costs, different governance mechanisms often present different trade-offs between benefits and costs. Nevertheless, choosing from the alternative schemes of project deliveries entails careful evaluation of the comparative tradeoffs between transaction costs and internal capabilities or benefits. Therefore, it is critical to study when and why PPPs may not be an appropriate governance structure for public infrastructures.

In terms of governance structure, PPPs can be considered an alliance between the government and private parties, which is governed by a long-term concession/contract agreed by two major joint partners, the PPP concession firm and the government. From the resource-based view, the use of PPPs can be explained by the rationale for alliances as argued by Das and Teng (2000) that value-creation potential of resources can be obtained when the resources are appropriately pooled together. The partnering parties share, exchange and aggregate their own valuable resources with each other in order to seek synergy and improve efficiency and effectiveness. However, from the transaction costs perspective, there might be distinctive and sometimes substantial transaction costs embedded in PPP alliances because (1) PPP projects are often public service/facility oriented, (2) project finance is typically used in PPPs, and (3) one of the partners is government. These differences contribute to many problems which may cause significant transaction costs. These transaction costs include those that can be observably identified and measured and those that are hidden, not easily assessed. The hidden transaction costs may significantly undermine the expected benefits and sometimes cause disastrous impacts on the society. Specifically, Ho and Tsui (2009) argue that there are two major sources of transaction costs in PPPs, namely, the principal-principal problems mainly caused by unbalanced profit structure and the hold-up problems mainly caused by government's soft budget constraints. Based on Ho and Tsui (2009), this paper derives two hypotheses concerning when PPPs are not appropriate as a governance structure, and empirically examines the hypotheses by studying two of the world's largest PPP cases, the Channel Tunnel project and Taiwan High Speed Rail project.

We test and evaluate the proposed hypotheses using case study research, a suitable method for examine a contemporary phenomenon in its real-life context and obtaining context-dependent knowledge (Yin 1981). Through the case studies, how the principal-principal conflicts and hold-up problems affect the performance of PPP projects were explored. We collected the empirical data from primary source archive including project contracts, official records, financial statements, court decisions, and other governmental rulings. Secondary source materials that include journal articles and corporate correspondence were used as well. Evidence from various sources of data corroborated each other and, thus, established the internal validity. The two studied projects were selected because they shared some critical characteristics: (1) the Build-Operate-Transfer (BOT) model was applied, (2) these two mega projects involved high construction costs, high business risks, and high public interests, (3) when the concession was awarded, the related institutional environments and financial markets were inexperienced and immature for adopting PPPs, and (4) during the operation period, both projects ran into financial difficulties.

The rest of this paper is structured as follows. Section 2 explicates the significant sources of transaction costs which may cause the failure of PPP projects. Two hypotheses were developed. Section 3 and section 4 study the Channel Tunnel project and Taiwan High Speed Rail project, respectively, and perform within-case studies. Section 5 conducts cross-cases analysis and evaluates the hypotheses through both within-case and cross-cases analyses. Section 6 draws conclusions.

2. Transaction Cost View of PPPs and the Hypotheses

2.1. Unbalanced Profit Structure and Principal-Principal Problems

Principal-principal problems refer to the interest conflicts between the firm's controlling shareholders and minority shareholders. The controlling principal who appoints the major directors of board and top managers of the firm might exploit their private information and dominant positions to appropriate from minority shareholders. The problems generally result from business group structures, concentrated ownership, and weak legal protection of minority shareholders, etc (Young et al. 2008). Unfortunately, principal-principal conflicts seem to be embedded in PPPs due to the profit structures of PPPs, even if the projects are undertaken in developed countries. The forms of appropriation may include below-market value asset transfers to the private holdings of the controlling shareholders and corporate expenditures on non-value creating assets for the private consumption of controlling principal, etc.

In PPPs, the sources of the promoters' investment returns will not only come from the returns of equity investments in the concessionaire, but also from the construction and operation contracts since the promoters would often act as the *major* contractors for construction and operation. Therefore, the promoters, being the controlling principal, will aim to maximize the overall value of the combined pool of profit components. In other words, the profit structure of promoters is inconsistent with that of the passive shareholders of concession firms.

An unbalanced profit structure underlying PPPs gives the controlling principal the incentives of opportunism. The ownership structure of PPPs further gives the controlling principal the capability to exploit private information in seeking appropriable rents from passive investors. The controlling principal may benefit from manipulating the construction contract prices and clauses and, as a result, the minority shareholders, subject to severe information asymmetry, will suffer from losses in equity returns. As such, principal-principal conflicts may seriously impair the financial situation and performance of the project and lead to significant transaction costs in PPPs.

Hypothesis 1: *When the profit structure of a project is prone to be unbalanced, PPPs may not be an appropriate governance structure due to principal-principal problems.*

2.2. Soft Budget Constraints and Hold-up Problems

The phenomenon of soft budget constraints was first studied in the context of transitional socialist economies, in which firms were always bailed out by government from financial difficulties with refinance or other forms of subsidies. Thus, it is said to have soft budget constraints when firms in the event of financial failure can always expect to be bailed out (Kornai, Maskin et al. 2003). Among the variety of motives for the government to bail out poor projects, some deserve to be explicated here: First, in order to avoid economic spillover effects, very often, government is left few choices but to rescue the failing enterprise where the enterprise is often deemed "too important to fail." Second, it might be prohibitively costly to liquidate some poor projects; for instance, a large scale project can be "too big to fail."

The problems of soft budget constraints lie in its ex ante effects on the behavior of the firm, that is, the expectation of the capability to hold-up government and renegotiate. The firm will then use less costly efforts in operation, make aggressive investments (Schaffer 1989) or bid opportunistically. As a result, the softness of budge constraints may result in aggravate opportunism and subsequent economic inefficiency (Ho 2006). In PPPs, the projects are usually for serving the public and have significant influences on public interests. Thus, failures of these projects may also result in chain reactions of bankruptcies, mass redundancies, and political shock. As such, government may prefer to rescue the concessionaire ex post via various means such as reducing project's liabilities, increasing service charges, granting subsidies, and lengthening the contract duration, etc.

Therefore, PPP governance has the tendency to create soft budget constraints and, consequently, cause substantial transaction costs from hold-up problems. In particular, the high opportunity costs of replacing the incumbent concession firm, even in the early stage of a concession, are one of the major causes that hold up the government for renegotiation. This explains why, as we observed in practice, government is so easy to open the door for renegotiation once the contract is awarded and so reluctant to enforce the concession contract when government has the right to terminate the concession. Therefore, we propose the second hypothesis as follows.

Hypothesis 2: *When the government is subject to soft budget constraints, PPPs may not be an appropriate governance structure due to the hold-up problems.*

3. Within-Case Analysis of Channel Tunnel

3.1. Project Background

Channel Tunnel is one of the largest privately financed infrastructure projects in the world. As a result of expenditure cut on public projects and the depression of the construction market in the U.K. during the late 1970s and early 1980s, the development of the Channel fixed-link and its financing scheme were importance issues in the U.K. during the early 1980s. The British government decided that the project should be financed by private parties and developed in BOT scheme. The *Treaty of Canterbury* signed by U.K. and French governments on February 12, 1986 provided that, "The Channel fixed link shall be financed without recourse to government funds or to government guarantees of a financial or commercial nature."

3.2. The Tendering and Construction of the Project

In April 1985, developers were solicited to submit proposals for a fixed-link channel crossing. In January 1986, the project was awarded to Channel Tunnel Group/France-Manche (CTG/FM), who had started to structure Eurotunnel in early 1986 in readiness for flotation. The concession agreement was entered into between Eurotunnel and both governments on 14 March 1986. Subsequently, Eurotunnel awarded the single contract to design and build the Channel Tunnel to TransManche Link (TML), the construction consortium, whose executives sat on and controlled the board of Eurotunnel. TML was formed by France and the UK's ten major contractors, who were the major founders of CTG/FM and later withdrew from the CTG/FM due to government policies. At this moment, Eurotunnel existed only on paper without acquiring its own autonomy. The

client of the contract could be deemed as weak or even absent. There was no strong representative of the future shareholders to negotiate such a critical contract at arm's length with the contractors. The terms and conditions were unfavorable to Eurotunnel and the project (Genus 1997; Grant 1997).

Although withdrawn from the Eurotunnel as shareholders, the founder construction companies had controlled Eurotunnel until October 1986. As required by the investment institutions, TML must give up the control of Eurotunnel and permit an independent majority on its board in order to avoid the conflict of interests. This seemed to have avoided the problem that the contractor of the project was also the major shareholders of Eurotunnel. However, this was nearly eight months after the award of the concession to CTG/FM and five months after TML was awarded the construction contract. The seed of contention had been sowed from the outset.

The project was completed with one year delay. The formal estimated construction cost shown in the 1987 shareholder prospectus was £4.8 billion, including financing and other indirect costs. The actual overall construction cost on Channel Tunnel's completion was about £10.5 billion, nearly twice the estimate.

3.3. Financial Distresses and Restructuring

Due to the spiraling construction costs and the overly optimistic traffic forecasts, Eurotunnel has been faced with financial difficulties since the very first year of operation. In 1995, approximately £8 billion was in bank loans, and the interest burden was about £2 million a day. Moreover, the Channel Tunnel faced strong competition and potential price wars from ferry and airline companies. The overall shortfall in traffic volume, the escalation of construction costs and the price reductions as a result of the competitive battle altogether led to Eurotunnel's financial difficulties (Anguera 2006).

On 14 September 1995, Eurotunnel announced a moratorium on the repayment of its junior debt which comprised the bulk of its nearly £8 billion in outstanding debt. This action initiated the debt restructuring process. The restructuring package with the French Court's intervention in negotiation was eventually achieved and agreed among the company, shareholders, and creditors.

After the 1995 restructuring, Eurotunnel still continued to struggle with financial difficulties due to the high level of outstanding debts. Thus, the second financial restructuring took place. On 11 July 2006, Eurotunnel sought legal protection of the Commercial Court of Paris pursuant to the French law "procédure de sauvegarde." With the assistance of the court-appointed representatives, the creditors, suppliers and bond holders voted in favor of the restructuring plan proposed by Eurotunnel.

3.4. Within-Case Analysis

From the perspective of project profit structure, the unbalanced profit structure and the subsequent principal-principal problems had caused significant transaction costs for the project and government. The construction companies that formed TML were the original major promoters of the Channel Tunnel project. They virtually were the controlling principals during the initial stages of project and sought their main returns from the construction of Channel Tunnel, rather from its operation. Although Eurotunnel later acted to distance itself from this core group of founder shareholders, it nevertheless let a single contract for the design and construction of the Tunnel to its founders in the new

guise of TML. The absence of a clear owner of the project from the outset gave rise to the conflicts of interest and principal-principal problems. Although the two main shareholders, the construction firms and the banks, had quite incongruent interests and should have naturally competed with each other, Eurotunnel was in the control of TML when both parties entered into the construction contract. As a result, according to Holliday et al. (1991), incomplete contractual documents and the "fast-track" design, dominated by TML, contributed to sources of many significant claims over the lump sum contract prices. The future shareholders' interests and the operation of the project were in lack of adequate protection. The occurrence of the excessive transaction costs in the Channel Tunnel project exactly matched the syndromes of the principal-principal problems caused by the unbalanced profit structure.

From the perspective of the softness of budget constraints, the U.K. and French governments committed themselves to hard budget constraints by effecting the legal document, the Treaty of Canterbury, at the beginning of the privately financed project. Thus, any attempt to break the commitment would have induced political condemnation. The concessionaire had little chance to hold the government up and extract subsidies from government. Thus, during the courses of the two financial restructurings, there were no direct and substantial subsidies extended from the government to Eurotunnel in order to bail the project out of financial difficulties. Although all of the shareholders, creditors, bondholders, and suppliers of Eurotunnel suffered huge losses or dilutions from the financial restructurings, the governments were able to maintain the incentive mechanism of PPP scheme and prevent the government from being hold-up. Efficiency can be achieved only when the ex-ante expectation of hold-up opportunities becomes remote. However, the hard budget constraints did not seem to be capable of reducing the aforementioned impacts of principal-principal problems.

4. Within-Case Analysis of Taiwan High Speed Rail

4.1. Project Background

The Taiwan High Speed Rail (THSR) project is the largest transportation infrastructure in Taiwan and also one of the largest PPP projects in the world. The concession period is 35 years. The high speed rail connects Taiwan's major cities from north end to south end by running trains up to 300 km/hour through the 345 kilometers route. The capital structure of the THSRC was originally targeted at 30% equity and 70% debt ratio, and was later revised to 25%: 75% equity and debt ratios. Using almost seven years, Taiwan High Speed Rail was completed in January 2007, with a 14 month delay. The actual total costs of the project upon completion were about $17.3 billion, including $3.2 billion costs committed by government and $14.1 billion invested by private parties, taking accounts of $1.7 billion cost overruns.

4.2. The Tendering and Construction of the Project and the Crises Encountered

There were only two alliance teams competing for the project, Taiwan High Speed Rail Alliance (THSRA) and China High Speed Rail Alliance (CHSRA). Since the technical concerns were limited due to the technology maturity, the competition was focused on the financial issues. In their financial proposal, CHSRA requested government to invest $4.6 billion to make the project financially viable. On the other hand, THSRA requested zero

additional government investment, and further promised that the government may receive at least $3.2 billion royalty-like payback from the project operation revenue. Finally, the project was awarded to THSRA in September 1997. The financial projection of THSRA immediately received criticism for being overly optimistic.

The first crisis faced by the Taiwan High Speed Rail Corporation (THSRC), the concession firm, was the inability to obtain the debt financing of $10 billion after winning the concession. In this project, the private promoters did not utilize the international debt markets for financing partly because Taiwan government to subsidize the loan interest by a rate far below the market. However, since the THSR was the first PPP mega project in Taiwan, the banks had no faith in financing the project at a below market fair rate without government's "full" debt guarantees. At last, a trilateral agreement was entered into among the government, THSRC, and the syndicate bank, which provided that the government shall assume the outstanding debt in the event that the concession agreement is terminated [for any causes]. Among the $10 billion of debt financing, $8.6 billion came from government owned/controlled banking systems and only $1.4 billion belonged to private commercial banks. Note that in this event the Prime Minister Mr. Hsiao explicitly expressed his attitude toward the project that "the project is not allowed to fail" and "government will do everything to support the project."

The second crisis concerned the raising of equity. According to the concession contract, the total amount of equity to be raised was $4 billion and the timetable for equity raising was specified in the debt financing contract. The fulfillment of the timetable was a prerequisite for withdrawing funds from the loan credit facility. For the following seven years before project completion, the THSR constantly had difficulties fulfilling the equity requirement. The inability to raise sufficient equity had caused the crisis of the THSRC's breach of the concession contract. The major reason of the crisis was because the market had substantial doubt on the project profitability and regarded that the THSRC's financial proposal was too optimistic. Note that the doubt on the project profitability could also be seen from the initial shareholders' reluctance and refusal of investing more equity later on although they had the capacity to do so. As a result, a couple rounds of renegotiation took place and finally the banks had to accept the THSRC's proposal to reduce the total equity amount to $3.3 billion.

Taiwan government played a crucial role in bailing out the THSRC from the equity raising crisis. The government was criticized of having the government owned/controlled enterprises (GOEs) make substantial equity investment in the THSRC. However, the last equity investment of $0.23 billion by the government controlled non-profit organizations in September 2005 caused one of the most serious criticisms for government's unjustifiable aids and failure in monitoring the project. During this equity raising crisis, the government announced again that "government is determined to ensure the completion of the high speed rail." As discussed previously, for projects that are too important or too big to fail, government will often suffer from the soft budget constraints. In fact, the government's "September 2005 equity investment" was later determined by the court that it was illegal for this non-profit organization to make the equity investment. Up to date, the total passive equity investment by GOEs, government controlled non-profit organizations, and government owned banks was about 37.4% of total equity, while initial equity invested by the promoters was only about 28.5% of total shares.

The third crisis was the cost overrun. Around one year before the project completion, only three months after the government's "September 2005 equity investment," the THSRC announced that the total cost overrun was estimated to be $1.7 billion or so due to the estimated one year schedule delay and construction cost overrun. Due to the serious political impact of previous government illegal equity investment, the government had ruled out the possibility of providing any equity investment or liability guarantees. For the first time, the government formally announced that the government would make plans to takeover the project if the THSRC could not raise either equity or debt to finance the additional capital needs. After the government took the "hard" position on the budget constraint, the THSRC could no longer hold up to renegotiate and, thus, decided to supplement the capital gap through debt financing, even though it was a daunting task for the THSRC to obtain another $2 billion debt at this stage to supplement the capital needs for cost overruns.

4.3. Financial Distresses

THSRC has been facing financial difficulties since the commencement of operation in 2007 due to the overly optimistic forecast of market demands. The actual operational revenues met only less than half of the forecast. As a result, the revenue could not cover the operating costs and expenses. In 2008, THSRC generated $0.7 billion in revenue, while the total costs and expenses amounted to about $1.47 billion, including depreciation and amortized expenses $0.58 billion and interest expenses $0.53 billion. Until the end of 2008, THSRC had suffered from an accumulative loss of equity in the amount of $2.05 billion, more than 60% of the total equity amount. According to the concession contract, THSRC shall maintain its equity/debt ratio above 25% at the end of each fiscal year. In fact, THSRC could not have complied with such requirement since the year 2003. By the end of the year 2008, the equity/debt ratio had dropped to 6.96% and THSRC had no capability to fill the financial gap, which had obviously constituted the material breach of the concession contract. Notwithstanding, the government continued to tolerate the breach of contract. As of January 2010, the government was still determined to bail out the project and kept lending its hands to the concessionaire. Government's current plan is to help THSRC obtain a new loan to repay the old one.

4.4. Within-Case Analysis

From the perspective of project profit structure, the original promoters/shareholders controlled the whole procurement of the construction in the amount of $14.1 billion while only $0.89 billion were injected by the original investors in the equity of THSRC. Therefore, given such unbalanced profit structure, the controlling investors naturally had the incentives to overly estimate the traffic demands to win the concession, recoup their investment, and let the passive stakeholders suffer the losses during the operation period. In fact, the promoters were seriously criticized that they had recovered most of their investments from the undertaking of the construction contracts of the project.

From the perspective of soft budget constraints, taking over the project by government involves substantial costs because of the original debt guarantee provided by the government for the first syndicate loan. If the concession contract is early terminated, the government must assume the outstanding amount of the first syndicate loan, around $8.45 billion according to THSRC's annual report of 2008. As a result, the government

was subject to soft budget constraints and intended to grant subsidies to THSRC in expectation of turning the situation around and delaying the project's insolvency.

5. Overall Evaluation of the Hypotheses

First, the two cases demonstrated a clear pattern how transaction costs were incurred through opportunistic bidding behaviors. When the promoters identified rent seeking opportunities due to government's soft budget constraints or project's unbalanced profit structure, they would bid very aggressively using overly optimistic financial projection so as to win the project. In both cases, the actual traffic demands during operation were only half of the original estimates in their bids and the projects were both delayed by a year or so. Since the projects were awarded to the firms with the most unrealistic forecasts, they soon faced financial difficulties either during the construction phase or in the early stage of operation. The opportunistic promoters/principals would have made excess profits during the courses of government rescues and/or undertaking the project's major contracts. The failure of the projects and the inefficient project execution created substantial transaction costs to the governments.

Second, the principal-principal problems due to an unbalanced profit structure happened to both projects and contributed to the project failures. We found that the two projects exhibited similar project characteristics that had led to unbalanced profit structure in PPPs. In both cases, the projects were unique and the first of their kinds in the country. Consequently, the information asymmetry between government/public and constructors was considerable and created excess construction profits and the incentives for the constructors to become the controlling promoters. In addition, since the projects scales were so big that investments from passive shareholders were needed, the constructor-promoters could limit their equity investments to relatively smaller proportions. As a result, the two projects were prone to highly unbalanced profit structures, which then led to principal-principal problems and subsequent project failures and transaction costs.

Third, the two PPP projects also exhibited some characteristics that might cause governments to be soft on budget constraints. For example, since the two projects were the largest PPP projects in the world, the political and economical impacts of project failures could be extremely high. However, in the more matured institutional environments such as the UK and France, the inefficiency caused by soft budget constraints was well recognized and the public had very limited tolerance toward soft budget constraints. Thus, in Channel Tunnel project, the governments made it explicit that the budget constraints were strictly hard. In developing countries such as Taiwan, the budget constraints tended to be soft and, as expected, the hold-up problems were common in PPPs.

From the above cross-cases analysis and the two within-case analyses, the two hypotheses proposed in this paper are reasonably supported. From the perspective of principal-principal problems, the two cases show the unbalanced profit structure contributed the controlling principals/promoters' opportunistic behaviors, which caused project failures and subsequent transaction costs. As predicted by hypothesis one, PPPs were not appropriate in the two cases as their governance structure. From the perspective of hold-up problems, the second hypothesis is reasonably supported by two facts. First, the UK and French governments had to explicitly bind them into hard budget constraints.

Second, the soft budget constraints of Taiwan government had caused the hold-up problems right after the project awarding and incurred substantial transaction costs not only in bailing out the project but also in encouraging future PPP promoters' opportunistic behaviors.

6. Conclusions

In this paper, we take the view of transaction cost economics and argue that the use of PPPs as a governance structure is contingent on project characteristics and institutional environments. Particularly, it is hypothesized that the principal-principal problems caused by unbalanced profit structure and the hold-up problems caused by soft budget constraints will result in significant transaction costs and render PPPs an inferior governance structure. Based on the case studies of Channel Tunnel project and Taiwan High Speed Rail project, the two hypotheses are reasonably supported.

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Volume 2

Construction Research Congress 2010

Innovation for Reshaping Construction Practice



Proceedings of the
2010 Construction Research Congress

Edited by
Janaka Ruwanpura, Ph.D.
Yasser Mohamed, Ph.D.
SangHyun Lee, Ph.D.

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Preface

We are very pleased to welcome you to the 2010 Construction Research Congress sponsored by the Construction Institute (CI) of the American Society of the Civil Engineers (ASCE) and the University of Alberta, in collaboration with the University of Calgary and the Canadian Society for Civil Engineering. The 2010 Construction Research Congress is being held at the Fairmont Banff Springs in Banff, Alberta, Canada - one of Canada's premiere hotels in the heart of the Canadian Rockies.

The theme of the Congress is "Innovation for Reshaping Construction Practice". The Congress aims to provide academics and industry professionals a forum to present and discuss revolutionary research findings, technological advances, emergent trends, and functional characteristics that are shaping the future of the architecture-engineering-construction industry. The purpose of the Construction Research Council is also to advance engineering knowledge and practice related to construction through stimulating and guiding research and assisting the financing thereof; to interpret and promote the utilization of the findings of research for the construction industry; and to identify future needs in the construction field and publicize them to stimulate appropriate research.

The two-volume Proceedings contain 156 peer reviewed papers covering the following 15 general state-of-knowledge research areas in construction engineering and management. There were 259 abstracts initially submitted that were reduced to 169 accepted draft papers following a peer review. From this, a final 156 papers were accepted for publication and presentation based on the same peer review process used in selecting abstracts.

- Automated/Real-Time Systems
- Construction Modeling and Simulation
- Disaster Planning and Mitigation
- Information Technology and Computer Applications
- Infrastructure Management and Underground Construction
- Knowledge Management
- Productivity, Benchmarking and Workforce Issues
- Organizational Leadership and Management
- Procurement, Contracting and Legal Affairs
- Project Planning and Control
- Project Risk Assessment and Management
- Quantitative Methods and Models
- Sustainable Construction and Facilities
- Construction Education
- CII Research

We are delighted to see that this event is truly global with representation from 14 countries including Australia, Canada, China, Egypt, Hong Kong, India, Indonesia, Korea, Netherlands, Saudi Arabia, Taiwan, Turkey, United Kingdom and United States.

We believe that you enjoy these Proceedings and have a memorable experience of both the Congress and spectacular Banff.

Janaka Ruwanpura, Ph.D., PQS
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A Critical Analysis of Innovations in Construction Manager-at-Risk Project Delivery

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ABSTRACT

Construction Manager-at-Risk (CMR) is an integrated delivery approach to the planning, design, and construction of civil engineering projects. CMR is well accepted in the building industry and is beginning to emerge as a viable delivery method for transportation projects. This paper correlates a comprehensive literature review documenting the advantages and disadvantages of CMR innovation with the output of 19 case studies involving structured interviews of project practitioners in the U.S. building, highway, airport, and rail transit sectors. The primary topical areas include the cost, scheduling, and quality aspects of CMR. The paper concludes that the innovations reported in the literature are not actually applicable to all types of projects. While the case study interviews confirmed at least one instance of each cited advantage, the primary innovation that can reshape construction practice lies in the constructability, biddability, and sustainability input that the constructor makes during the preconstruction services phase of a CMR contract. The paper recommends that owners leverage this advantage by carefully synchronizing both the design contract and the CMR preconstruction services contract.

INTRODUCTION

Integrated project delivery methods, which have become prevalent throughout the U.S. construction industry (Alder 2007), require that the constructor be engaged at a point in the design process where the constructor can make substantive input to the final design. Construction Manager-at-Risk (CMR) project delivery (also called Construction Manager/General Contractor [CM/GC]) is one such project delivery method. It brings the owner; the designer, who might be an owner's in-house engineer; and the at-risk construction manager together during the design process through a two-part contracting process that entails a preconstruction services contract as well as a construction contract. The preconstruction services contract is carefully coordinated with the design contract to achieve a high degree of collaboration among all parties. CMR project delivery also provides a way for the owner and the contractor to negotiate risk allocation via the method's guaranteed maximum price (GMP) pricing mechanism. The GMP is established at a point during the design process

when the contractor can minimize the contingency for scope creep. In contrast to design-build (DB) projects, CMR project delivery engages at-risk construction expertise early in the design process to enhance constructability, manage risk, and facilitate the concurrent execution of design and construction without the owner giving up control over the details of design.

CMR projects are characterized by a contract between an owner and a construction manager who will be at risk for the final cost and time of construction. In this agreement, the owner authorizes the construction manager to make input during project design. The owner will either complete the design with the owner's own design personnel or outsource the design work to a consultant.

METHODOLOGY

The methodology for this project was designed to analyze the output from multiple research instruments. Intersections were identified between the findings of a literature content analysis and points derived from structured interviews with members of owner agencies.

Structured Interviews

The primary research input was gathered through structured interviews with the agency personnel, consultants, and contractors who had implemented CMR project delivery. The structured interview outlines developed were similar to the method prescribed by the U.S. Government Accounting Office (GAO 1991). The GAO method states that structured interviews can be used where "information must be obtained from program participants or members of a comparison group… or when essentially the same information must be obtained from numerous people for a multiple case-study evaluation" (GAO 1991). Both of these conditions apply to this synthesis. Therefore, the tool is appropriate for the research.

Each of the structured interviews of agency personnel with CMR experience was centered on a single case study project. However, for those agencies that had completed several CMR projects, the interviews were broadened to include a more general set of policies, procedures, and effective practices. A total of 19 agency representatives were interviewed either face-to-face or by telephone, depending upon their availability. The total value of the case study CMR projects associated with these agencies is $2.3 billion. Table 1 shows the salient details on each agency interviewed. This list includes most departments of transportation (DOTs) with some type of CMR experience, as well as two non-state transportation agencies with significant CMR experience. The list also covers a wide-range of project sizes, from a low of $10 million to a high of $1.3 billion, and nearly all modes of transportation.

Literature Content Analysis

The literature on implementing CMR contracting is reasonably rich and contains the lessons learned by public agencies in all transportation sectors. A content analysis was performed on over 30 pieces of literature; the analysis concentrated on identifying those factors of CMR that were cited repetitively by a diverse group of authors/agencies. Tables 2 and 3 summarize the advantages and disadvantages found in the literature. If two or more authors specifically cited a specific factor as an advantage, the factor was recorded in Table 2. The disadvantages cited by the authors,

shown in Table 3, were then tabulated to show the authors' complete experience, regardless of how many times an item was cited.

TABLE 1 Agency Structured Interviews

Agency (Abbreviation)	CMR Experience (# projects)	Case Study Project	Location	Size ($)	Primary Type
Highway Agencies					
Alaska DOT&PF (AK)	2	Fairbanks Intl Airport Expansion	Fairbanks, AK	$99.0 million	Building
Florida DOT (FL)	9	Miami Intermodal Center	Miami, FL	$1.3 billion	Building, Rail, Road, Bridge
City of Glendale (CG)	18	Glendale Pedestrian Improvements	Glendale, AZ	$16.2 million	Road, Utilities
Michigan DOT (MI)	1	Passenger Ship Terminal	Port of Detroit, MI	$10.0 million	Building, Marine, Utilities
Oregon DOT (OR)	1	I-5 Willamette River Bridge	Eugene, OR	$150.0 million	Road, Bridge
Pinal County Public Works (PC)	5	Ironwood-Gantzel Road (US 60)	Florence, AZ	$63.7 million	Road, Bridge
Utah DOT (UT)	13	I-80 State St to 1300 East.	Salt Lake City, UT	$130.0 million	Road, Bridge
Airport Agencies					
Atlanta- Int'l Airport (ATL)	5	Non-project specific interview	Atlanta, GA	$20 million - $1.2 billion	Building, Runways, Road
Boston-Logan Int'l Airport (BOS)	3	Non-project specific interview	Boston, MA	:$10,000 to $165 million	Building, Runways, Road
Port Columbus Int'l Airport (CMH)	2	Non-project specific interview	Columbus, OH	$50,000 to $165 million	Building
Dallas-Fort Worth Airport (DFW)	30+	Non-project specific interview	Dallas, TX	$5 million to $100+ million	Building, Runway, Road, Light Rail
Denver Int'l Airport (DEN)	4	Non-project specific interview	Denver, CO	$500,000 to $150 million	Building, Special Equipment
Memphis Shelby County Int'l Airport (MEM)	25	Whole Base Relocation	Memphis, TN	$245.0 million	Runway, Building
Tampa Int'l Airport (TPA)	3	Non-project specific interview	Tampa, FL	$50,000 to $80 million	Building, Road
Transit Agencies					
Utah Transit Authority (UTA)	4	Weber County Commuter Rail	Salt Lake City, UT	$241.0 million	Rail, Road, Bridge, Building
Tri-Met Transit Authority (TTA)	5	Portland Mall Project	Portland, OR	$144 million	Rail, Road, Building
Commercial Building Agencies					
Dept. of Central Services (DCS)	20+	American Indian Cultural Center & Museum.	Oklahoma City, OK	$88.9 million	Building
Texas Tech University (TTU)	40+	Lanier Law School Center	Lubbock, TX	$13.7 million	Building
University of Oklahoma (OU)	12	Student Housing	Norman, OK	$29.2 million	Building

Table 2: Intersection of Literature Content Analysis (Advantages) with Case Study Project Structured Interviews.

Advantages Cited in Literature (15 total) & Case Studies (19 total)	Times Cited		Highway							Airport							Tran-sit		Building		
	Citations	Case Studies	AK	FL	CG	MI	OR	PC	UT	ATL	BOS	CMH	DEN	DFW	MEM	TPA	UTA	TTA	DCS	TTU	OU
CMR design input	12	18	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
Ability to fast-track	10	16	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	
Early knowledge of costs	10	13	X		X	X	X		X	X		X		X	X		X	X	X		X
Ability to bid early work packages	10	11			X		X	X	X	X	X	X		X	X					X	X
Owner control of design	8	14	X		X		X		X		X		X	X	X	X	X	X	X	X	X
GMP creates cost control incentive	6	13	X	X	X	X	X		X		X	X			X	X	X	X		X	
Reduces design costs	5	2							X						X						
Select GC on qualifications	4	10	X		X		X	X	X							X	X		X	X	X
Open books contingency accounting	4	15	X	X	X	X	X	X	X	X	X	X		X	X	X	X			X	
Focus on quality and value	4	15	X	X	X	X	X	X	X	X	X	X		X	X	X	X				X
Flexibility during design/ construction	4	12	X	X	X	X		X	X	X	X			X		X		X	X		
Spirit of trust	4	12			X		X	X	X	X	X		X		X	X	X	X		X	
Competitive bidding possible	4	13			X		X	X		X			X	X	X	X	X	X	X	X	X
CMR is owner's advocate during	3	4			X		X		X											X	

design																					
Third party coordination facilitated	3	10			X		X	X	X		X			X	X	X	X	X			
Less radical change from DBB than DB	2	10	X				X						X	X	X		X	X	X	X	X
Risk transfer	2	15	X	X	X		X	X	X	X	X	X			X	X	X	X		X	X

The content analysis uncovered two major differences of opinion among the authors reviewed. First, disadvantage 2 in Table 3 (the need to administer two contracts) conflicts with advantage 5 in Table 2 (owner control over design). Table 2 shows that two authors considered CMR a "less radical change than DBB" (Strang 2002) because the owner retains the design contract. Therefore, these two citations along with the eight citations of advantage 5 appear to overwhelm the four citations of the disadvantage. The second conflict revealed between the two tables is the disagreement between disadvantage 3 (cost not known until GMP is set) and advantage 3 (early cost certainty). Intuitively, the disadvantage is certainly real. However, there is a difference between "final actual cost" and "early cost certainty." While one of the agencies cited in the structured interviews the need to gain access to real-time construction pricing, one concluded that cost certainty can be achieved without knowing the exact GMP amount. In fact, the "actual" final cost of the project is truly not known until construction is complete. Thus, two of the top four disadvantages are discarded from the analysis.

Table 3: Intersection of Literature Content Analysis (Disadvantages) with Case Study Project Structured Interviews.

Disadvantages Cited in Literature (11 total) & Case Studies (19 total)	**Times Cited**		**Highway**							**Airport**							**Transit**		**Building**		
	Citations	**Case Studies**	**AK**	**FL**	**CG**	**MI**	**OR**	**PC**	**UT**	**ATL**	**BOS**	**CMH**	**DEN**	**DFW**	**MEM**	**TPA**	**UTA**	**TTA**	**DCS**	**TTU**	**OU**
CMR and designer have different agendas	7	9	X	X		X			X	X		X		X					X		X
Still have two contracts to manage	5	1								X											
Actual cost not known until GMP is set	5	3					X												X		X
Training required for agency	4	8	X				X				X	X		X		X			X		

Must pick CMR early in process	3	1																		X
Different procurement culture	3	8	X			X	X			X	X	X				X				X
Designer not obligated to use CMR input	2	3																	X	
CMR design liability via review comments	2	3																X		X	X
Contingencies difficult to allocate	2	5		X			X						X	X							X
Lack of clear leadership during design	2	1															X				
CMR underestimates preconstruction costs	1	1																			X
Reduced competition among subs	1	6		X			X		X		X	X		X							
CMR doesn't control the design schedule	1	6		X								X	X		X			X			X

ANALYSIS OF CMR IMPLEMENTATION

Taking the advantage output from the literature content analysis and intersecting it with the output from the structured interviews yields Table 2. Table 3 is the intersection of the disadvantage output from literature content analysis and the structured interviews. Parsing the information contained in the two tables allows the discussion to be organized in three primary categories: (1) Quality advantages and disadvantages, (2) Schedule advantages and disadvantages, and (3) Cost advantages and disadvantages.

Quality Aspects of CMR

Two of the major advantages cited deal with quality: constructor design input and owner design control. Through the preconstruction services contract with the CMR, the constructor is formally included in the design process. "Contractor experience and expertise can aid the design team in preparing more cost-effective traffic control plans, construction staging plans, and perhaps more realistic construction schedules" (Anderson and Damnjanovic 2008). Two of the services performed by the CMR

during the design phase are constructability reviews and design validation. C*onstructability* is defined by the Construction Industry Institute (CII) as "the integration of construction knowledge and experience in planning, design, procurement, and construction phases of projects consistent with the overall project objectives" (CII 1997). One of the papers cited in Tables 2 and 3 provides useful advice for appropriately timing reviews as follows:

> Constructability is achieved through the effective and timely integration of construction input into planning and design as well as field operations. For maximum effect, it should be initiated early in the design process and performed at predefined points during the design process in accordance with a well thought-out plan (Martinez et al. 2007).

This quote argues for selecting the CMR early in the design process to gain the "maximum effect" or benefit from the constructors' knowledge and experience before design effort is wasted developing potential alternatives that need to be changed as a result of the budget and constructability reviews. This discussion leads to the idea that the constructability process adds value to the project by enhancing the quality of the design and driving the design to produce a buildable project (Jeargas and Van der Put 2001; Dunston et al. 2002). An NCHRP study (Russell et al. 2002) found that one of the major research issues in the transportation sector was implementing a constructability review program in the planning and design phases that focuses specifically on "deficiencies in quality and clarity of construction plans." The study went on to recommend research on how to leverage constructability reviews as a means to increase the speed of construction. "The constructability review process (CRP), therefore, is recommended as an *indispensable means toward achieving quality* in the delivery of transportation projects" (Dunston et al. 2002, italics added).

CMR design reviews are *not* technical peer reviews of the design by the constructor. The unintentional assumption of design liability through CMR reviews was a disadvantage cited twice in the literature and in three case studies. However, none of those citations came from highway or airport case study projects. One authors states: "[t]he construction manager is not the licensed architect or engineer for the project and should avoid comments in the constructability reports that would more properly be included in a peer review by design professionals" (Martinez et al. 2007). That paper goes on to recommend that design validation reviews by the CMR be limited to "industry standards, previous construction experience with similar designs, and previous experience related to re-work or warranty issues." The benefits of design validation reviews are confirmed by another paper that reported that CMR project delivery "provides for flexibility in the implementation of design changes late in the design process without impacting construction schedules and final delivery dates" (Kwak and Bushey 2000). The fact that CMR design input was the most cited advantage in both the literature and the case study interviews demonstrates that the industry has developed a method to achieve the benefit without transferring the liability from the designer. The bottom line is that "[q]uality [construction] documents facilitate quality construction and good relations with the construction industry, and projects delivered cost-effectively without extended duration greatly enhance public image for the STA [state transportation agency]" (Dunston et al. 2002).

In order to accrue these potential advantages, the owner can develop a process that manages the greatest disadvantage reported in both the literature and the case study interviews: reconciling the differing agendas of the CMR and the designer during design. By contract, the CMR is cost-focused during the design phase because the primary reason for an owner to select CMR project delivery is to have access to the real-time cost estimating capability that exists only in the construction industry (Martinez et al. 2007). Thus, the owner's primary charge to the CMR is to ensure that the project does not exceed the budget. On the other hand, the owner charges the designer with ensuring that the project design details conform to all applicable codes, laws, and regulations while at the same time furnishing the desired technical capabilities and capacities. If the project does not meet these requirements, then the designer is liable to correct the problem. Additionally, the designer's liability for a structural failure in the project tends to last longer than the builder's. As a result of this issue, designers tend to be conservative in their designs, which can cause the construction cost to push against budget limits.

It can be seen from this discussion that CMR provides a mechanism to enhance the quality of the design, which necessarily translates into in better construction quality due to increased constructability (Dunston et al. 2002). This improvement is confirmed by the fact that four of the papers cited in Table 2 said that CMR created a "focus on quality and value" rather than on minimizing cost. This is nicely expressed by Dunston et al. (2002), who state, "The message is conveyed that the standard for top performance is measured by quality in terms of biddability, buildability, and maintainability in the project rather than by merely meeting a predetermined schedule." And this focus on project quality leads to the discussion of schedule issues in CMR project delivery.

Schedule Aspects of CMR

The second major advantage of CMR project delivery was cited by 10 of the authors reviewed for this report. The advantage concerns the enhanced ability to accelerate the schedule. Like DB, CMR projects do not have to wait for the design to be complete to begin building. The primary benefit of CMR comes from the ability to arrange the work in bid packages that correlate directly with design packages. This ability permits the CMR to bid out those packages as soon as each package's design is ready. In order to effectively accelerate the delivery period, the owner forms both the design and the construction contracts with this goal in mind. The owner cannot assume that the two can run independently and achieve this mutual goal.

Martinez et al. (2007) explain this feature of CMR as follows: "The construction manager should review the overall project schedule and conduct coordination meetings with the design professionals to make sure the design activities are in compliance with and integrated into the construction schedule." This issue speaks to the second most often cited disadvantage, which is the owner's need to properly coordinate and administer two contracts as opposed to the single contract in a DB project. This feature of CMR also advocates contractually assigning both design and construction scheduling responsibilities to the CMR. Doing so would ameliorate the cited disadvantage of "lack of clear leadership during design" by requiring the engineer to coordinate its efforts through the CMR for the best interests of the overall project's schedule. If the design contract does not have this type of language, the

owner regresses to dealing with the major disadvantage of refereeing the different agendas of the designer and the builder.

Cost Aspects of CMR

Two of the top five CMR advantages were directly related to cost. First, the owner is able to achieve cost certainty earlier in CMR than in DBB because the constructor is furnishing estimates during design, as well as a GMP before 100% design completion. Additionally for the first advantage, the owner can choose to use a progressive GMP, where the CMR commits to incremental bid package GMPs as design packages are completed and finalizes the project GMP when the majority of the work has been bid out to trade subcontractors and material suppliers. This feature of CMR reduces the risk to the constructor and the amount of contingency that the CMR must maintain against the cost risks of material price escalation, subcontractor availability, and scope creep during design. The second advantage deals with the role of the GMP as an incentive to control costs. The fact that the CMR is allowed to provide design input and then prepares progress estimates based on that input creates "buy-in" to the final design for the CMR. As Strang (2002) explains, "If the CM At-Risk has been on board all along, [it] will find asking for changes because of ambiguities in the plans as difficult as ever."

These benefits are offset in the literature by the requirement to select the CMR early in the project development process and then wait until the design progresses to the point where a GMP can be established without excessive contingencies before the actual total cost is known to the owner. While this knowledge comes earlier than in DBB, a lump-sum DB project fixes the design and construction costs at award. One of the other cited disadvantages is that the designer is not obligated to incorporate the CMR's design recommendations into the final design.

CONCLUSIONS

Through a literature review and structured interview methodology, this paper examined the use of CMR for transportation projects. While the structured interviews confirmed all cited advantages, the paper concludes that the innovations reported in the literature are not actually applicable to all types of projects. From Table 2, the top five advantages based on frequency of citation in the literature are as follows, with commentary from the interviews:

1. The ability of the constructor to make substantive/beneficial input to the design.
    a. This is the greatest advantage in the all four sectors of transportation, with the primary innovation for reshaping construction practice lying in the constructability, biddability, and sustainability input that the constructor makes during the preconstruction services phase of a CMR contract. It is recommended that owners leverage this advantage by carefully synchronizing both the design contract and the CMR preconstruction services contract.
2. The enhanced ability to accelerate the project's delivery schedule.
    a. This advantage is valued by all of the transportation projects but is not valued as highly for the building projects, possibly because an accelerated project for those public agencies is not critical.
3. Enhanced cost certainty at an earlier point in design than DBB.

   a. This advantage is valued by public agencies, but it is valued to a lesser extent in the airport sector. However, the airport sector greatly values the fourth advantage, early bid packages.
4. The ability to bid early work packages as a means to mitigate the risk of construction price volatility and accelerate the schedule.
   a. The airport sector greatly values this advantage, possibly because this sector gets funding from many different sources: bonds, revenue, federal, state, local, etc.
5. Owner control over the details of the design.
   a. This advantage is cited extensively by all but the highway sector in the interviews, possibly due to the fewer instances of buildings completed by this sector.

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Emergency Accelerated Construction

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Abstract: There are a number of transportation agencies that have experience with accelerated construction strategies. California and Alabama have in the last several years completed major accelerated construction projects. These projects served as the proving ground for acceleration approaches and methods. When on two occasions a fuel truck collision damaged a bridge at the I-65/I-59 interchange in Birmingham, the Alabama Department of Transportation dedicated the necessary staff resources to accelerated project delivery under emergency conditions. Caltrans has had similar emergency projects both in rural and urban settings. This paper identifies, through a set of project case studies, construction operational and management practices that support accelerated project delivery. From this study it is evident that successful project acceleration is achieved through a partnering atmosphere and contracting methods such as design-build plus incentive/disincentive clauses that encourage a contractor to expend the planning effort and resources necessary to reduce construction time.

INTRODUCTION

When Minnesota's I-35W Bridge across the Mississippi River in Minneapolis collapsed in 2007, the Minnesota Department of Transportation (Mn/DOT) was faced with the challenge of rapidly replacing a structure that carried more than 140,000 vehicles a day. Mn/DOT chose to accelerate the delivery of the I-35W Mississippi River replacement bridge using the design-build (DB) procurement method. A casting yard for the precast concrete segments was set up on the closed interstate highway pavement just south of the bridge and the segments delivered to the bridge construction location by barge. By these efforts Mn/DOT and its contractor were able to complete the replacement bridge in less than a year.

Many other transportation agencies have faced similar situations where a river crossing or roadway needed to be reopened with only minimum inconvenience to the traveling public after a sudden event had severely damaged or destroyed the system structure. Therefore, a team sponsored by The American Association of State Highway and Transportation Officials, the Federal Highway Administration, and the National Cooperative Highway Research Program recently sought to identify the key

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factors that lead to agency success in delivering projects under emergency conditions. Descriptions and finding from two of the projects the team analyzed are presented here. The conclusions, however, are draw, from the two dozen projects studied during the NCHRP work.

RESEARCH MEHODOLOGY

The research utilized two research methodologies to gather information: 1) desk scan; and 2) case studies. A desk scan is much like a literature review in that it entails review of current and past literature about the subject. In addition to the literature review, the desk scan involved contact with agency personnel to directly discuss specific projects and identify information about the projects. This enabled the research team to select agencies and projects for further exploration in the later phases of the study.

Case studies were the second research methodology that was utilized in this study. The case study projects were selected after examination of the Desk Scan information by the NCHRP team. The cases were selected bases on a geographical distribution and to examine the multiple issues affecting accelerated construction. This case study selection approach was used to ensure the team's ability to generalize the findings as well as the need to document successes and capture lessons learned regarding emergency project acceleration. One benefit of case studies is the ability to conduct a comprehensive interview with those individuals intimately familiar with the subject matter.

The research team began the case studies by developing a survey that included over 30 open ended questions. Two separate sets of survey questions were prepared, one set prepared from state highway agency perspective and one set prepared from a contractor perspective. The survey instruments covered the following areas with a focus on emergency project acceleration:

- General Program Level Issues;
- Contracting Strategies/Contract Administration;
- Planning and Scheduling;
- Construction Practices – Cost, Time, Quality;
- Traffic Control and Management; and
- Post-Construction – WHAT DID HAPPEN.

The findings of this study were confirmed through triangulation of information from multiple sources for each case study. The sources in this research included information from the desk scan as well as information gathered during the on-site interviews. Information obtained from case studies included the presentation, question and answers throughout the site visit, as well as from the completed survey instrument. There were multiple parties involved in each method, representing multiple stakeholders in each project. This provided the basis on which the identify strategies for successful planned project acceleration were formulated.

REPLACEMENT OF THE I-65/I-59 INTERCHANGE BRIDGES, BIRMINGHAM

On Saturday morning, January 5, 2002, a tanker truck loaded with gasoline crashed into a bridge pier in the northbound lanes of Interstate 65, killing the driver. The fiery crash virtually destroyed the overhead steel girder bridge carrying the southbound

lanes of I-65. This location in the I-65/I-59 interchange handles 240,000 vehicles per day (100,000 on I-65 and 140,000 on I-59/I-20). Temperatures in excess of 2,000℉ caused the bridge girders to sag 8 feet and extensively damaged the columns, caps, and pavement.

PROJECT DESCRIPTION (THE FIRST TIME)

The replacement three-span, 290-ft bridge designed by Alabama Department of Transportation (ALDOT) was longer and wider to provide additional future lanes for southbound traffic on the bridge and for northbound traffic moving under the bridge. Design options considered included:

- Replacing Spans 1 and 2 and bent 2 only using plans from the original bridge (i.e., replace in kind, steel girders).
- Replacing the entire bridge with a single-span bridge using steel girders perpendicular to the roadway (eliminating skew).
- Replacing the entire three-span bridge using AASHTO Type IV modified Prestressed Concrete PSC girders.

The ALDOT decided to use a precast concrete girder design to replace the bridge because the girders could be fabricated and delivered to the site faster than steel (Precast 2002).

PROJECT EXECUTION

The main span required 15 140-ft-long girders. The original ALDOT design was for AASHTO Type IV modified girders but that was changed as a result of a value engineering (VE) proposal submitted by the contractor. The contractor's VE proposal specified modified bulb tee girders (BT-54). These girders were 54 inches in height with an 8-inch web, a 44-inch top flange, and a 28-inch bottom flange. A standard BT-54 has a 6 in. web, a 26 in. bottom flange, and a 42 in. top flange. The design required an increase in the cross-sectional properties of the standard BT-54 in order to provide the structural capacity needed for the 140 foot span. This modified section also provided better lateral stability during transport and erection of the girders. The two end spans each required eight standard BT-54 girders 70 feet 2 ¾ inches long.

The project required 160 HP 12 × 53 steel piles, approximately 820 cubic yards of substructure concrete, and 825 cubic yards of superstructure concrete. It was a calendar day project but only 14 hours were lost due to weather. The contractor received an early completion bonus of $1.3 million as shown in Table 1.

Table 1. I-65 bridge replacement cost (2002)

	Cost
Second bid	$3,780,654.15
Low bid	$2,096,421.20
Incentive received, 52 Days @ $25,000	$1,300,000.00
Total (low bid + incentive)	$3,396,421.20
Net difference between first (w/incentive) & second bidder	$384,232.95

PROJECT DESCRIPTION (DÉJÀ VU: SAME INTERCHANGE, DIFFERENT BRIDGE)

On October 21, 2004, it happened again: a fully loaded tanker truck turned over on a ramp carrying the eastbound lanes of I-20 (FIG. 1) and exploded in a ball of flame. Again the bridge's overhead steel girders were severely damaged.

ALDOT engineers drew on their earlier experience and quickly chose precast concrete for the project. "We gave only a cursory consideration to steel. It would have taken far too long to replace the bridge with another steel-girder structure. Fabrication, erection, and painting of the bridge would have required two to three months" (Precast Aids 2006).

The second bridge replacement contract included an incentive clause that awarded the contractor $50,000 per day for each day the project was completed prior to December 31, 2004. A $50,000 for every day later than December 31 disincentive clause was also included (Table 2).

PROJECT EXECUTION

The precast concrete girders specified for this bridge replacement required a special design. Each of the three spans had 12-66-inch bulb tees. The girders had lengths of 87 feet 3 inches, 151 feet 3 inches, and 163 feet 9 inches. That final length, 163 feet 9 inches, was 24 feet longer than any girder ever shipped in the state. The components were specially modified, high-performance concrete, AASHTO-PCI modified bulb tee 63 girders, to which 2 inches of width and 3 inches of depth were added for strength and to allow for additional prestressing steel. The concrete strength requirement for the girders was 7,500 psi at release and 8,500 psi at 14 days.

FIG. 1 Sites I-65/I-59 interchange accidents 2002 and 2004



Table 2 I-65 bridge replacement cost* (2004)

	Cost*
Second bid	$5,535,693
Low bid	$5,450,000
Incentive, 27 Days @ $50,000	$1,350,000
Total (low bid + incentive)	$6,800,000

* Total cost including bridge and road work.

The engineering manager for the prestressing yard said that "At 2.9 million pounds, the prestressing was the highest force we ever pulled. We were concerned about the stability of the beams. We especially wanted to make sure that they would withstand shipping and erection." To answer the shipping question, the fabricator conducted transportation tests in the yard prior to shipping the girders the 12 miles to the site. The first girders were delivered and set in place just 16 days after the contract was let; the final girders went into place just three days later.

The fabricator used special 13-axle vehicles to deliver the girders to the site. The Alabama State Police provided escort service in addition to the usual escorts required for transit of oversize loads. The entire project was completed and the bridge reopened to all traffic on December 4. This earned the contractors a $1.35 million incentive. A comparison of the timelines for the two accelerated bridge projects is given in Table 3.

Table 3. I-65/I-59 interchange bridge replacement comparison

Event	Time 2002	Time 2004
Demolition	6 days	6 days
Design and Plans	8 days	6 days
Advertise and bid	2 days	1 day
Construction	37 days	36 days
Detour maintenance	54 days	46 days

SYNOPSIS OF ACCELERATION EFFORTS

Partnership

The State Bridge Engineer said, "We did things we don't normally do, working closely with each other and spending some weekends working out problems. It was refreshing to be that closely involved in a project." Decisions were made at the project level; requests and approvals were given verbally. Occasionally the contractor was not able to meet specified pile tolerances, so ALDOT had to reevaluate strength based on actual pile locations.

Mutual Trust

ALDOT met with contractors and suppliers the week after the accident to discuss replacement bridge design plans. With the information that came from those meetings, suppliers began preparations for casting the girders.

Fabricator Collaboration

Well before the letting the state entered into discussions with fabricators about prestressed girder designs. While the design was eventually changed, the discussions

were invaluable in establishing a project schedule. The discussions also assured ALDOT of material availability.

Cooperation

DOT guaranteed one day turnaround of shop drawings and material certifications.

Planning

The contractor stated, "We worked on a tight schedule and did a lot of planning." ALDOT noted that the "contractor was very good at scheduling." The contractor scheduled everything in hours from the start of the project and for all suppliers. Furthermore, the contractor took the approach that the job was a cost and time project.

Work Multiple Fronts

On the first project there were 60 workers plus considerable equipment working many parts of the project at the same time.

Methods

- A separate demolition contract began almost immediately after the incident.
- The highway contractor partnered with a vertical construction contractor that had an available labor force.
- To speed construction precast box culvert sections were used as shoring and footing forms.
- An accelerator was used to obtain high early strength (7,500 psi release strength). As soon as the required strength was achieved, crews moved forward instead having the normal wait for curing. For this project, the fabricator put together a detailed production schedule. Acceleration raised the cost of the girders 1.4 times above the normal selling price.
- Many of the old piles were pulled, which made the foundation design simpler.
- The state furnished the elastomeric bearings.
- Only one ready-mix plant was used, and it was within visual distance of the project.
- The contractor worked 24/7 until the very end of the project.

Traffic Management

Local media were a great help in educating the public and keeping it informed about the detour routes the DOT established. Additionally, ALDOT created a Web site to inform the public about detours and progress.

Bonding

By requiring the contractors to bring the required contract bonds to the bid, ALDOT was prepared to award the contract as soon as the bids were evaluated.

Implementation of New Technology

The prestressed girder fabricator had been involved with an ALDOT HPC Show Case event years before that provided experience with 9,000 psi in 24-hour mixes. With that knowledge and ALDOT approval, the fabricator decided to implement this mix design for the project.

Project Delivery

Design-Bid-Build (DBB) was used for this project because of its limited scope and because the only critical aspect was material availability.

UNDERLYING FUNDAMENTALS OF SUCCESS

Teamwork is always the key element to a successful execution of an accelerated project. Both of these bridge contracts were held by the same two contractors in joint venture (JV). The success of the projects can be traced directly to the fact that both ALDOT and the contractor placed focused teams on the projects. These teams continually displayed mutual understanding and teamwork. Everyone understood the urgency of the projects and the need to reopen the interstate.

The design that was produced by ALDOT used materials that the department knew could be procured in the shortest timeframe – precast concrete girders. ALDOT also had the capability to produce a full design in only four and a half days.

Detailed planning and scheduling allowed the contractor to effectively attack the work on multiple fronts. The smaller JV partner (in terms of contractor volume) was a veteran bridge builder with years of experience on DOT projects. This partner, who was familiar with DOT contracting requirements, managed the projects. The other partner was a general contractor with diverse experience building health-care, industrial, office, institutional, retail, educational, and water-treatment facilities. This second contractor had little DOT experience but brought a higher standard of scheduling practice to the team.

Together the two contractors created a schedule that displayed activities by the hour.

Contractor capacity is a crucial component to successfully completing an accelerated project. Contractors must have the ability to draw people and to staff the projects as necessary plus an equipment fleet that can support the activity demands of working on multiple fronts. In the case of large projects, only a contractor or JV with a large capability in terms of workforce and equipment inventory has the capability to execute an accelerated project. For smaller projects, experience with transportation projects and DOT contracting requirements becomes an important selection factor. However, as these two bridge projects demonstrate, there are many ways to bring critical resources to a challenging project.

A unique aspect of the first bridge replacement contract was the use of a vertical construction contractor to furnish the labor force. Most states would question the ability of a contractor unfamiliar with highway construction to handle such a project, yet the close coordination between the JV contractors made their workforce efforts a success.

REPAIR OF THE I-5 TUNNEL, LOS ANGELES, CALIFORNIA

A 31-vehicle accident in an I-5 bridge (tunnel) superstructure north of Los Angeles shortly before 11 p.m. on Friday, October 12, 2007, resulted in a blazing inferno (FIG. 2.). The fire caused significant damage to the 1,000-foot-long tunnel and the closure of I-5. A subcontractor who worked on the rehabilitation project stated, “There were truck tires, batteries, seats ... melted to ash. It was emotional for me to look at it when I saw it the first time. The heat was so intense, concrete had spalled off the walls and concrete on the ground had exploded 6 inches deep.”

FIG. 2. Location of I-5 Tunnel, Los Angeles, California



PROJECT DESCRIPTION

The I-5 tunnel is a truck bypass that runs beneath eight lanes of I-5, the major West Coast interstate linking Mexico to Canada. After the accident Caltrans maintenance personnel and emergency response agencies diverted the truck traffic onto the roadway above. The diversion caused heavy traffic congestion at this vital link between the Central Valley and Southern California. It was obvious that extensive work would be needed to repair the tunnel, and it would have to be accomplished quickly. The governor immediately declared a state of emergency. However, due to debris and potential toxic conditions, Caltrans and the consulting engineer could not enter the tunnel until three days after the accident (October 15). The consulting engineers were from the same firm that supported Caltrans after the I-580 MacArthur Maze fire only five months before.

All agreed that the pavement would have to be completely replaced and the tunnel walls repaired; in some places the walls sustained damage inches deep. Parts of the ceiling could be retained or repaired; others needed replacement. "A lot of the damage came because as the concrete heated and the fire crews sprayed water in, it caused the concrete to spall." Twenty-four inches of fire-damaged concrete pavement and sub-base material had to be removed.

Caltrans desired a maintenance-free surface that could be easily cleaned, would enhance visibility for safety, and would reduce the energy requirements for lighting. Paint was considered, but has a limited life and degrades over time, particularly when washed with high-pressure water blasting. Concrete made with white cement, however, would be expected to last the entire life of the tunnel and would have the added benefit of enhancing the lighting in the tunnel.

White cement concrete is brighter because it possesses a higher albedo rating. The standard unit of measurement for pavement reflectivity is albedo (ASTM C1549), which is a simple ratio of the amount of light reflected from a material to the amount of light projected on the material. The higher the albedo number, the more light is reflected from the surface. A typical asphalt surface can range from 0.04 to 0.12. Concrete pavements can range from 0.2 to 0.5 but sometimes higher. The albedo

rating of white cement concrete is 0.7 to 0.8; it reflects double the light of gray concrete.

Caltrans began the tunnel contracting process almost immediately. The engineering evaluation was completed around October 19, and on October 27 Caltrans hosted a bidder walk-through and solidified the project strategy. A 33-day contract was awarded on October 29. The work was complicated by the confined quarters and the fact that to stay on schedule a high number of personnel were employed at all times (Prokopy 2008). The repair contract, which was let using an A+B-type contract, was for $11 million and included an I/D clause. The incentive for early completion was capped at $2.9 million; the disincentive was $150,000 per day plus liquidated damages for each day beyond the stated duration. Table 4. shows the tunnel project timeline.

Table 4. I-5 Tunnel repair timeline

Date	Event	Day	Const. day
12 Oct. 2007	Wreck and fire; I-5 NB and SB lanes closed	1	
15 Oct. 2007	Crews inspect damage to tunnel	4	
27 Oct. 2007	Walk through and bid	16	
29 Oct. 2007	33-day contract awarded	18	
30 Oct. 2007	First workday (demolition)	19	1
6 Nov. 2007	Shotcrete completed	26	8
7 Nov. 2007	Girders set	27	9
9 Nov. 2007	Concrete paving	29	11
15 Nov. 2007	Tunnel opens	35	17

PROJECT EXECUTION

There was a full closure of the southbound truck lanes during the work. The work included replacing portions of the fire-damaged bridge superstructure with precast concrete girders left, repairing portions of the fire-damaged retaining walls and abutment walls, and replacing the fire-damaged pavement with rapid-set concrete. Acceleration techniques used on this project included precast concrete girders and rapid-set concrete for the pavement.

Twenty hours of demolition was the first item of work. Demolition involved chipping back the walls and water-blasting to remove the damaged concrete. The crews had to chip out the worst areas by hand. The depth of wall concrete removal ranged from 3 to 4 inches (the walls are 18 to 22 inches thick). The first 90 feet of the tunnel (nearest the site of the accident) was entirely rebuilt. While the demolition was proceeding, the mix designs for the paving were finalized.

Shotcrete work to repair the walls followed the demolition and wall preparation. The first layer in the heavily damaged areas was a 4,000-psi ready-mixed concrete designed to replace all the damaged concrete. A specialty bagged, high-strength, noncorrosive material was used to patch areas with deep damage. Following the

repair work, the entire tunnel area (27,000 square feet) received a refractory shotcrete lining. This was a specialty mix incorporating white cement for reflectivity and durability. Procuring the necessary raw materials did require a significant effort. The mix included a blend of 50% ground granulated blast furnace slag, 50% white cement, and silica sand. It was not the easiest component to find in Southern California because of its use in stucco buildings. The walls received a troweled finish.

The pavement concrete mix was also unique. In addition to color specifications, Caltrans had stringent strength requirements for the pavement. Typically the specification is for 550-psi flexural strength in 10 days; for this project the DOT specified 550 psi in 24 hours. There was also a flexural strength requirement of 650 psi in seven days.

The mix contained Type I white cement plus five admixtures, one mineral and four chemicals. Metakaolin, the mineral admixture, is white and is typically included to improve the durability of concrete. A super-plasticizer was used to provide workability and reduce the water-to-cement ratio. A large quantity of hardening accelerator helped provide high early strength. A shrinkage-reducing admixture limited drying shrinkage and a hydration stabilizer was used to provide sufficient time for the mix to remain workable.

The original goal was to use high-grade white aggregates from another area of the state, but the team chose local aggregates instead, so the final concrete mix is not pure white. The compromise of using local aggregates that were not pure white still provided good reflectivity. The concrete is extremely light; in fact, it was necessary to paint black stripes on either side of the white pavement stripes to make them stand out.

The low clearance in the tunnel limited equipment options for handling the concrete. A Texas screed was used to place the first 8-inch lift of lean concrete. Because the concrete was extremely fast-setting, the contractor had 15 to 20 workers finishing the pavement behind the screed, hand-floating it with a rough finish. The final layer of concrete across the four 12-foot lanes was placed with a Whiteman roller screed. The time for finishing was again minimal, so a crew of six followed the roller screed for finishing. A final pass of profile grinding on the surface took an additional 15 hours.

SYNOPSIS OF ACCELERATION EFFORTS

Contract

A+B bidding was used effectively with an I/D to emphasize the importance of time.

Design

Readily available precast concrete girders were used.

Partnering (Teamwork)

The contractor commended Caltrans, saying that it was a full team player, with staff available 24/7. “Everybody in the whole Caltrans group were really awesome.”

UNDERLYING FUNDAMENTALS OF SUCCESS

Caltrans developed its design considering speed of construction and availability of materials. When it was not possible to obtain the white aggregate, the DOT was open

to modifying the requirement so that the highway would be back in service in the shortest time possible. I/D provisions of the contract should encourage the contractor to complete the tunnel as quickly as possible.

SUMMARY OBSERVATIONS

Successful delivery of accelerated projects under emergency conditions is highly dependent upon these underlying factors:

- **Contractor** – Find a contractor that has the resources to start immediately. The contractor must have the technical capability together with the ability to mobilize the necessary people and equipment rapidly. The contractor must also have the financial capacity and established trust with suppliers and fabricators so that critical material will move with only a phone call. Communications with the agency, engineering support, suppliers, and fabricators is critical and sometimes in the case of emergency projects the contractor may have to assume responsibility for establishing a communication network.
- **Detailed Planning** – A detailed execution plan must be prepared and updated regularly to include concurrent activities, multiple fronts tp push construction activities, look ahead plans and contingency plans for possible impediments such as equipment breakdowns or loss of batch plants.
- **Experts** – Timely decisions are crucial to accelerated project completion. In the case of an emergency project, communication can be difficult and distances can create time lags, therefore, ensure that key experts are located on the project or immediately accessible. Decisions are best made on the project site by experts that have full comprehension of the issues.
- **Delegate** – Push decision making, including contract award and execution, to the lowest possible level. Empowering project personnel and the designer of record to make project decisions accelerates the work.
- **Design-Build** – Scope for the basic need and allow the contractor to develop solutions. Often design is controlled by available materials that can be drawn to the project site.

CONCLUSIONS

Much more up-front planning is required to successfully complete emergency accelerated construction. Contractors seeking to accelerate their work have to develop their construction process plans to a much greater level of detail. Additionally, the agency must research available materials before developing a design.

The foundation of accelerating project construction is a design based on resources that can be moved quickly to the project site. As protection against problems that can be caused by project unknowns the design team should strive for a conservative design. The designer must maintain flexibility in the design approach. There is going to be change and the design must be such that it can easily accommodate adjustments.

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Assessment of Responsibilities of Project Teams for Owner Managing Contractor Tasks – A Fuzzy Consensus Approach

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Abstract

This paper proposes a fuzzy consensus approach that helps project teams in resolving conflicting responsibilities on their shared tasks in the Owner Managing Contractor (OMC) project delivery system. A list of shared OMC tasks is introduced to experts. Experts assign the responsibilities of project team members for every task using fuzzy preference relations on pairs of responsibility alternatives. Consensus degrees are computed for the preference values that are selected by the largest number of experts for the pairs of responsibility alternatives. The responsibility for each task is determined based on the pair of responsibility alternatives that receives the highest preference value. The approach is illustrated by a numerical example. This approach is relevant to the construction industry as it can be used to determine the responsibilities of project teams in the OMC or any construction project delivery system to ensure alignment between project teams prior to project execution.

Introduction and Problem Statement

For the past few decades, construction project owners have been reconsidering their project delivery methods, as some projects have failed to live up to their expectations due to time and cost overruns. As a result, many owners have shifted from the conventional design-bid-build approach to total project delivery systems (Kirschenman 1986), such as the design-build and the traditional construction management project delivery systems. Most of these approaches encourage contracting out project management and control functions to other entities. Unfortunately, as these approaches evolved, owner organizations have focused on overseeing projects' major phases through a reduced number of owner representatives, which resulted in less control over their projects. Thus, the majority of their competencies, including detailed design, project management, process engineering, construction management, and project controls were reduced or eliminated. This problem encouraged construction project owners to investigate new

approaches that may allow them to regain the lost control over their projects. The owner managing contractor (OMC) project delivery system is proposed by a large Canadian owner organization in the field of oil and gas to solve this problem. This organization had previously adopted the engineering, procurement, and construction management delivery system (EPCM) in managing its projects. There is no clear definition of the OMC project delivery system in the literature, yet interviews with construction experts from several oil and gas construction projects in Canada and a previous research study by Elbarkouky and Fayek (2009) have provided a basic understanding of this approach. The OMC is similar in nature to the construction management delivery system, yet it encourages owners to rely less on the use of external expertise, such as construction management consultants or EPCM contractors. The OMC is also different from partnering, as it allows the owner to manage its projects using its internal resources for most project management (PM), construction management (CM), and project control functions.

A large oil and gas construction owner organization in Alberta provided the motivation for the study of the OMC project delivery system. Its key managers wanted to describe the tasks that they would handle versus their EPC contractors in their OMC projects, as well as the roles and responsibilities of each party on these tasks. The owner organization wanted to apply the judgement of its experts in different projects to standardize their OMC projects' tasks. Based on an extensive literature review of various project delivery systems, Elbarkouky and Fayek (2009) proposed a preliminary roles and responsibilities structure for the tasks to be handled by the owner versus its EPC contractors in the OMC delivery system. The results of that study were based on the feedback of experts on generic PM and CM tasks that were collected from the literature. Three hundred and twenty seven tasks were listed under 18 work processes, such as project initiation, and project controls, based on an internal OMC model of the owner organization. Experts from both the owner's organization and its contractors rated the extent of responsibility of the owner's project team members on the tasks via a web-based questionnaire using a crisp rating scale. The scale ranged from one (No Responsibility) to seven (Sole Responsibility). The rating of four represented an intermediate value on the scale, which meant that the responsibility is shared equally between the owner's project team members and those of its contractors. The results in terms of responsibility ratings were analyzed statistically, and each task was categorized under one of three lists, namely owner's responsibility list, contractors' responsibility list, and shared responsibility list. The statistical analysis showed consistent results between experts' opinions on the tasks with average responsibility ratings of more than five (i.e., owner's responsibility) or less than three (i.e., contractor's responsibility) on the rating scale, which defined clear responsibilities between the owner and its contractors. However, consistency analysis, which was based on the calculation of standard deviations and skewness coefficients of the average responses, showed conflicting opinions in terms of responsibilities when the average responsibility rating for a given task was close to four, which is the rating of shared responsibility. Eighty-one tasks were rated as shared in terms of responsibilities based on the previous study. Table 1 illustrates a sample of these tasks.

Table 1: Sample of shared tasks in terms of responsibilities

Work Process	Sample Tasks
1. Initiation	Preparing the Design Basis Memorandum (DBM).
2. Project Management	Developing risk mitigation plans. Preparing the project's detailed work breakdown structure.
3. Project Control	Progress monitoring of the project activities. Identifying scheduling alternatives and improvements.

General Description of the Fuzzy Consensus Approach

The goal of this paper is to present a methodology to help in resolving the conflicting opinions between experts in terms of responsibilities of shared tasks by introducing the tasks to experts to make further responsibility assessments using fuzzy preference relations. Fuzzy logic is suitable for modeling this problem as it efficiently deals with imprecision and vagueness, which are often inherent in deciding on conflicting responsibilities using expert opinions. The proposed methodology allows the owner and its contractors to measure the degree of consensus of their experts on the final decision as to whether each standard shared task could be shifted to the owner or to the contractor, or if it should still be described as shared. First, the list of shared tasks is introduced to experts. Three responsibility alternatives, which define the final responsibility per task, are introduced to experts in a reciprocal matrix form (Table 2); these are "owner's", "contractors' ", and "shared" responsibility alternatives.

Table 2: Preference relations reciprocal matrix

	Owner's Responsibility	Contractor's Responsibility	Shared Responsibility
Owner's Responsibility		Certain	Certain
Contractor's Responsibility	Impossible		It May
Shared Responsibility	Impossible	It May	

Experts are asked to present their opinions regarding the responsibilities of every task using fuzzy preference relations as per Table 2. Preference relations allow experts to present their opinions or preferences linguistically over a set of possible alternatives, using a fuzzy preference scale that ranges from 0 to 1. In this case, the scale consists of seven linguistic preference values. Each preference value is denoted by a linguistic label. Each linguistic label represents a certainty expression (linguistically assessed) that describes a degree of certainty of an expert for a given preference. Figure 1 illustrates the linguistic labels that form the scale. The same scale is also used later to compute the consensus degrees linguistically. The linguistic terms of the scale are used to define the level of consensus on each preference, where each linguistic term defines a certain level of consensus that ranges from "*impossible"* to "*certain.*"

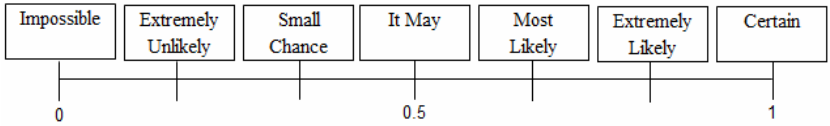


Figure 1: Fuzzy preference scale representing degrees of certainty

For every task, experts are asked to assign their preference values in the matrix on pairs of responsibility alternatives, such as "owner's over shared responsibility" or "owner's over contractors' responsibility." For example, for a given task, if an expert prefers a certain alternative (e.g. owners' responsibility) over another (e.g., contractors' responsibility), then he or she may choose the linguistic label *extremely likely*. On the other hand, an expert would choose the linguistic label *it may* if he or she can not easily distinguish one alternative over another. The frequency of experts' opinions is then calculated for each selected preference value for each pair of responsibility alternatives. The preference value selected by the largest number of experts for each pair of responsibility alternatives is considered the aggregated opinion of experts for that pair and is called the "consensus label". For example, for a given pair of responsibility alternatives (e.g., owner's over shared responsibility), if three experts out of eight have selected the preference value *certain*, while five experts have selected the preference value *small chance*, then the consensus label that would represent this pair is *small chance*. This means that there is a *small chance* that the owner would handle this task over having it as a shared task. A finalized matrix is created for each task that contains the consensus labels of each pair of responsibility alternatives. Consensus degrees are then computed for each consensus label of each pair of responsibility alternatives. If the required consensus is not reached, then a second round of data collection and consensus reaching is conducted. After reaching the required consensus level on consensus labels, the responsibility for each task is determined based on the pair of responsibility alternatives that has the highest preference value on the scale. For example, for a given task, if the consensus label for the pair of responsibility alternatives (owner's over contractors' responsibility) is *extremely likely*, while the consensus labels for other pairs have the preference value *it may* then the task is a sole responsibility of the owner. The three task lists that were previously prepared by Elbarkouky and Fayek (2009) are updated accordingly.

Fuzzy Consensus Approaches

There are several approaches to solve the problem of conflicting responsibilities by using fuzzy logic-based methods. For example, Ishikawa et al. (1993) proposed an interval values approach to represent the judgment of experts, which was applied to forecasting of time periods rather than the aggregation of opinions on sets of linguistic alternatives. Bardossy et al. (1993) outlined different additive and non-additive methods for combining the beliefs of different experts into a single fuzzy number, but they did not consider the measurement of consensus during aggregation. Lee (2000) illustrated the use of fuzzy similarity measures to aggregate experts' opinions by classifying similar elements and distinguishing between similar groups

of individual decisions before aggregating their opinions. The main problem in most similarity approaches is that they do not formulate a measure of consensus for each stage of data collection. Kacprzyk et al. (1992) outlined the basics of using fuzzy preference relations in group decision making using numerical preference values, while Herrera et al. (1996) outlined a consensus measure for preference relations using linguistic preference values. The latter linguistic consensus approach of Herrera et al. (1996) is adopted in this paper as it allows for the vagueness and imprecision that are inherent in the problem of resolving responsibility conflicts. This approach allows experts to compare responsibility alternatives in pairs, similar to the Analytical Hierarchy Process (AHP) (Saaty 1980), which is efficient and practical in resolving decision conflicts between experts on a set of similar alternatives. The proposed approach ensures that the required level of consensus is reached between experts on the final responsibilities. It measures the level of consensus in every stage of data collection using linguistic assessments, and the process of data collection is repeated if the required consensus level is not reached.

Fuzzy Preference Relations Consensus Approach

This section outlines the steps of the fuzzy consensus approach to aggregate opinions to reach consensus across a panel of experts $E = \{e_1,\ldots, e_n\}$ on a finite set of responsibility alternatives $X = \{x_1$: owner responsibility, x_2: contractors' responsibility, x_3: shared responsibility$\}$. As described earlier, the alternatives are rated by experts in pairs of responsibility alternatives in a matrix form (Table 2).

Step 1: Defining the Fuzzy Preference Scale
The first step is to define the fuzzy preference scale that experts will use to determine their preferences on each pair of responsibility alternatives. Seven linguistic labels were determined with experts in order to describe the set of preference values *S* on a continuous fuzzy scale that ranges from 0 to 1. The membership functions (MF) of the linguistic labels are constructed based on the modified horizontal approach combined with the least sum of errors calculation. The linguistic labels that are used in this step and their finalized shapes are illustrated in Table 3. Each MF is represented by the 4-tuple (a, b, α, β). The first two parameters indicate the interval in which the membership value is 1, while the third and fourth parameters indicate the left and right endpoints (i.e., membership value of 0).

Table 3: Description of the linguistic labels of preference

Symbol	Linguistic Label	4-Tuple Describing the MF
C	Certain	(1,1,0,0)
EL	Extremely Likely	(0.8, 0.9, 0.1, 0.1)
ML	Most Likely	(0.7, 0.9, 0.2, 0.1)
IM	It May	(0.5, 0.7, 0.3, 0.1)
SC	Small Chance	(0.20, 0.40, 0.20, 0.11)
EU	Extremely Unlikely	(0.1, 0.2, 0.1, 0.11)
I	Impossible	(0,0,0,0)

The modified horizontal approach determines preliminary non-uniform shapes of the MFs representing the linguistic labels. Then, the MFs are transformed to fit triangular or trapezoidal shapes. The supports and shapes of each linguistic label are determined based on the results of a simple questionnaire. Six project managers from the owner organization and two from the EPC contractors, each with more than 15 years of experience in the construction industry, responded to this questionnaire. Questions were posed regarding the ranges of elements that experts think are appropriate to represent the MF of each label on a scale from 0 to 1. One question was posed regarding each linguistic label. All questions were in the form of "*what are the range of elements (x_i) that may represent this linguistic label on the scale from 0 to 1 - please circle as many answers as applicable*". The replies of experts were counted in terms of frequencies of responses ($P(x_i)$) to the total number (N) of responses for every element x_i in order to calculate its membership value ($A(x_i)$). This resulted in the preliminary non-uniform shapes of each MF as illustrated in Figure 2(a). The finalized standard shapes of the membership functions that best fit the non-uniform shapes were determined using the least sum of errors calculation. The sum of errors is calculated between the membership values ($A(x_i)$) of the elements (x_i) composing the non-uniform shapes and their relevant elements in each proposed standard shape. The elements of the standard shape with the least sum of errors to those of the non-uniform shape are considered the best fit for the data. Based on error calculations, only trapezoidal shapes fit all the non-uniform shapes. Figure 2(b) illustrates the finalized membership functions after data fitting.

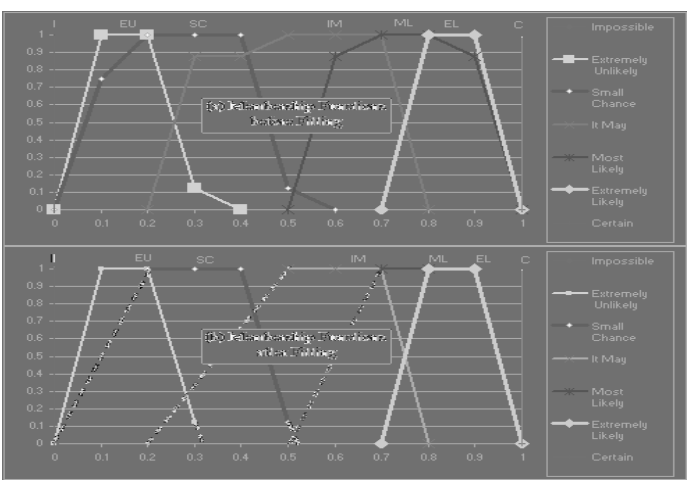


Figure 2: Linguistic labels' membership functions (a) before and (b) after data fitting

Step 2: Assigning Preference Values on Pairs of Responsibility Alternatives
This step involves assigning the preference values by each expert on pairs of responsibility alternatives (x_i over x_j) for each task in a reciprocal matrix (P_i). The

elements of each reciprocal matrix for each expert contain the preference values selected by the expert for each pair of responsibility alternatives. An example is shown in Table 2.

Step 3: Counting Process to Aggregate Preference Values
This step involves aggregation of experts' preferences for each pair of responsibility alternatives in order to determine the consensus labels. This step is repeated for each task. Consensus labels determine the final aggregated preference on each pair of responsibility alternatives. The frequency of experts' opinions over each selected preference value is calculated for each pair of responsibility alternatives. The preference value selected by the largest number of experts determines the consensus label for each pair of responsibility alternatives. Consensus labels are inserted in the relevant location in a finalized aggregation matrix, called Label Consensus Relation (LCR), which is created for each task. Prior to calculating the consensus degrees on pairs of responsibility alternatives in the next step, an individual consensus relation matrix (ICR) is created for every task. The elements of the ICR contain the proportion of the number of experts who chose each consensus label LCR_{ij} relative to the total numbers of experts.

Step 4: Computing Process to Measure Consensus Degrees on Consensus Labels
The last step involves measuring experts' consensus degrees on the consensus labels that represent their aggregated preferences on each pair of responsibility alternatives. The linguistic quantifiers Q are used for this purpose (Zadeh 1983). Some examples of quantifiers are "*as most", "at least half",* and *"all",* which are represented by fuzzy membership functions defined on the range between [0, 1]. The choice of the linguistic quantifier depends on the decision made by the user. For example, if the user is aggressive in terms of consensus reaching, then the selected quantifier could be *at least half.* This means that if at least half the number of experts agreed on a given consensus label for a given pair of responsibility alternatives, consensus on this label is described by the maximum linguistic label on the scale of preferences. The parameters and the method of calculating the consensus degrees are illustrated in Equation 1.

$$Q(r) = \begin{cases} l_0 & \text{if } r < a \\ l_i & \text{if } a \le r \le b \\ l_u & \text{if } r > b \end{cases} \qquad [1]$$

where, l_0 is the minimum label in S, l_u is the maximum label in S, and l_i equals (r-a)/(b-a). Note that a and b are the parameters that determine the supports of the MF of the linguistic quantifier Q, and r is the ICR_{ij} value for each pair of responsibility alternatives. Calculation of the degree of consensus for a preference value on a given pair of responsibility alternatives is determined based on the ICR_{ij} value of this pair compared to the values of the supports of the selected quantifier. The next section presents an example that illustrates how the proposed approach is applied to a sample task to determine the responsibility of that task.

Example to Illustrate Fuzzy Consensus Approach

Eight experts were asked to indicate their preference reciprocal matrices (P_i) for the sample task "*conducting project feasibility studies*" using the linguistic labels provided in Figure 1; their responses are shown in Figure 3. Figure 4(a) illustrates the finalized LCR that stores the aggregated consensus labels. Figure 4(b) illustrates the elements of the ICR matrix that shows that four experts agreed on the label *extremely likely* (EL) for the alternatives pair (x_1, x_2) with r equal to 0.500. Assuming that the linguistic quantifier "*at least half*" is used with parameters a = 0 and b = 0.5, according to Equation 1, the degree of consensus is the maximum label (l_u) in S, which is *"certain"* (*C*) for that label (case r > b) as illustrated in Figure 4(c).

Expert (e_1)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	EL	EL
x_2:EPC	EU	-	IM
x_3:Shared	EU	IM	-

Expert (e_2)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	EL	IM
x_2:EPC	EU	-	IM
x_3:Shared	IM	IM	-

Expert (e_3)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	IM	EU
x_2:EPC	IM	-	EU
x_3:Shared	EL	EL	-

Expert (e_4)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	EU	SC
x_2:EPC	EL	-	ML
x_3:Shared	ML	SC	-

Expert (e_5)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	IM	SC
x_2:EPC	IM	-	SC
x_3:Shared	ML	ML	-

Expert (e_6)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	IM	EU
x_2:EPC	IM	-	EU
x_3:Shared	EL	EL	-

Expert (e_7)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	EL	EL
x_2:EPC	EU	-	IM
x_3:Shared	EU	IM	-

Expert (e_8)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	EL	EL
x_2:EPC	EU	-	IM
x_3:Shared	EU	IM	-

Figure 3: Preference Relations Reciprocal Matrices (P_i)

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	EL	EL
x_2:EPC	EU	-	IM
x_3:Shared	EU	IM	-

(a) LCR Matrix

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	0.500	0.375
x_2:EPC	0.500	-	0.500
x_3:Shared	0.375	0.500	-

(b) ICR Matrix

	x_1:Owner	x_2:EPC	x_3:Shared
x_1:Owner	-	C	SC
x_2:EPC	C	-	C
x_3:Shared	SC	C	-

(c) Consensus Degrees

Figure 4: LCR and ICR Matrices, and consensus degrees

Figure 4(c) illustrates the final consensus degrees as obtained from the scale (Figure 1), where experts were "*certain*" that the owner was *extremely likely* to be responsible for the task over the EPC contractor, and were also "*certain*" that the task was *extremely unlikely* to be handled by the EPC contractor. Thus, one can

conclude that the task "*conducting project feasibility studies*" is the sole responsibility of the owner.

Figure 5 illustrates the classification of responsibilities for five tasks in the initiation work process. After conducting one consensus round, two tasks were amended to the original owner's tasks list and one task remained in the finalized shared tasks list. Experts did not reach consensus on tasks numbers three and five, which need a second consensus round with experts until the required consensus is reached. In order to test the validity of the approach, the classification of responsibilities for tasks will be compared to the actual responsibilities on a successfully completed oil and gas construction project that used an OMC project delivery model.

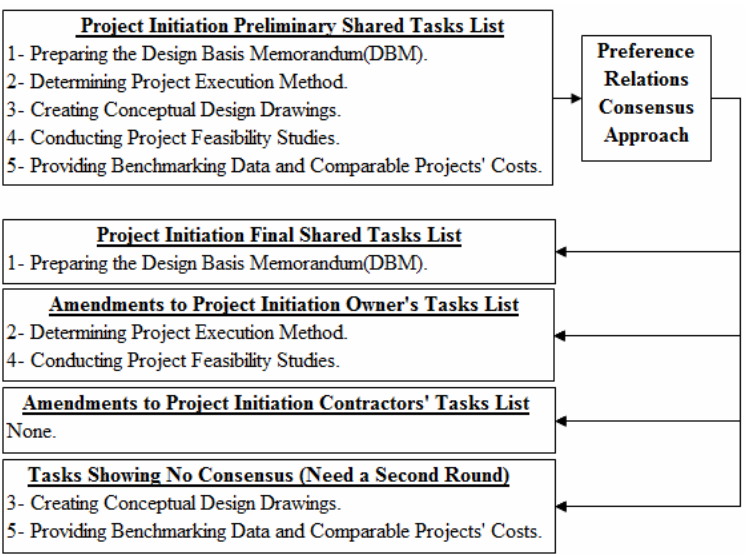


Figure 5: Final results after a single consensus round – initiation work process

Conclusion and Future Development

This paper proposes a fuzzy preference relations consensus approach to help owner organizations in resolving a fundamental problem in the construction industry, that of determining the appropriate responsibilities for a given set of tasks in a project delivery model. The proposed methodology measures consensus between experts regarding the responsibilities of project team members for individual tasks. This approach ensures early alignment between project teams on conflicting responsibilities, which may help in reducing responsibility gaps or redundancies between the owner and its contractors at the early stages of construction projects. The methodology is flexible enough to be used to help project owners in resolving

responsibility conflicts in different project delivery systems other than the OMC. As a future development to this study, the qualifications of experts will be determined and combined with their linguistic assessments in order to aggregate their opinions. Experts' weights will be computed using a standalone fuzzy expert system that considers the quality of different experts' opinions, based on the characteristics of the experts, in the consensus reaching process.

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Comparison of Water/Wastewater Project Performance by Project Delivery System and Payment Provision

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ABSTRACT

Municipal water and wastewater facilities play an important role in the infrastructure of this nation. In a continued effort to provide such facilities, public owners have been using a variety of project delivery methods and contract pricing provisions for design and construction of facilities. The increased use of design-build project delivery with a guaranteed maximum price (GMP) contract pricing structure in the water and wastewater industry has created an opportunity to collect performance data to measure the effectiveness of these methods. Through a detailed survey of public water and wastewater facility owners, data were collected to compare project performance based on schedule and cost growth measures. Data were collected on 100 projects completed since 2003 and with a total price of at least $3 million. Results show that design-build projects have a greater intensity (cost delivered per unit of time), with no difference in quality from design-bid-build projects. Also, the results of this study indicate that contracts using GMPs are more likely than projects with lump-sum contracts to have no schedule or cost growth. Overall, the results of this study provide new data for water and wastewater projects that can be used by owners to improve future project performance.

INTRODUCTION

An increasing number of utility owners are using project delivery methods other than design-bid-build for water and wastewater projects. Under design-bid-build, design

services are selected on the basis of the firm's qualifications, and the services are paid for using a cost-plus-fee payment provision. Construction firms in design-bid-build contracting have traditionally been selected using a low-bid method and facilities are paid for through a lump-sum payment provision. With the growth of integrated project delivery methods, such as design-build, there have been changes regarding how the design-build entities are paid. Under design-build, both the design and construction work is included in a single contract with a single payment provision. Two of the common payment provisions for design-build projects are lump sum and cost-plus-fee with a negotiated guaranteed maximum price (GMP) for both the design and construction services. With the growth in alternative project delivery methods and the GMP payment provision in the water and wastewater industry, there is a need to evaluate how these factors affect project performance.

This paper presents the results of a comprehensive national survey of 100 water and wastewater projects. The goal of the paper is to present an analysis of project delivery methods, contract payment provisions, and project performance and to show the influence that project delivery method and contract payment provisions have on schedule and cost performance.

BACKGROUND

The water and wastewater industry uses numerous project delivery methods, such as traditional design-bid-build, construction manager-at-risk, and design-build. Recent advances in project delivery methods and changes in state procurement laws are enabling public water and wastewater utilities to use innovative delivery techniques, like design-build, for the construction of new facilities and the upgrade or expansion of existing facilities. The use of design-build has been increasing in the water and wastewater industry (Molenaar et al. 2004), which has prompted this study comparing the performance of water and wastewater projects that have been performed using either the design-bid-build or design-build project delivery system.

Songer and Molenaar (1997) conducted research into public-sector design-build projects and found that a number of characteristics (project, owner, market, and relationship) impact project success, as measured by the project being budget, being on schedule, conforming to user expectations, meeting specifications, providing high quality workmanship, and minimizing construction aggravation. Other scholars determined that the key criteria of successful projects include cost (unit cost, cost growth, intensity), time (construction speed, delivery speed, schedule growth), quality (turnover quality, system quality, equipment quality), owner's satisfaction, and owner's administrative burden (Ling et al. 2004). Research comparing the use of project delivery methods has established these evaluation criteria as standard (El-Wardani et al. 2006, Gransberg et al. 2003, Konchar and Sanvido 1998, McWhirt 2007).

The most common goal of design-build is to reduce project delivery time. Overall, research has shown that design-build has a high potential to actually accrue time savings compared to projects delivered using design-bid-build. Additionally, research has typically concluded that design-build performs better than other delivery

methods in terms of cost. No research has drawn such conclusions about the relationship between design-build and quality performance (Chan et al. 2002, Gransberg et al. 2003, Konchar and Sanvido 1998, Ling et al. 2004).

The water and wastewater industry also uses various contract payment provisions, such as lump sum and cost-plus-fee. The lump-sum payment provision is the most common for both construction contracts (under design-bid-build) and design-build contracts. Under a lump-sum provision, the contractor agrees to complete the project for a fixed price. Interim payments are generally made based on the amount of work in place after each period. With lump-sum provisions, the contractor assumes the risk of cost overruns. Any change in the scope of the work results in a change order and must be negotiated between the owner and the contractor. This type of contract payment provision is best when the work is well defined (Hinze 2001, ACEC 2005).

Cost-plus-fee contract provisions allow contractors to be paid for their actual costs (labor, materials, etc.) plus a fee to cover overhead and profit. The fee can be stated as a fixed amount or as a percentage of the final costs. Payment is made based on documentation of the actual costs (typically through subcontractor costs and payments) that were incurred on the project during the payment period. This type of contract payment provision typically includes a GMP, which limits the owner's risk on excessive costs. Costs incurred above the GMP are not reimbursed by the owner. However, owners may agree to share any savings with the contractor when total costs come in below the GMP. Cost-plus-fee contracts have been employed in the industry when the scope of work is less well defined (Hinze 2001, ACEC 2005). GMP contract payment provisions are also applicable to alternative project delivery methods, such as design-build and construction manager-at-risk because the design-builder or construction manager at risk is hired in the earliest stages of design when the use of a lump sum would be unfeasible for the builder or imprudent for the owner.

While significant research exists regarding project delivery performance for buildings and transportation projects, little research has been conducted on water or wastewater project delivery performance. Likewise, little research exists regarding project performance under different contract payment provisions. Previous research has compared project delivery methods based on common performance metrics, including budget, time, cost, quality, satisfaction, expectation, functionality, schedule, and administration. Performance metrics can be broken down into three types: relative, static, and dynamic. Relative metrics include cost growth and schedule growth; static metrics contain items such as design unit cost, construction unit cost, and design-build unit cost; dynamic metrics comprise design placement, construction placement, and construction intensity. Many of the project delivery performance metrics for building projects are also appropriate for water and wastewater projects. The performance metrics addressed in this paper are schedule growth and cost growth, which measure the final project performance (schedule or cost) relative to the planned performance. Unfortunately, treatment technologies vary too greatly in water/wastewater projects to make a unit cost comparison feasible, so only cost growth is examined in this paper.

RESEARCH APPROACH

Data Collection and Analysis

A questionnaire was used to collect data for this research study. The questionnaire was distributed to owners who were identified as having completed a water or wastewater project between January 2003 and January 2008 with a minimum total project cost of $3 million. The minimum cost value was used to ensure that all data came from projects with a significant design and construction effort. The questionnaire was made available to the owners online and by mail. The questionnaire for data collection was first deployed in late June 2008.

The data analysis consisted of several steps, including cleaning the raw data, summarizing the descriptive statistics of the data, and presenting inferential statistics for the data. After data collection had been completed, the data set was first reviewed to remove incomplete responses or duplicate responses. Descriptive statistics were then used to describe the information provided in quantitative terms. Examples of descriptive statics that provide an overall sense of the data include measures of dispersion, such as averages and deviations.

Inferential statistics, which provide a means of drawing conclusions for the whole population based on a smaller sample, were also used. Three different statistical tests were performed in this study:

- t-test, to test for the difference between two population means;
- Pearson goodness-of-fit (chi-squared), to test for the difference between two population medians; and
- z-distribution, to test for the difference between two population proportions.

The t-test is a common analysis for comparing two population means. This analysis assumes that the population values are normally distributed around the population mean when the sample size is small. However, cost and schedule data have been shown to be skewed such that it is more likely to see large cost or schedule overruns than it is to see large underruns. In addition, cost and schedule data are limited on the low side, since there is some absolute minimum value below which a project cost ($3 million for this study) or schedule (zero months) cannot go. When the sample size is large, one does not need to assume normality, as a consequence of the Central Limit Theorem. Given the type of data collected for this study (especially the cost and schedule data) and the relatively small number of projects under consideration, the normality assumption may not hold in this situation. Furthermore, the data are not necessarily from randomly selected projects. Therefore, a randomization test instead of the standard t-test was conducted to test for the difference between two population means. In addition, the research team tested the difference between two population proportions and two different population medians. These comparisons were preferred given the type of data that were collected.

Performance Measures

Overall Schedule Growth

Overall schedule growth compares schedule certainty between project delivery methods or contract payment provisions. Overall schedule growth was calculated using the following four dates: as-planned request for proposal/invitation for bid (RFP/IFB) date, as-completed RFP/IFB date, as-planned end-of-construction date, and as-completed end-of-construction date (Equation 1). This set of dates was used to measure the change between the planned and actual project schedule from the RFP/IFB dates through the end of construction. The project was said to begin with the start of the procurement of the design consultant. The project is completed when construction was finished. To calculate schedule growth for each project, the total time between the RFP/IFB and the end of construction was calculated for both the "as-planned" dates (AP) and the "as-completed" dates (AC). The formula used to calculate schedule growth is as follows:

$$S = [(AC - AP)/AP] \times 100\%$$

Equation 1 Schedule Growth

where S represents schedule growth, AC represents the number of months between the date of the RFP/IFB and the date of the end of construction for the "as-completed" category, and AP represents the number of months between the date of the RFP/IFB and the date of the end of construction for the "as-planned" category.

Design and Construction Schedule Growth

Design and construction schedule growth provides a comparison of schedule growth, planned versus actual, from the beginning of design to the end of construction, without consideration of procurement time. This measure provides information about the total time that consultants and general contractors are involved with the project. To calculate the design and construction schedule growth, the following four dates were used: as-planned design start, as-completed design start, as-planned end of construction, and as-completed end of construction. For design-bid-build, design start was considered to occur at the notice to proceed (NTP) with design services. For design-build, design start was considered to occur at the NTP with project design and construction. To calculate the design and construction schedule growth, the total time between the start of design and the end of construction was calculated for both the "as-planned" category and the "as-completed" category. Then the design and construction schedule growth for each project was calculated according to Equation 1.

Construction Schedule Growth

Construction schedule growth provides a comparison of the time, planned versus actual, that the project is under physical construction. This is primarily the time when the general contractor is involved. To calculate construction schedule growth, the following four dates were used: as-planned construction start, as-completed construction start, as-planned end of construction, and as-completed end of construction. To calculate the construction schedule growth, the total time between the start of construction and the end of construction was calculated for both the "as-planned" category and the "as-completed" category. Then the schedule growth for each project was calculated according to Equation 1.

Design and Construction Cost Growth

Design and construction cost growth compares cost certainty between contract payment provisions. Four costs were needed to calculate design and construction cost growth for design-bid-build projects: design contract cost, design final cost, construction contract cost, and construction final cost. For each design-bid-build project, the sum of the design contract cost and the construction contract cost was referred to as the contract cost total and the sum of the design final cost and the construction final cost are referred to as the final cost total. For each design-build project, two costs were needed to calculate cost growth: total contract cost (excluding RFP development costs) and total final cost (excluding RFP development costs). The cost growth for all projects was calculated as follows:

$$C = [(FC - CC)/CC] \times 100\%$$

Equation 2 Cost Growth

where C represents cost growth, FC represents the final cost total, and CC represents the contract cost total.

Construction Cost Growth

Construction cost growth compares project delivery methods on the basis of cost certainty in the construction phase. Two costs were needed to calculate construction cost growth for design-bid-build projects: construction contract cost; and construction final cost. For design-build projects, the data collection method in this project did not allow for the separation of design and construction costs. However, separation of design and construction costs should not impact the analysis as design costs are a relatively small portion (< 7 percent) of the design-build contract cost and should follow the same relative direction of cost growth because the activities are closely correlated. The following two costs were needed to calculate cost growth for design-build projects: contract cost and final cost. The cost growth for all projects was calculated using Equation 2.

RESULTS

More than 500 owners of public water and wastewater facilities were contacted to gather project information. A total of 252 questionnaires were received, of which 100 respondents completed most of the questionnaire and had completed a water or wastewater infrastructure project that met the minimum criteria. A total of 31 of the surveyed projects were completed using design-build, and 69 were completed using design-bid-build. The projects analyzed in this study represent a wide variety of owners from around the United States. Responses were received from 33 of the 50 U.S. states.

Another important feature of this project was to study the contract payment provisions used. Nine of the 31 design-build projects used a cost-plus-fee structure with a GMP. Cost-plus-fee without a GMP was not used on any design-build projects. For design-bid-build projects, the majority of contractors were paid using a lump-sum contract payment provision, while engineers were paid using a more equal distribution of the three payment methods. For design-bid-build projects, lump sum and a variation of cost-plus-fee were used approximately equally in the project

engineer's payment provisions. However, a majority of the contractors in design-bid-build projects were paid using a lump-sum structure. It should be noted that not all of the survey respondents supplied information in all areas.

Comparison of Project Delivery Methods

This study objectively compared the performance of design-bid-build and design-build project delivery for public water and wastewater facilities. The research team chose a range of key performance indicators from the existing literature to allow for a comparison of the final results with the results of similar studies from other construction sectors. Table 1 presents the comparison results for the design and construction portion of the surveyed projects.

Table 1. Comparison by Delivery Method for Design and Construction (median values)

Performance Measure	Design-Build	Design-Bid-Build
Schedule Duration (months) *	23	40
Schedule Growth (months) *	1.0	2.0
Proportion of Projects with Schedule Growth ≤0	41%	36%
Cost ($millions)	12	8
Proportion of Projects with Cost Growth ≤0 *	38%	20%
Intensity ($millions/month)-mean value*	1.5	0.6
Overall Project Satisfaction (1 = Did not Meet Expectations 5 = Exceeded Expectations)	4.5	4.5

* statistically significant results

Schedule

The overall schedule compares the total design and construction time between design-bid-build and design-build projects. A statistical analysis of the delivery methods' design and construction durations indicates that there is a statistically significant difference between design-build and design-bid-build. The median duration of design and construction on design-build projects was 23 months, compared to 40 months for design-bid-build projects. This difference indicates that projects were delivered much faster using design-build.

In addition, schedule growth is a key project delivery performance indicator relating to schedule certainty. The results of this study indicate that design-build projects have less schedule growth than design-bid-build projects. In terms of design and

construction schedule growth, design-build projects had less overall schedule growth than design-bid-build projects (1.0 months vs. 2.0 months, respective median values). Schedule growth is a significant point for utility owners when committing to a project delivery date for their stakeholders. Another important point, though not statically significant, is that more design-build projects were completed on time or early (41 percent for design-build vs. 36 percent for design-bid-build) when the overall project delivery schedule was considered. Again, when the overall project schedule certainty was important, design-build performed better than design-bid-build.

Cost

The data from this study indicate that the median cost of design-build projects was $12 million, while the median cost of design-bid-build projects was $8 million. This difference, however, was not statistically significant.

Similarly to schedule, cost certainty is important to utility owners. The differences in cost growth between the delivery methods were not found to be statistically significant. The cost growth metric that was found to be statistically significant at the 90 percent level was the proportion of projects that finished at or under budget. Design-build projects finished on or below budget 38 percent of the time, while design-bid-build projects finished on or below budget only 20 percent of the time.

Intensity

A unique measure that can be useful when examining project delivery methods is intensity. Intensity is a measure of cost delivered per unit of time ($/month). This study found that there is a statistically significant difference in intensity between design-build and design-bid-build. Design-build projects have a mean intensity factor of $1.5 million/month, whereas design-bid-build projects have a mean intensity of $0.6 million/month.

Quality

Quality is the key project delivery performance indicator, and the most difficult to measure. In this study, respondents were asked to rate a number of quality items, including overall project satisfaction. An analysis of the quality questions in relation to the project delivery method indicates that there is no difference in quality between design-build and design-bid-build projects.

Comparison of Contract Payment Provisions

Selecting a of contract payment type is also a critical decision for an owner to make. For this study, the analysis was limited to a comparison only of contract payment terms because there were not enough responses to analyze each project delivery method by each type of contract payment term. The payment terms analyzed are lump sum and GMP as shown in Table 2 using the previously identified statistical tests.

Schedule

The negotiated GMP pricing structure showed less schedule growth than the lump-sum method. However, these results are not statistically significant. The statistically

significant difference between payment structures is the proportion of projects that finish on time or early. For the design and construction portion of the projects, 52 percent of the projects using a GMP contract were completed on time or early, compared to only 28 percent of lump-sum projects. This difference indicates that the GMP structure offers greater schedule certainty.

Table 2. Comparison by Contract Type for Design and Construction (median values)

Performance Measure	Lump Sum	GMP
Schedule Growth	8%	0%
Proportion of Projects with Schedule Growth ≤ 0 *	28%	52%
Cost Growth *	4%	1%
Proportion of Projects with Cost Growth ≤ 0 *	19%	42%

* statistically significant difference

Cost

The projects in this study displayed a statistically significant difference in cost growth between lump-sum and negotiated GMP projects. For design and construction, the median GMP project experienced 1 percent cost growth, compared to 4 percent for lump-sum projects. Projects completed using a GMP were also more likely to complete both design and construction at or below cost. Forty-two percent of projects were completed at or below expected construction costs using a GMP contract, compared to only 19 percent of projects completed using a lump-sum contract. This finding was statistically significant.

CONCLUSION

Utility owners have a range of project delivery methods that can be used for infrastructure projects, including traditional design-bid-build methods and alternative methods such as design-build. To help owners evaluate project delivery methods, a survey was conducted to collect data on project performance for design-bid-build projects and design-build projects in the water and wastewater industry. The results indicate that some performance measures show a statistically significant difference between the two delivery methods, while other performance measures show no statistically significant difference.

In terms of schedule, design-build projects had a shorter design and construction duration than design-bid-build projects, as well as smaller schedule growth. The design-build projects were also larger than the design-bid-build projects in terms of total cost, which means that design-build projects had a much higher intensity (value of work performed per month) than design-bid-build projects. Design-build projects also delivered on or below, the owner's budget almost twice as often as design-bid-

build projects. At the same time, there was no statistically significant difference in quality between design-build and design-bid-build projects.

When projects are compared by contract payment type (lump sum versus GMP), projects with negotiated GMP contracts perform better with respect to cost and schedule than projects with lump-sum contracts. Both schedule and cost growth were lower under GMP contracts and the proportion of projects with schedule or cost growth less than or equal to zero was higher for GMP contracts.

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CONFIGURATIONAL COMPARATIVE METHODS FOR ALIGNING PPP STRATEGIES WITH PUBLIC-POLICY OBJECTIVES

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Abstract

Although public-interest ideals, such as transparency and efficient risk allocation, are widely recognized as crucial to well-structured public-private partnership (PPP) contracts, successful PPPs must also satisfy the public-policy objectives intended by the owner. Despite the pivotal role of toll-rate and concession-length options in shaping PPP agreements, relatively little research has addressed which of these contract strategies contribute most effectively toward achieving specific public-policy outcomes, such as managing congestion or limiting private-sector "super-profits."

Various research methods are considered for investigating this topic. Acknowledging the limitations of traditional quantitative and qualitative approaches, this study proposes the use of configurational comparative methods (CCM). This family of recently-developed approaches is classified partway between quantitative and qualitative methods, enabling smaller sample sizes but retaining rigor and replicability. An example of CCM's application is presented, illustrating how this method can assist public-sector decision-makers in identifying PPP toll-rate and concession-length strategies which contribute toward achieving specific public-policy objectives.

Introduction

"Balancing public and private interests" is a frequently-emphasized principle in the development of public-private partnership (PPP) contracts. While the adherence to sound procurement practices is indeed vital to successful infrastructure delivery, this pursuit must also be accompanied by consideration of the public-policy objectives that a project is to achieve. Unlike public and private interests, these policy goals can vary from procurement to procurement, requiring public owners to recognize and prioritize the desired project outcomes.

The significant role of PPP contract variables in achieving these objectives is not always understood. Over half the state agencies surveyed in McGraw-Hill's market report (2009) considered "unacceptable profits by private entities at expense of users" as the largest single factor negatively impacting the use of PPPs. Yet this possibility of excessive private-sector returns can be effectively contained through appropriate contract structuring, if this objective is prioritized during procurement.

To develop a decision-support tool identifying which PPP toll-rate and concession-length strategies support specific public-policy objectives, configurational comparative methods are presented and explained. A brief example illustrates the application and validation of this approach.

Use of this tool presumes the PPP delivery method has already been determined as the most appropriate contracting form for a given infrastructure project. As cautioned by Miller (2000), owners must consider the full range of project-delivery options, avoiding the temptation to pre-select a specific procurement strategy independent of a facility's characteristics and then forcing the project to fit that method.

Public/Private Interests and Objectives

Public Sector

What differentiates public interests from public-policy objectives? Much literature (as summarized in Buxbaum and Ortiz 2009) considers the former to be synonymous with the accepted best practices for procurement and capital programming: proper value, transparency, competition and selection criteria, risk allocation, use of proceeds, and so on (Miller et al. 2000). These elements are indeed crucial to a successful PPP, and some procurements have failed (either financially or from a public-perception standpoint) because they did not comply with these basic principles.

Yet the satisfaction of public-policy objectives is an equally vital requirement for successful PPPs. These objectives are the concrete aims that an owner intends to achieve through a procurement; as such, they do not represent a static goal or single ideal which one optimal contract structure can satisfy. Rather, the public-policy objectives which may be addressed by an infrastructure project are numerous and often contradictory. For instance, the public sector may have a genuine interest in both maximum revenue and maximum vehicular throughput on a new tolled roadway, yet for practical purposes these goals are inherently in conflict and are difficult to satisfy simultaneously. Other public-sector objectives might include minimizing exposure to traffic risk, limiting the prospect of private-sector "super-profits," and so on. An owner may target one or more of these objectives in a specific procurement.

According to Benouaich (2007), the necessary arbitration among these conflicting objectives must be government decisions. Although one could profitably study which public-policy outcomes the state *should* favor under various conditions, such a focus is not the intent of this research. What this investigation seeks to offer is some clarity as to which PPP contract strategies support specific objectives, providing public-sector decision-makers a tool to identify those means which most efficiently accomplish the desired ends.

Private Sector

How should private-sector interests be accommodated? In contrast to the public sector's multiple interests and diverse objectives, the private sector can be considered to have a single primary goal, as noted by Mayer (2007) and Vining and Boardman

(2008): to earn profits. This profit motive is not improper, but rather it is a necessary incentive for promoting business and innovation. Without an opportunity to achieve returns greater than costs, the private sector will not continue to participate in contracts, whether PPPs or otherwise.

Given this relative homogeneity in private industry, the following investigation focuses instead on the more complex decisions necessary in the public sector. This emphasis is further supported by the owners' dominant role in contract formation and their responsibility to structure the content of procurement documents to accomplish their specific aims. Among the most effective means for shaping PPPs to achieve such outcomes are these contracts' toll-rate and concession-length strategies.

Contract Strategies

The toolbox of available contract-strategy options for PPPs is immense, but its primary variables fall into the broad categories of cost and time. For the former, user-fee structures for direct-tolled projects can be categorized as supply-based (linked to the cost of constructing, maintaining, and/or operating a facility) or demand-based (adjusted to influence driver behavior in certain ways, such as through variable time-of-day congestion charges). Supply-based tolls involve average-cost pricing (ACP) models, which set user fees at a level just adequate to cover a facility's ongoing operations and maintenance costs (as well as capital expenditures, if not already recovered) and a nominal profit for the operator. Demand-based toll structures include marginal social cost (MSC) pricing, which recognizes tolls' ability to manage traffic congestion, and revenue-maximizing pricing (RMP), which estimates traffic demand for a specific facility under various toll rates, then sets user fees for that roadway at a level resulting in the highest overall toll revenue for the operator (Gross and Garvin 2009). Further variations on these basic pricing themes, such as different revenue-transfer and risk-sharing mechanisms, provide additional diversity in the range of possible cost strategies for a PPP agreement.

The time element of PPP contract options addresses concession lengths, which in the US can be classified as short (less than 50 years), long (50 years or more), and variable. Although 30-40 year concessions are common elsewhere, US PPPs often incorporate longer terms of 50 years or greater due to favorable tax treatment for depreciation of infrastructure assets, as well as to help mitigate traffic-demand risk for unproven facilities. Variable-length concessions are typically structured to continue until a certain rate of return or present value of toll revenues is attained.

Even within this brief summary of cost and time approaches, a myriad of options for combining these variables to form a PPP agreement exist. Not surprisingly, some of these alternatives tend to be more effective than others in achieving certain outcomes. The question then arises: how can combinations of PPP contract strategies be identified which most effectively support the attainment of specific public-policy objectives? Following a brief discussion of potential approaches for addressing this question, an answer is proposed using an application of configurational comparative methods.

Comparison of Research Methods

Taylor et al. (2009) noted research in the construction industry poses particular challenges not encountered in many other fields. The considerable magnitude and expense of construction pursuits often makes it prohibitive to investigate them using more traditional experimental methods; further, the variables involved can be too numerous to analyze quantitatively. Although case-study research can accommodate these issues by enabling analysis of small sample sizes, such qualitative methods can encounter challenges with rigor and replication, if not carefully applied.

A further option for construction investigations is the middle ground provided by configurational comparative methods (CCM), a family of research approaches which is often designated by its best-known representative, qualitative comparative analysis (QCA). QCA shares aspects of both quantitative and qualitative methods, as reflected by the method's French name, *Analyse Quali-Quantitative Comparée.* As with the case-study approach, QCA retains a contextual sensitivity to interactions among variables, unlike statistical methods which analyze variables in isolation. Yet QCA also incorporates the systematic analysis and fixed rules characteristic of quantitative methods, thus adding rigor and strengthening its replicability and transparency. Due to its emphasis on case histories and the researcher's judgment at decision points throughout the process, QCA is considered closer to the qualitative end of the research-methods spectrum (Figure **1**). It is capable of analyzing both small and large populations.

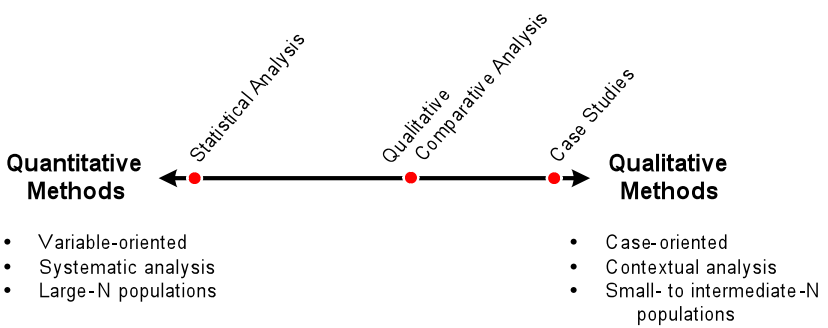


Figure 1: Spectrum of Research Methods

QCA is a relatively new approach, first propounded by the sociologist Charles Ragin in 1987, but its principles have since been applied extensively, primarily in the fields of sociology and political science, but also in management and economics. To date, construction research has used this method sparingly.

Under QCA, the investigator first identifies a specific outcome of interest, along with conditions which are posited to affect that outcome. Individual cases such as PPP procurements are then evaluated to determine, for each case, whether these conditions were present and whether the outcome was achieved. These characteris-

tics are converted into numerical data which can be condensed logically to identify patterns of conditions which support, or do not support, the outcome of interest.

Although Ragin's initial formulation of QCA (now also termed *crisp set QCA*, or csQCA) required the strict dichotomization of condition data into binary "present" or "absent" categories (notated as 1 and 0, respectively), concerns about the resulting loss of information led to the development of *multi-value QCA* (mvQCA) and *fuzzy-set QCA* (fsQCA) variants, which accommodate stepped and continuous gradations of non-binary variables, such as cost and time. Each of these members of the CCM family has domains for which it is methodologically best suited.

A basic example illustrating the application of multi-value QCA to the evaluation of PPP contract strategies and public-policy objectives follows.

Application of Configurational Comparative Methods

The following example outlines the CCM process for identifying patterns of contract strategies which support a single outcome, or public-policy objective. Further development of this research, not presented here, will repeat the analysis for other objectives to provide a full toolbox of options for public-sector decision-makers.

Identifying Outcomes of Interest

Even prior to case selection, the outcomes under investigation must first be defined. This step facilitates subsequent deliberate selection of cases with sufficient representation of each outcome, since the analysis will be less robust if the conditions and outcomes under study exhibit little variation. For this example, the objective of minimizing public-sector exposure to traffic risk was selected.

Selecting Conditions and Assigning Values

Conditions are the variables which differentiate one case from another—in this study, the PPP contract strategies. Careful consideration is necessary for establishing both the number and identity of conditions in a CCM investigation. Although no quantity is ideal, more conditions add complexity to the logic model and can obscure the identification and interpretation of the resulting patterns. Berg-Schlosser and De Meur (2009) offer the following guidance:

> A good balance must be reached between the number of cases and the number of conditions. The ideal balance is not a purely numerical one and will most of the time be found by trial and error. A common practice in an intermediate-N analysis (say, 10 to 40 cases) would be to select from 4 to 6-7 conditions.

Table 1 represents selected variables for this study, along with the assignment of values for each condition and outcome. Among the reasons the CCM approach is well suited for this investigation is that most of the condition values are unambiguous: revenue sharing, for instance, is clearly either present or absent. Little information is lost in converting these PPP contract characteristics to numeric values.

For conditions involving continuous variables, such as cost or time, careful attention (and potentially sensitivity analysis) is necessary in specifying cutoff values to convert continuous data sets to discrete values, since the choice of these thresholds can materially affect QCA results. The 50-year threshold for dividing short and long concession lengths represents one such cutoff value.

The mvQCA alternative was chosen for this study instead of csQCA because several of the conditions, by their nature, required more than a binary partition of the contract-strategy options. As shown here, mvQCA can accommodate both binary and multi-valued variables simultaneously.

Table 1: mvQCA Variables (Conditions and Outcome) and Values

CONDITION (PPP Contract Strategy)	**Value**	**Definition**
Pricing Approach	0	Average cost pricing (ACP)
(variable name: "PRICING")	1	Marginal social-cost pricing (MSC)
	2	Revenue-maximizing pricing (RMP)
Concession Length	0	Variable length
("LENGTH")	1	Short concession (< 50 years)
	2	Long concession (≥ 50 years)
Upside Revenue Sharing	0	Absent
("UPSIDE")	1	Present
Downside Risk Sharing	0	Absent
("DOWNSIDE")	1	Present
Renegotiation of Contract	0	Absent
("REVISION")	1	Present

OUTCOME (Public-Policy Objective)	**Value**	**Definition**
Minimize Public-Sector	0	No
Exposure to Traffic Risk?	1	Yes
("TRAFRISK")		

Selecting Cases

In applying CCM, identification of cases exhibiting the greatest possible variety of configurations is desirable. Although the conscious selection of cases with certain conditions and outcomes might appear to be an inappropriate manipulation of the data set, this practice is not improper under CCM. The method's logic is not probabilistic: that is, it does not consider whether few or many cases exhibit certain characteristics. Of interest is rather the existence at all of specific combinations of contract strategies and objectives. Hence the identification of cases exhibiting maximum heterogeneity

of condition and outcome values contributes to the richest possible explanations of relationships among the widest array of data.

The number of cases is significant also from a procedural standpoint. Due to the algorithms involved, the different QCA variants produce more robust results with certain data-set sizes: csQCA is well suited for the smallest data sets, mvQCA for intermediate, and fsQCA for the largest. For the current mvQCA example, a total of 16 PPP cases were evaluated, a subset of which are shown in Figure 2 below.

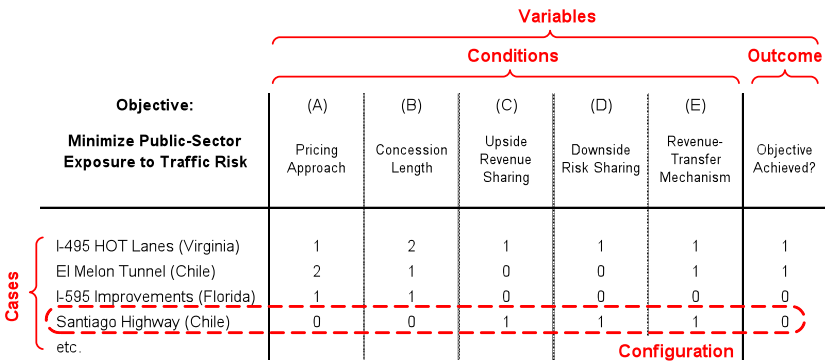


Figure 2: Sample Configuration Table with Nomenclature

Constructing and Reviewing the Data Table

Once the CCM outcomes, conditions, values, and cases are established, case data are tabulated for the objective under study, which in this example is to minimize public-sector exposure to PPP traffic risk. Numerical values, as indicated in Table 1, are assigned to the conditions and outcome for each case, resulting in a table as shown in Figure 2. The zero outcome, "objective not achieved," does not indicate a failure of the PPP procurement represented or of its component contract strategies, but rather serves as a neutral statement of fact that a certain outcome did not occur with the strategies under consideration.

One issue which may arise at this point is that of contradictory configurations—cases for which all condition values are identical, but whose outcomes are different. Such cases must be resolved before proceeding with the analysis, for instance by adding or replacing conditions, reconsidering the scope of the outcome variable, or examining whether the conflicting cases should indeed be classed within the same population (Rihoux and De Meur 2009).

Analysis, Interpretation, and Refinement

Once a contradiction-free data table is constructed, the next step is to condense or minimize the table to identify patterns of conditions which correspond to the 0 and 1 outcomes. For the example presented above, TOSMANA software (Tool for Small-N Analysis) was used for this data-reduction process; the algorithm, which first isolates configurations with the desired outcome and then seeks the most logically succinct combinations of conditions necessary and sufficient to produce this outcome, is explained in detail by its developer Cronqvist (2007).

The result is a set of expressions, or minimal formulae, which summarize patterns in the data leading to the presence or absence of the outcome under study. From the example above, one such minimal formula (expressed in Boolean notation) is as follows:

PRICING[2] + LENGTH[2] + PRICING[0] DOWNSIDE[0] REVISION[0] → TRAFRISK[1]

Comparing these variables and values with **Table 1** yields the following interpretation: "Public-sector exposure to traffic risk is minimized (TRAFRISK = 1) when

a. Revenue-maximizing pricing is used (PRICING = 2), or
b. Concessions are 50 years or longer (LENGTH = 2), or
c. Average-cost pricing (PRICING = 0) is combined with agreements which have no downside risk protection (DOWNSIDE = 0), and contracts are not renegotiated (REVISION = 0)."

According to this interpretation, each of these three options represents necessary and sufficient conditions to accomplish the objective of minimizing traffic risk, based on the PPP cases considered. But as indicated in the research-methods spectrum above, QCA's qualitative characteristics require judgment on the researcher's part to evaluate initial findings and potentially refine the analysis if inconsistencies are found. In this example, a common-sense check is applied to each of the three options above:

a. Yes, this finding is plausible: RMP increases a concessionaire's income, making the concessionaire more willing to assume traffic risk.
b. Plausible. Similarly, long concessions make the private sector more willing to assume traffic risk.
c. This combination is dubious. These three elements have little logical connection, and further consideration suggests the final element (contract renegotiation) may in fact be out of place as a contributing factor to public-sector traffic-risk exposure.

This review indicates the analysis can be strengthened by repeating it with a stronger, more descriptive condition in place of contract renegotiation; another possibility is to treat the REVISION variable as an outcome instead to evaluate whether certain combinations of conditions tend to foster or avoid renegotiation of PPP contracts. This process illustrates how initial CCM findings can be made more robust through iterative refinement, identifying shortcomings through an initial trial analysis.

The above procedure of analysis, interpretation, and refinement may be repeated for the zero outcome, if explicit identification of strategy patterns tending not to support each public-policy objective is desired. The entire analysis is then performed again for other objectives, such as congestion management or revenue maximization, and the findings are validated through comparison with a small number of additional case studies. The resulting collection of strategies provides a decision-making toolkit for public-sector owners, who can thus determine which contract strategies support their desired objectives, based on patterns from past PPPs.

Summary

Through this simplified example, the selection of CCM outcomes, conditions, and cases is illustrated, along with the iterative process of analysis, interpretation, and refinement. In addition to applying the plausibility review shown, the robustness of CCM outcomes may also be probed by verifying interpretations with additional cases and/or triangulating with the findings of other quantitative or qualitative methods.

To expand this investigation of PPP contract strategies, the impact of varying external influences can also be considered: presence of congestion, untolled parallel facilities, and user tolerance for tolls, for instance. Refining the outcomes to incorporate these project settings will enable tailoring more precise recommendations for the PPP contracting choices which public decision-makers face.

Conclusion

Despite the key role of PPP contract strategies in shaping infrastructure procurements to achieve specific public-policy objectives, the nature of this relationship is not broadly understood. The recently-developed option of configurational comparative methods, which draws on the strengths of both quantitative and qualitative research approaches, offers a promising methodology for investigating which toll-rate and concession-length strategies are best aligned with various public procurement aims.

Through a brief example, the CCM procedure and its application to this question are illustrated. The toolkit resulting from this research will offer multiple benefits to public-sector decision-makers such as: (a) considering explicitly which goals they hope to achieve through a given procurement, (b) recognizing potential conflicts among these objectives during the planning stage, and (c) prioritizing these objectives and selecting contract strategies accordingly. It is hoped that this study will also encourage increased consideration of the CCM approach for future application to other construction research topics.

Acknowledgements

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Construction Legal Decision Support Using Support Vector Machine (SVM)

By
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ABSTRACT

This paper represents a step in a line of research aiming at mitigating the negative effects of conflicts on the construction industry through developing a construction legal decision support methodology. This step developed Support Vector Machine (SVM) models to automatically extract latent legal factors, upon which judges base their verdicts, from precedent cases. The adopted research methodology developed and compared the output of first, second, and third degree polynomial kernel SVM models while implementing 4 weighing mechanisms namely term frequency (tf), logarithmic term frequency (ltf), augmented term frequency (atf), and term frequency inverse document frequency (tf.idf). The models were trained and tested over two sets of Differing Site Condition (DSC) cases compiled from the Federal Court of New York. The two sets were composed of 120 and 450 cases respectively. The highest accuracy of extraction of 76% was attained using first degree polynomial kernel SVM while implementing tf.idf weighing with the first set. With the second set, a higher accuracy of 85% was achieved using third degree polynomial kernel SVM while implementing tf.idf weighing.

INTRODUCTION

The construction industry is considered to be one of the corner-stones of the nations' economies. It is estimated that the world construction market has reached US $5.5 trillion at the end of 2007 (Harmon 2003). In the U.S., the construction industry employs 7.5 million employees and contributes to nearly US $1.2 trillion to its economy (El-adaway 2008). The dynamic nature of this industry demands extensive interaction of diversified parties, thus enhancing the likelihood of conflicts and disputes (Caldas et al. 2002). Consequently, the advancement and contribution of the construction industry to the nations' economies has always been threatened by the increasing number of conflicts in construction projects. In a study performed by Ren et al. (2001) it was found that 52% of all construction projects in UK ends up with a

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claim; while in Canada, 50% of the construction projects faced an extra value of 30% of the original contract price, 33% reached up to 60%, and 17% exceeded the original contract price due to construction claims. As stated by Jervis and Levin (1988), in large, complex projects, disputes are resolved in courts unless a private construction contract demands a different resolution method. Despite the numerous pros of litigation it has two major limitations that make it unfavorable dispute resolution mechanism for the construction industry. First, a complex construction dispute may take anywhere from two to six years before it reaches trial. Treacy (1995) demonstrated that within a period of 8 years from 1984 to 1992, the number of construction litigation cases that have been in courts with no final decision for three or more years have doubled. In addition, court decisions may be appealed if any of the involved parties wish to contest the first judgment. Escalation mechanisms of litigation cases for appeals differ from one jurisdiction to the other; however, they cause an extended period of resolution. Second, the prolonged, detailed, factual discovery process makes litigation very expensive (Jervis and Levin 1988). A previous study indicated that fees paid to lawyers and experts in litigation had increased by 425% within the period of 1979–1990 while verdicts had increased only by 309% (Marcotte 1990). Furthermore, Peña-Mora et al (2003) estimated the total annual cost of construction conflicts and disputes in the U.S. to be $5 billion.

The aforementioned drawbacks motivated research efforts in the Artificial Intelligence (AI) field to developed tools and methodologies for modeling judicial reasoning to resolve them. Attempts ranged from initial Rule Based Reasoning systems (RBR) (Diekmann and Kruppenbacher 1984, Cobb and Diekmann 1986, and Kim 1989), to Artificial Neural Networks (ANN) systems (Arditi et al. 1998, Chau 2005, and Chau 2006a), Case Based Reasoning systems (CBR) (Arditi and Tokdemir 1999, and Chau 2006b), and Hybrid Systems (HS) (Arditi and Pulket 2005, and Chen and Hsu 2007). Despite the success of some of these systems, they were not based on detailed analysis of legal factors that govern litigation outcomes. The success of any prediction system is always limited by its input parameters. To fill this research gap, this paper represents a step in a line of research aiming at mitigating the negative effects of conflicts on the construction industry through developing a legal decision support methodology for the construction industry. To test and validate the proposed research methodology, the focus of the analysis is targeted towards Differing Site Condition (DSC) claims. The papers utilized a set of cases from the Federal Court of New York to develop Support Vector Machine (SVM) models to automatically extract latent legal factors, upon which judges base their verdicts.

BACKGROUND

The first application of a DSC clause is dated November 22nd, 1921. It was first applied under the title of "Change Conditions" by the Federal Government (Tarkoy, unpublished book, 2008). On August 20th, 1926 the first standard general conditions form for construction including "changed conditions" clause was formulated and approved by the president of the United States for use in the federal government contracts (Tarkoy, unpublished book, 2008). From that date on, Federal Regulations made the use of DSC clause compulsory in all U.S. Government Contracts. It was incorporated as part of the Federal Acquisition Regulations (FAR) to prevent contractors from bidding on a worst-case-scenario basis (North Slope 1988). This

clause imposes upon the government the risks for conditions that the contract documents fail to disclose, but leaves upon the contractor the costs of encountering those conditions described in the contract (Erickson-Shaver 1985). Subsequently, other standard contract forms like AIA, FIDIC, and the Engineers Joint Contract Committee incorporated similar clauses. Analysis of the language of the DSC clause of the federal government contracts addresses two types of DSCs (Type 1 and Type 2). The former relates to physical conditions which differ materially from those indicated in the contract documents. The latter authorizes compensation "equitable adjustment" for unknown conditions which differ materially from those that would normally be encountered in projects of similar nature. From the literature in the construction legal domain, to prevail on a Type 1 DSC claim, a plaintiff must show: (1) the contract documents affirmatively indicate subsurface conditions; (2) she acted as a reasonably prudent contractor in interpreting the contract documents; (3) she reasonably relied on the indications of subsurface conditions in the contract; (4) the subsurface conditions actually encountered differed materially from those indicated in the contract; (5) the actual subsurface conditions were not reasonably foreseeable; and (6) her damage was attributable to the materially different subsurface conditions (Weeks 1987). Whereas, to prevail on a Type 2 DSC claims, a plaintiff must show that: (1) the encountered subsurface conditions were not reasonably foreseeable; (2) she did not have prior knowledge of the existence of the subsurface conditions; (3) the encountered conditions vary from the norms in similar construction projects.

The high frequency of occurrence and complicated nature of DSC claims in the construction industry have prompted researchers in the AI field to devise cost and time saving tools to proficiently resolve them. Diversified in nature, these tools include RBR models, ANN systems, CBR models, and Hybrid Systems. The success of RBR models or expert systems was very limited due to (1) the failure of the developer in deducing all the necessary rules upon which the system operates; (2) the assumption of the existence of a full domain model that captures all required rules about a specific claim type. As a result, they are much localized to a specific aspect of a certain domain; (3) their accuracy and performance are crucially affected by the computational limitations. In addition, although ANN had achieved improvements over RBR in this domain (Arditi et al. 1998), their excessive training stage and their ability to deal only with numeric data opened the horizon for the use of other AI techniques like CBR. Despite the success of some of these systems in litigation outcomes prediction, they were not based on detailed analysis of legal concepts that govern such outcomes. Consequently, this paper attempts to fill this gap by implementing SVM analysis.

METHODOLOGY

The objectives of this paper are (1) to develop SVM model to automatically extract significant latent legal factors upon which judges base their verdicts from textual documents; and (2) to study the effect of training corpus size on the performance of the developed model. In order to achieve these objectives, this research, (1) developed and compared the output of 3 SVM models namely first, second, and third degree polynomial kernel SVM while implementing 4 weighing mechanisms namely term frequency (tf), logarithmic term frequency (ltf), augmented term frequency (atf), and term frequency inverse document frequency (tf.idf); and (2) utilized two sets of

construction DSC cases for the model development and validation. The adopted methodology under this paper is illustrated in figure 1. The rest of the methodology section is organized as follows: (1) Data processing; (2) Preparation of the processed data for model development (weighting scheme); and (3) SVM models specification and development.

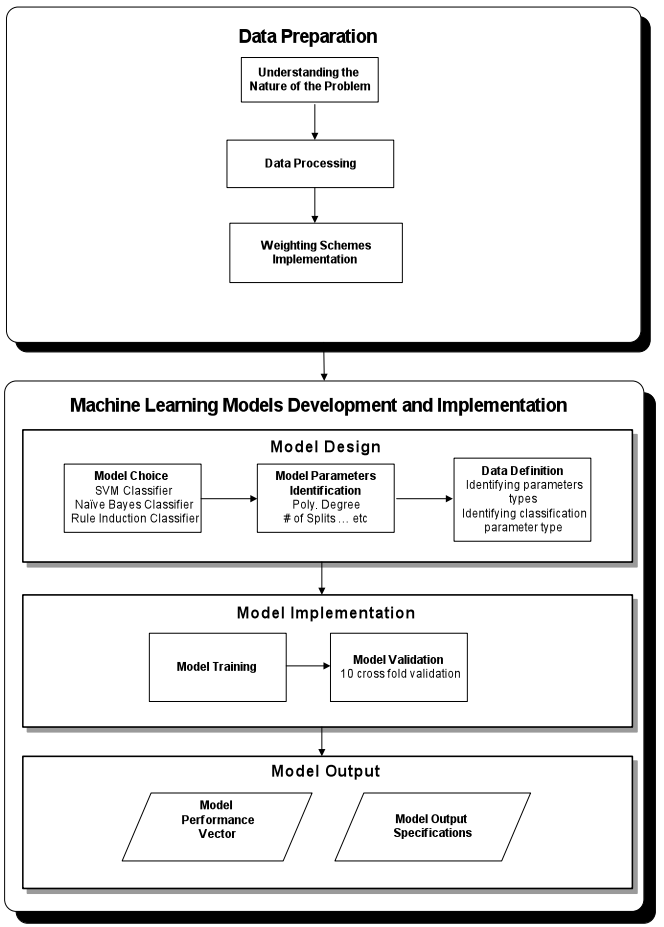


Figure 1 Methodology implementation for legal factor extraction

Data processing

The corpus utilized for this research is gathered from LexixNexis a web legal case retrieval engine. Two sets of cases, including 120 and 450 cases respectively, filed between 1912 and 2007 were compiled from the Federal Court of New York due to the large number of construction precedent cases in this jurisdiction. The cases were gathered based on the following factors: jurisdiction, winning side, level of court,

presence of appeals and overturning rulings, and utilization of landmarking precedent cases. Characteristics of gathered corpus are illustrated in Table 1.

Although each case implicitly includes the required knowledge for such analysis, it also includes textual representations that are not related to this sub-task. This step involves preparing the collected dataset in an appropriate manner to enhance the analysis. Consequently, the processing step will include data cleaning, data integration, and data reduction (Ng. et al. 2006).

Table 1 Descriptive data of cases

	Owner (%)	Contractor (%)
Judged for	53%	47%
Appeals won	50%	50%
Appeals affirmed	32%	14%
Appeals reversed	36%	18%

For more illustrations, textual representation of cases might include frequent words that carry no meaning, misspelled words, outliers, noise, and inconsistent data. While data processing is performed on each textual case representation separately, data integration is performed over the entire dataset. In this step, the entire processed dataset is stored in a coherent manner that facilitates their use for further analysis. While the integrated data might be very large, data reduction can decrease the data size by aggregating and eliminating redundant features. To perform the aforementioned sub-steps, an algorithm was developed and implemented in C++. The basic principle of the developed program is to represent each document as a vector of certain weighted word frequencies. The parsing and extraction steps implemented by the algorithm are as follows (refer to Figure 2): (1) Extract all words in a document; (2) Eliminate non-content-bearing words, also known as stopwords (Rijsbergen 1979); (3) Reduce each word to its "root" or "stem" eliminating plurals, tenses, prefixes, and suffixes; (4) For each document, count the number of occurrences of each word; and (5) Eliminate low frequency words (Salton 1989, Ng et al. 2006). Low frequency words are those that were repeated less than three times in a document. The output of the implementation of this algorithm is w unique words remain in d unique documents; a unique identifier is assigned between 1 and w to each remaining word, and a unique identifier between 1 and d to each document resulting in a term-frequency (tf) matrix.

Preparation of the processed data

A mere representation of significant words in the form of (tf) is not sufficient to accurately extract the required knowledge from the case corpus. For example, a word like contract might exist in all processed documents in high (tf). However, a decision must be made about whether this word would help define a latent legal concept or not. Consequently, an appropriate weighting mechanism must be implemented to create a representative matrix of these documents within the entire dataset. Literature in the field of ML and text mining illustrated the effectiveness of alternate term weighting schemes like logarithmic term frequency (ltf) (equation 1), augmented weighted term frequency (atf) (equation 2), and term frequency inverse document frequency (tf.idf) (equation 3) (Manning and Scheutze 1999).

$$ltf_{i,d}=1+\log\left(tf_{i,d}\right);\ tf_{i,d}>0 \qquad 1$$

$$atf_{i,d}=0.5+\frac{0.5\times tf_{i,d}}{max_t(tf_{i,d})} \quad 2$$

$$tf.idf_{i,d}=(1+\log(tf_{i,d}))\times\log\left(\frac{N}{df_i}\right) \text{ if } tf_{i,d}>0 \quad 3$$

The four above mentioned weighting schemes were utilized for the analysis under this research. The developed C++ program implements the required calculations to develop 4 matrixes (refer to Figure 2).

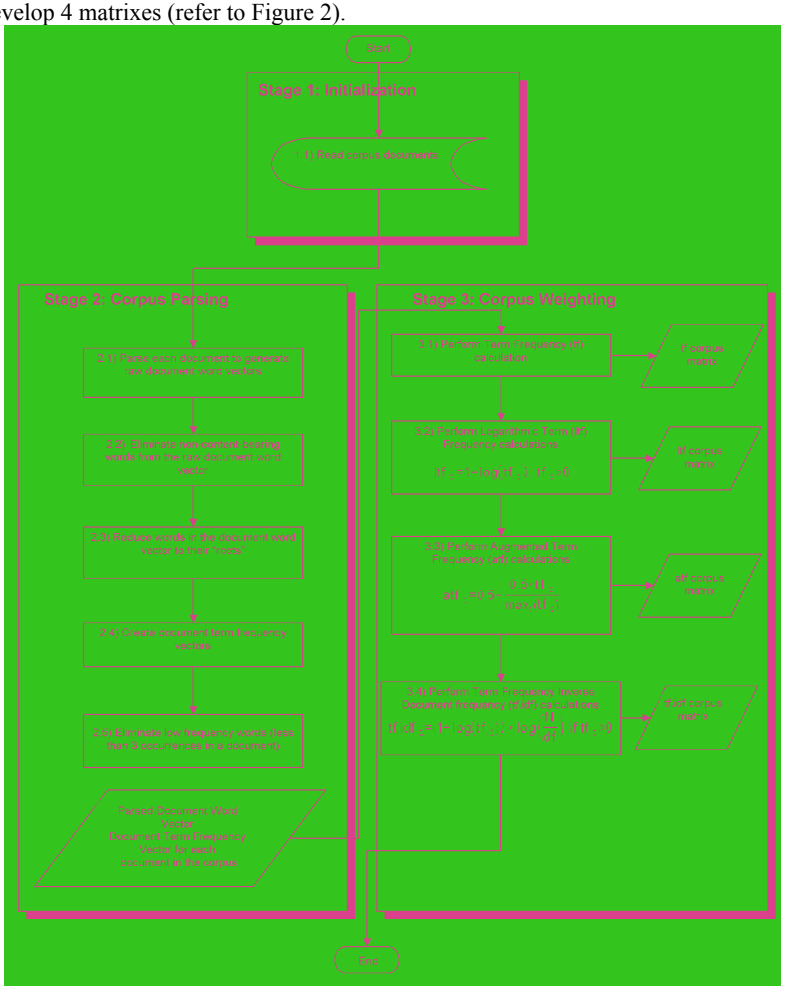


Figure 2 Weighing scheme implementation

SVM model specification and development

The proposed research methodology developed and compared the outputs of 12 SVM models as follows (1) four 1st degree polynomial kernel SVM models each utilizing one of the four weighing mechanisms tf, ltf, atf, and tf.idf; (2) four 2nd degree

polynomial kernel SVM models each utilizing one of the four weighing mechanisms; and (3) four 3rd degree polynomial kernel SVM models each utilizing one of the four weighing mechanisms. Validation of the best developed model was based on prediction accuracy and Kappa measures. Since the analysis is pertinent to automating the extraction of significant legal factors related to each case, each model is developed as a multiple classifier. "SVMs are learning systems that use hypothesis space of linear functions in high dimensional space, trained with a learning algorithm from optimization theory that implements a learning biased derived from statistical learning theory" (Shawe-Taylor and Cristianini 2000). In the current research, SVM Classification aims at separating the training 120 cases into multiple classes (each class defines a set of significant legal factors assigned to each case based on the reduced weighted word matrix for the data set developed by the C++ algorithm implementation. In other words, each case is tagged with the set of existing significant legal factors defined statistically in an earlier research. For the details of the statistical analysis refer to Mahfouz and Kandil (2009). In the training stage, the SVM classifier learns the latent relation between the existing word matrix and the tagged legal factors. The learning process is performed on a 10 fold cross validation mechanism. For more elaboration, the set of training data is divided into 10% and 90% portions in each fold. The model is trained on the 90% and tested on the other 10% cases. The process is done in an iterative manner until the model is trained and tested over the whole set of cases. The prediction accuracy of the model is developed as the average accuracy attained among all folds and the Kappa as the measure of agreement between all folds.

RESULTS AND DISCUSSION

The results of the application of the aforementioned research methodology are presented in Table 2 and Figure 3. The following is closer examination of these results. Comparing all developed models yields the followings:

- Among the developed 1st degree polynomial SVM models, the highest prediction accuracy of 76% was achieved by using atf and tf.idf weighting schemes. An increase of 12% and 5% over tf and ltf schemes was attained, respectively.
- Among the developed 2nd degree polynomial SVM models, the highest prediction accuracy of 72% was achieved by using atf and tf.idf weighting schemes. An increase of 8% and 3% over tf and ltf schemes was obtained, respectively.
- Among the developed 3rd degree polynomial SVM models, the highest prediction accuracy of 74% was achieved by using tf.idf weighting schemes. An increase of 14%, 3%, and 2% over tf, ltf, and atf schemes was obtained, respectively.

It is clear from the above discussion; tf.idf weighting mechanism achieved better performance than tf, ltf, and atf. This could be attributed to that fact that raw term frequency (tf) representation suffers from a critical problem. That is all parsed terms in the corpus are considered equally important when it comes to assessing their relevance to a query. However, some terms, like highly occurring ones over all cases in the corpus, have no discriminating power in legal knowledge extraction. For example, a legal term like "contract" exists in almost all cases in the corpus.

Consequently, this term holds no power to differentiate the existence of significant legal factors. This problem is slightly resolved by modifying the raw term frequency with the logarithmic and augmented weighting mechanisms. However, the term frequency inverse document frequency (tf.idf) mitigates this problem by scaling down the term weight of terms with a high frequency of occurrence. This is done by weighting a term frequency with respect to its occurrence in all cases within the corpus. In this case, discrimination between cases is done through the case-level statistic (such as the number of documents containing a term), which is considered to be of higher power than to use a cases-wide statistic. Consequently, the importance of terms increase proportionally to the number of times a term appears in the case but is offset by the frequency of that term in the corpus which leads to a suitable weighting mechanism for the purpose of the current research study.

Table 2 Accuracy Measures of Developed Models

Weighting Scheme	Classifier		
	1st Poly. Deg. SVM	2nd Poly. Deg. SVM	3rd Poly. Deg. SVM
tf	64%	64%	60%
ltf	71%	69%	71%
atf	76%	72%	72%
tf.idf	76%	72%	74%

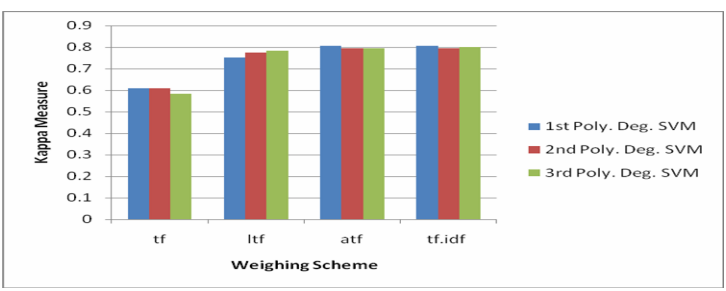


Figure 3 Kappa Measures of the Developed Models

Expanded Corpus Analysis

The problem analyzed under this research is a real life complex one. The extraction of latent legal factors from textual representation of cases based on available terms integrates a lot of factors that are not linearly separable in nature. Consequently, simple classifiers are not suitable for the task. However, Support Vector Machine (SVM) is a state-of-the-art classification and regression algorithm, which implements strong regularization techniques, that is, the optimization procedure maximizes predictive accuracy while automatically avoiding over-fitting of the training data (Cannon et al. 2007). Furthermore, the transformation of the data into a higher dimension space through Kernel estimation provides the strength of the SVM model in solving this complex problem. On the other hand, the analysis utilizes 120 cases and is considering a large number of features (2354 terms). The fact that the number of cases is less than twice the number of features deteriorates the active learning

feature of SVM. "SVM models grow as the size of the training data set increases…. Active learning forces the SVM algorithm to restrict learning to the most informative training examples and not to attempt to use the entire body of data" (Oracle 2009). Consequently, this section of the paper tested the aforementioned methodology while using a larger corpus including 450 cases from the Federal Court of New York. The following is a closer look at the outcomes.

- A comparison of the weighing mechanisms illustrates a higher performance of the tf.idf over tf, ltf, and atf with all developed models.
- The highest prediction accuracy of 85% was attained while implementing 3rd degree polynomial SVM kernel models.

SUMMARY AND CONCLUSION

The objective of this paper was to investigate the feasibility of using SVM for the development of an automated model to extract latent legal factors upon which judges base their verdicts from textual representations of cases and to test the effect of the training corpus size on the performance of the developed models. The implementation of the aforementioned methodology highlights the followings:

1. SVM represents a feasible methodology for extracting latent legal knowledge from textual representation of documents.
2. Term frequency inverse document frequency tf.idf is the best weighing mechanism to represent the latent knowledge in textual representation of documents.
3. As the number of documents within a training corpus increase, the active learning feature of SVM models enhances. The analysis illustrated an increase of 9% in the prediction accuracy as the number of cases in the training corpus increased from 120 to 450 cases.
4. As the number of cases in the training corpus increase, the performance of the SVM model increases and the complexity of the analysis increases too. Consequently, the highest precision accuracy of 76% was attained with a training corpus of 120 cases while implementing 1st degree polynomial kernel SVM model. As the number of cases increased to 450, the increased complexity of the analysis yielded a heist precision accuracy of 85% while implementing a 3rd degree polynomial kernel SVM model.

FUTURE WORK

The outcomes of this research illustrate the strong potential of Machine Learning (ML) techniques for developing automated models to extract latent knowledge from textual representations of precedent cases. Therefore, the enhancement of the methodology implemented in this paper by incorporating other ML methodologies like Naïve Bayes and Rule Induction Learning classifiers will be the subject of future study by the authors.

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Contracting Strategy Decision Framework for Highway Maintenance

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Abstract

Billions of dollars are expended annually on maintenance outsourcing to preserve the existing highway network. Selection of the activities to be outsourced and the type of contracting strategy to implement primarily depend on the judgment of highway maintenance directors. While there are a large number of maintenance contracting strategies being used worldwide, maintenance directors often make their selections based on contracting practices they have used successfully in the past rather than by examining all possible methods and choosing an appropriate contracting strategy that meets specific selection criteria. In fact, there currently is no systematic method for choosing an appropriate maintenance contracting strategy. This paper contributes to the body of knowledge on the maintenance contracting selection process by summarizing 13 strategies being used worldwide to deliver maintenance services, identifying specific selection criteria that should be considered when making a decision, and presenting a decision framework that will aid highway maintenance personnel with the selection of effective maintenance contracting strategies.

***Keywords*:** decision making, maintenance outsourcing, contracting strategy

Background and Problem Statement

To address the deteriorating highway system, the Federal Highway Administration (FHWA) has encouraged state highway agencies (SHAs) to implement pavement maintenance techniques. However, while pavement maintenance programs have historically used in-house personnel to perform the work, shortages of in-house resources, including expertise, equipment, and experienced personnel, have caused many agencies to outsource a significant amount of their maintenance work. Some states have experimented with hybrid methods that bring together in-house and contract staff to maximize cost, quality, expertise, and efficiency while maintaining a comfortable tradeoff between control and efficiency. Yet, other agencies have outsourced nearly all of their maintenance work using performance-based contracting

which essentially turns control over to the contractor.

Numerous contracting alternatives exist to accomplish maintenance goals, but little documentation of these variations has been published. For example, the Houston District of the Texas Department of Transportation (TxDOT) values control of the work but also needs to augment their limited workforce. As a result, they have implemented a General Maintenance Contract that outsources nearly all maintenance activities using a method-based specification and a unit price costing strategy. In contrast, Florida DOT (FDOT) has shifted nearly all risk of control to the contractor by utilizing a performance-based maintenance contract that can be tailored to each district. While these examples demonstrate two contracting strategies used in the U.S., there is a need to identify other methods being used and to provide a framework for selecting an appropriate contracting strategy to achieve specific maintenance goals.

Much of the research that has been completed in the past two decades has simply summarized the innovative maintenance contract methods utilized by different agencies. For example, Pakkala et al. (2007) investigated and summarized eight traditional and non-traditional maintenance delivery models implemented by various countries, including Australia, Canada, England, Estonia, Finland, The Netherlands, New Zealand, Norway, Sweden and the USA. Liautaud (2004) summarized two unique contracting strategies being used in South America. And, Ribreau (2004) critiqued the use of performance-based maintenance contracts by various U.S. states. While there are numerous innovative maintenance contract strategies being used worldwide, there has been very limited research on the selection of an appropriate maintenance contracting strategy for a specific set of circumstances. Currently, many maintenance directors still make their contracting decisions based largely on their previous contracting practices. Hence, there is a need to identify innovative maintenance contracting strategies that are being used successfully by various states and to develop a decision aid for selecting those strategies that may be appropriate for implementation to achieve specific maintenance goals.

This paper discusses three key components of a maintenance contracting strategy, including the delivery method, type of contract specification, and pricing strategy. This paper then presents a maintenance contracting strategy selection framework and selection criteria based on the preliminary research results.

Research Methodology

Through a comprehensive literature review, the researchers identified delivery methods that are used nationally and internationally for highway maintenance contracting. At the same time, in-person and phone interviews were conducted with five TxDOT maintenance experts to collect data on the following questions:

1. Which maintenance contracting delivery methods, associated specification types, and pricing strategies are used in the DOT districts?
2. Which criteria do district personnel consider when making a decision about whether to perform maintenance activities in-house versus outsourcing them?
3. Which criteria do district personnel consider when making a decision about the delivery method, specification type, and pricing stragey to use for outsourcing?

Based on the literature review and the interviews, 13 maintenance delivery methods were identified as being used nationally and internationally. The 13 delivery methods were used to develop an on-line questionnaire that was distributed to all 25 TxDOT districts and state highway agencies within the other 49 states. The questionnaire sought to identify which types of delivery methods, contract specifications, and pricing strategies were used, and whether the strategy resulted in successful maintenance performance. Overall, 79 DOT personnel responded to the questionnaire, with 20 responses received from the districts within TxDOT and 59 responses received from either central offices or district offices of other state transportation agencies. The results of the questionnaire were also used to identify districts within TxDOT and other state DOTs that should be interviewed face-to-face to learn more about their maintenance contracting and implementation strategies. As a result, six districts within TxDOT and five state DOTs were selected for participation in the interview process, including Pennsylvania, Florida, North Carolina, Kentucky, and Maine. An interview protocol was developed to investigate maintenance contracting strategies. A decision framework for selecting appropriate contracting strategies was developed based on results from the questionnaire and the interviews. Ultimately, a decision aid will be developed that can be used by maintenance personnel to select an appropriate contracting strategy for various maintenance goals and circumstances.

Innovative Maintenance Contracting Strategies

A *Contracting Strategy*, as defined in this paper, is a process for allocating the risks and responsibilities for maintaining an existing highway asset, and consists of three main components: (1) a delivery method, (2) a type of contract specification, and (3) a pricing strategy. This paper identifies 13 delivery methods, three types of contract specifications, and three pricing strategies being used worldwide.

Definitions of Thirteen Maintenance Delivery Methods

1. **Individual Activity Contract Method**: a single maintenance activity is outsourced, such as mowing.
2. **Moderately Bundled Activities Contract Method**: a few maintenance activities that are of a similar nature and have a compatible sequence of work are let out together, such as mowing, sweeping, and litter pick-up.
3. **Significantly Bundled Activities Contract Method**: *nearly all* maintenance activities are let out together, other than a few activities that are special or unique. A method-based specification and unit price are an integral part of this method. This contract method has also been called a General Maintenance Contract.
4. **Partial Competitive Maintenance Contract Method**: a percentage of the in-house workforce is retained to perform various routine maintenance activities, while the rest of the activities are bid out. In this method, in-house forces can competitively bid against contractors for the work. Often, the scope of work is large and may include nearly all maintenance activities (Pakkala et al. 2007).
5. **Jointly-Performed Maintenance Contract Method:** a portion of a specific maintenance activity is performed by in-house personnel and the remainder of the activity is outsourced to a contractor, typically due to a lack of sufficient equipment or labor. For example, snow removal can be jointly performed.

6. **Routine Maintenance Contract Method**: *all* routine maintenance activities are outsourced together, where routine maintnenace consists of work that is performed systematically to preserve the condition of the highway asset, such as pothole patching, ditch cleaning, mowing, or sign maintnenace (Pakkala et al. 2007). If a performance-based specification and lump sum pricing are used, the method can be regarded as a Total Asset Management Contract Method. If a method-based specification and unit pricing are used, the method is very similar to a Significantly Bundled Activities Contract.
7. **Integrated Maintenance Contract Method**: a combination of both routine and preventive maintenance activities are outsourced together as one contract, where preventive maintenance consists of work performed on an existing road asset that preserves the asset and prevents future deterioration, such as sealcoats and overlays. If a performance-based specification and lump sum pricing are used, the method can be regarded as a Total Asset Management Contract Method. If a method-based specification and unit pricing are used, the method is similar to a Significantly Bundled Activities Contract Method.
8. **Kilometer (or Mile) per Month Contract Method**: applies to a sub-network of paved roads that is in good to fair condition and is expected to remain in that condition over the next few years through routine maintenance alone, without any major strengthening or rehabilitation (Liautaud 2004). A performance-based specification and lump sum pricing are an integral part of this method.
9. **Total Asset Management Contract Method**: a systematic process of operating, maintaining, upgrading, and expanding physical assets throughout their lifecycle (*AASHTO Subcommittee on Asset Management, January 2006*). In the context of contracting, Total Asset Management involves outsourcing operations, maintenance, upgrades to, and expansion of, a road asset. A performance-based specification and lump sum pricing are an integral part of this method.
10. **CREMA Contract Method**: a Combined Rehabilitation and Maintenance (CREMA) Contract requires contractors to rehabilitate and subsequently maintain a sub-network of roads under a lump sum contract for a total period of five years (Liautaud 2004). This model is currently used in Latin America. A performance-based specification and lump sum pricing are an integral part of this method.
11. **Long-term Separate Maintenance Contract Method:** a single maintenance activity is outsourced across many areas or regions for a long duration, typically more than five years, often because it is unique or risky (Pakkala et al. 2007).
12. **Framework Contract Method**: several contractors are pre-approved and receive nominal contracts that make them eligible for award of maintenance projects (Pakkala et al. 2007). The method is often called a Multi-Agency Contract (MAC) or Job Order Contracting and is used widely by the U.S. military.
13. **Alliance Contract Method**: a contractor is selected based entirely on qualifications and has the opportunity to gain or lose 15% of the contract value depending on performance. This model typically uses cost plus fee as the pricing strategy (Pakkala et al. 2007).

Types of Contract Specifications

There are three primary types of contract specifications used to outsource maintenance

work: (1) method-based, (2) performance-based, and (3) warranty contract specifications. Under method-based contract specifications, the contracting agency typically specifies the methods, materials, and quantities to be used, and payment is based on amount of output (i.e., area of grass mowed) (Stankevich et al. 2005). Performance-based contract specifications allow the contracting agency to define an end outcome goal and the contractor can decide how best to achieve the desired outcome (i.e., the grass cannot exceed 3 inches in height more than 10% of the time) (Segal et al. 2003). Warranty contract specification requires the contractor to warrant the work for a specified length of time.

Pricing Strategies

Typical payment methods for maintenance contracting include unit price, lump sum, and cost plus fee. Unit price makes payment based on the amount of output of a particular bid item (e.g., price per square foot of grass mowed). Lump sum contracts usually fix a maximum payment amount in advance, and this amount is paid out monthly over the contract term. Cost plus fee allows the contractor to be reimbursed according to the cost it incurs plus a fixed fee as profit.

Contracting Strategy Selection Framework

Based on the decision criteria identified through the six TxDOT interviews and five interviews with other state DOTs, a *Maintenance Contracting Strategy Selection Framework* was developed (Figure 1). Eight decision nodes have been identified and included in the framework, along with the associated decision criteria used by DOT agencies. The selection process begins with an agency first deciding how many activities they would like to outsource (e.g., nearly all or less than all) followed by deciding which activities will be retained for in-house performance and which will be outsourced. Subsequently, the agency must select an appropriate maintenance delivery method, specification type, and pricing strategy that are appropriate for their maintenance outsourcing goals and circumstances. The *Maintenance Contracting Strategy Selection Framework* and its associated decision criteria are presented in the paragraphs below.

Decision Criterion 1: Select the Number of Activities to Outsource

As illustrated in Figure 1, the *Maintenance Contracting Strategy Selection Framework* is a hierarchical structure. A DOT should first determine how many activities it intends to outsource. The DOT can decide to outsource *nearly all* maintenance activities or it can decide to select a smaller subset of activities. Through the interviews, several criteria were identified that were used frequently to determine whether *nearly all* maintenance activities should be outsourced including:

1. A legislative mandate required all maintenance activities to be outsourced
2. There was political pressure to outsource nearly all maintenance activities

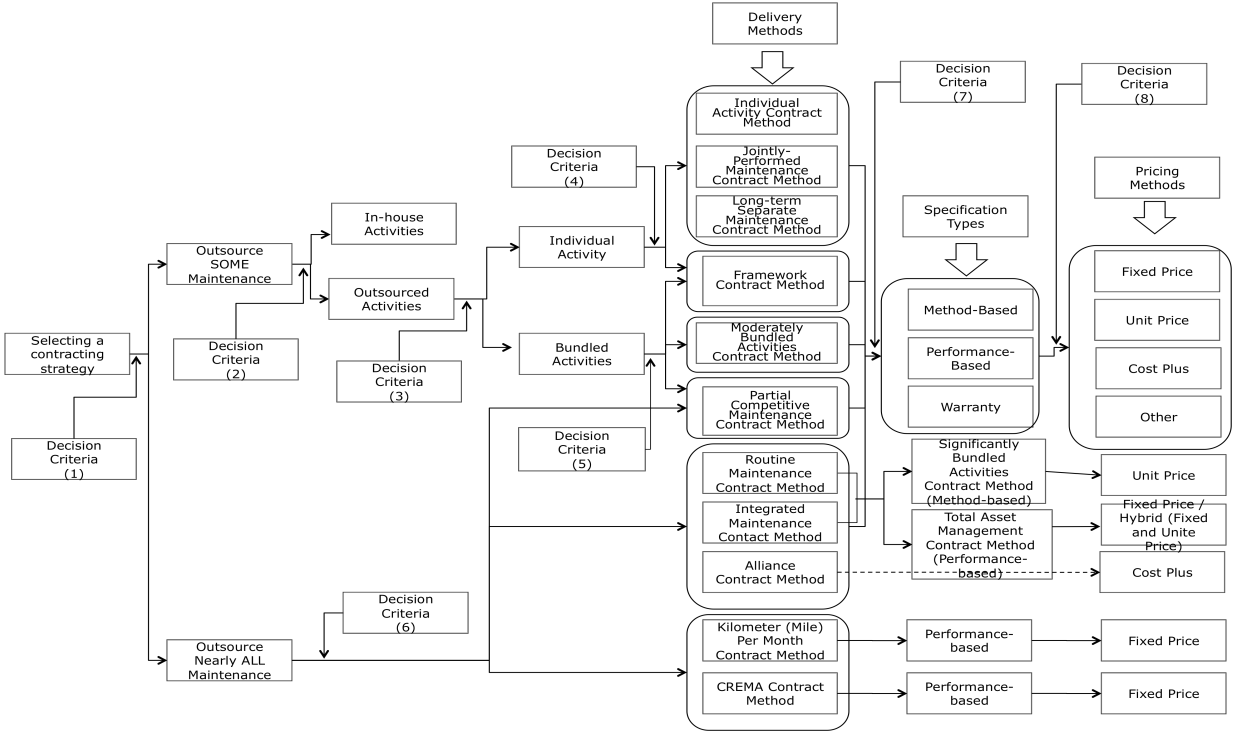


Figure 1. Maintenance Contracting Strategy Selection Framework

3. To reduce administrative time and cost, all or nearly all maintenance activities were outsourced together
4. The DOT was required to reduce the size of the in-house workforce; to accomplish this task, all or nearly all maintenance activities were outsourced

In the absence of one of these criteria, the DOT may elect to outsource only a portion of the maintenance activities and retain several activities for performance in-house.

Decision Criterion 2: Select Which Activities to Outsource

There are many factors that DOTs consider when deciding *whether* to outsource one or more activities and *which* activities specifically to outsource. The following factors were often considered when deciding whether and which activities to outsource:

1. Size of the maintenance budget
2. Availability of proper equipment
3. Availability of in-house workforce
4. Availability of in-house expertise
5. Availability of contractor expertise
6. Need to improve maintenance efficiency
7. Quality / experience of contractors
8. Need to augment peak workloads
9. Average daily traffic on the road
10. Required by legislative mandate
11. Political reasons or pressure
12. Need to encourage innovation
13. Need to increase Level of Service
14. Overall risk management strategy
15. Need to address weather challenges
16. Need to speed up maintenance delivery
17. Need to achieve a cost savings
18. Need to increase responsiveness
19. Need to accomodate work load
20. Need to accomplish emergency work
21. Large/small contract value is
22. Uniquenss or specialty of the work

Some criteria might specifically compel an activity to be outsourced. For example, lack of equipment and lack of expertise were criteria that would compel an agency to outsource an activity because the agency did not have the proper resources to perform the activity using their own in-house resources.

Decision Criterion 3: Select Which Activities Get Let Individually or Bundled

Once the DOT has selected one or more maintenance activities to outsource, the next step is to select which activities to individually let and which to bundle together. The following factors were often considered when deciding how to combine activities when preparing a bid package:

1. Level of control over the work that is desired and would be achieved
2. Efficiency that would be achieved by bundling activities together
3. Reduction in coordination effort that would be needed
4. Reduction in administrative load that would be achieved
5. Available equipment composition
6. How similar the bundled activities are and the logic of grouping them
7. Whether multiple subcontractors will be needed to complete all of the work
8. Time-sensitivity of the bundled work (such as sign repair)
9. Contractor's experience at performing the bundled activities
10. Cost effectiveness that might be achieved from individual or bundled activities

11. Volume of work that would result from individual or bundled activities

Decision Criteria 4/5/6: Select a Delivery Method for Outsourced Activities

The following criteria were identified by the respondents as some of the criteria typically considered when selecting a maintenance contracting delivery method. Respondents noted that maintenance goals and circumstances often influenced their decision; hence, the list below is generic and does not reflect the specific context in which a decision might be made (such as which activities are being outsourced or which maintenance goal must be achieved through outsourcing). Hence, for a single activity (*decision criterion 4*), a set of activities (*decision criterion 5*), or nearly all activities (*decision criterion 6*) that will be let, the DOT must select a delivery method that is appropriate for the maintenance goals and circumstances of the DOT. The following factors were considered when selecting a delivery method:

1. Insufficient equipment is available for performing the work
2. The DOT needs flexibility in when and how to complete the work
3. The duration of the work may be very short or very long
4. The activity is special, unique, or risky
5. There is a need to reduce the amount of time for bidding and awarding projects
6. There is a need to select contractors quickly for urgent projects
7. There is a need to reduce the overall administrative time, costs, and overhead
8. There is a need to increase the level of competition among bidders
9. There is a need to ensure an equal opportunity for in-house employees to get work
10. There is political pressure to outsource nearly all maintenance activities
11. There is a lack of manpower to perform the work in-house
12. The goal is to reduce the overall administrative load
13. The long-term duration of the contract makes it ideal for contracting out
14. There is a need to reduce coordination efforts for different types of activities
15. The level of control or desire to shift control are important considerations
16. There is a need to reduce conflicts between owners and contractors

Decision Criteria 7: Select a Type of Contract Specification

Three types of contract specifications are generally available for use by DOTs. In most cases, each of the three can be selected unless there is a compelling reason to eliminate a type from consideration (such as legislative mandate). These three contract specifications include: method-based, performance-based, and warranty specification. The following factors were often considered when selecting a type of contract specification for a delivery method:

1. Level of control over the work that the DOT wants to maintain
2. Level of trust between the DOT and the contractor
3. Quality and experience of the contractor
4. Political reasons or pressure
5. To encourage participation of contractors in bid processes

Decision Criteria 8: Selecting Pricing Strategy

Three typical pricing strategies are often used by DOTs, including fixed price, unit price, and cost plus pricing. The following factors were often considered when selecting a type of pricing strategy for a delivery method:

1. Legislative mandate requires or prohibits using a particular pricing strategy
2. The pricing method selected was most cost effective for the DOT
3. Flexibility was needed because of the unique nature of the work

Appropriate Delivery Methods for Individual and Bundled Activities

The *Maintenance Contracting Strategy Selection Framework* identifies 13 delivery methods that are appropriate for individually-let and bundled maintenance activities, including the bundling of *nearly all* maintenance activities. As shown in the framework, four delivery methods are appropriate for individually-let maintenance activities, three are appropriate for bundling a moderate number of maintenance activities, and six are appropriate for bundling *nearly all* maintenance activities. One delivery method is appropriate for either individually-let or moderately-bundled activities, and one delivery method is appropriate for either moderately-bundled or the bundling of nearly all maintenance activities. Identified in Table 1 are the 13 delivery methods that were defined previously, listed by whether they are most appropriate for individually-let or bundled activities.

Table1. Delivery Methods for Individual or Bundled Activities

Delivery Methods for Individually-Let Maintenance Activities
1. Individual Activity Contract Method
2. Jointly-Performed Maintenance Contract Method
3. Long-term Separate Maintenance Contract Method
Delivery Methods for Either Individually-Let or Moderately-Bundled Maintenance Activities
4. Framework Contract Method (also called a Multi-Agency Contract)
Delivery Methods for Moderately-Bundled Maintenance Activities
5. Moderately Bundled Activities Contract Method
Delivery Methods for Either Moderately-Bundled or Bundling of Nearly All Maintenance Activities
6. Partial Competitive Maintenance Contract Method
Delivery Methods for Bundling of Nearly All Maintenance Activities
7. Routine Maintenance Contract Method
8. Integrated Maintenance Contract Method
9. Total Asset Management Contract Method
10. Significantly Bundled Activities Contract Method
11. Alliance Contract Method

12. Kilometer (Mile) Per Month Contract Method
13. CREMA Contract Method

Conclusions and Future Work

Through a literature review, phone interviews, and in-person interviews with DOT personnel, the researchers identified 13 innovative maintenance delivery methods that are available for use by DOTs for accomplish maintenance goals and accommodating particular circumstances (such as a lack of equipment or expertise). Criteria were identified that are often considered by maintenance personnel when deciding which activities to outsource and which contract strategy to implement for the outsourced activities. Additional research is underway to develop a tool and guide to aid DOTs in identify their goals and particular circumstances, selecting activities to outsource, and deciding which contract delivery method, specification type, and pricing strategy to implement to efficiently complete the maintenance activities.

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DEVELOPING A FRAMEWORK FOR CONSTRUCTION CONTRACTOR QUALIFICATION FOR SURETY BONDING

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ABSTRACT

In the construction industry, contractor failure is always possible. Surety bonding is a technique that is used to reduce the risk the owner may face in case a contractor fails to complete a project. When a surety company undertakes to provide a contractor with the bonding facility for a specific construction project, the risks of project completion are shifted from the owner to the surety company. A very complex qualification or assessment process is done to assess project specifics and contractual risks. There are many qualitative and quantitative factors that are taken into consideration, and some of these factors have a nature of uncertainty and subjectivity. The purpose of this paper is to present a methodology for developing a framework for formalizing the contractor and project assessment process to obtain surety bonds for specific construction projects. The framework includes the integration of multiple technologies (genetic algorithms, fuzzy logic, neural networks, and learning from examples) into a single application.

INTRODUCTION

Construction projects are risk-filled and occur in a changeable environment, which is often full of uncertainty and is very dynamic. Contractor failure is defined by Russell (1991) as a contractor who is unable to fulfill his/her contractual duties. There are several unforeseen and uncontrollable events that may lead to contractor failure. Contractor default is always possible, and even capable and well-established contractors can ultimately fail. For these reasons, owners search for ways by which the risk of contractor failure can be mitigated. Public and private construction project owners can mitigate the risk of contractor failure by requiring bid, performance, and payment bonds.

Prior to providing bonding to a contractor for a project, a surety company must be satisfied that the contractor has the ability to meet current and future obligations, has the experience to fulfill the requirements of the project to be undertaken, has (or can readily obtain) the resources necessary to perform the work, and will finish the project within the required objectives of time, cost, and quality.

Surety underwriters in the construction industry are required to make a very important decision when it comes to providing the construction contractor with the surety bonding facility for a construction project. This decision is significant and very critical for two reasons: the first one, by accepting to provide the contractor with bonding, the risks of project completion are shifted from the owner to the surety company; the second reason is the nature of the evaluation criteria that should be considered in the underwriting process and the challenge in combining these criteria to obtain the final decision. Some of the evaluation criteria considered in making the surety bonding decision are uncertain and subjective, making them difficult to assess. Many criteria, such as the contractor's performance on previous projects, are assessed based on the opinion of the underwriter and of others (e.g., previous clients, architects, engineers, suppliers, and subcontractors), making them extremely subjective and with a range of acceptable values. Some of the criteria are qualitative and some are quantitative. Furthermore, some aspects of the evaluation process used by surety underwriters require expert knowledge and judgment and many times incorporate "rules of thumb". Combining all of the criteria into a single decision on whether or not to provide bonding requires complex decision-making, due to the non-liner relationship between the criteria and the decision.

The goal of this paper is to describe a model that formalizes the decision-making process used by surety underwriters in qualifying contractors for bonding when they request bonds to undertake a specific construction project. Several techniques will be integrated (genetic algorithms, fuzzy logic, neural networks, learning from examples) into a single application, in order to take advantage of the best features of each.

SURETY BONDING IN CONSTRUCTION

Surety bonding can be defined as a technique that can be used to reduce the risk the owner may face on a construction project in the case that the contractor fails to complete the project (Maxwell 2005). The Surety Association of America (SAA) defines a surety bond as: "An agreement providing for monetary compensation should there be a failure to perform specified acts within a stated period". This definition means that the surety company guarantees the owner of the construction project that the project will be constructed within the required time and according to the specifications and contract documents (Kangari and Bakheet 2001).

The steps for obtaining the bonding facility start with the contractor contacting a professional agent or broker who specializes in contract surety. After gaining an understanding of the contractor`s business and needs, the broker tailors the contractor's submission for the specific requirements of the surety underwriter. Once the surety bond broker collects all the necessary information, he or she submits it to a surety company underwriter that is best matched to the contractor's profile and needs. The underwriter takes an in-depth look at the contractor's entire business operations and must be satisfied that the contractor is capable of completing the project. Prior to providing the bonding facility, the surety underwriter conducts a rigorous qualification (evaluation) process. This process can be divided into two phases. The first phase is performed to establish a relationship between the contractor and the

surety underwriter, and the second phase is performed when the contractor requests bonding for a specific project.

Marsh (2008) and Marsh and Fayek (2009) developed SuretyAssist, a decision-making model designed to assist surety underwriters and brokers in evaluating general contractors in the construction industry in the first evaluation phase. Three categories of factors are considered in SuretyAssist: character, capacity, and capital. The second phase starts after the contractor has established a relationship with the surety underwriter and the contractor requests bonding for a specific project. At this point, the underwriter evaluates the project specifics, contractual risks, and contractor`s organizational practices.

CONTRACTOR QUALIFICATION CRITERIA

After conducting a literature review in surety bonding and contractor qualification, holding several meetings with surety industry professionals, and discussing several historical cases with the experts, a comprehensive list of evaluation criteria used in the second phase of the underwriting process was developed. This list of criteria was then circulated to surety brokers and underwriters to allow them to provide their input by adding additional criteria and modifying existing ones. The criteria were divided into three main categories: project specifics, contractual risks, and the contractor's organizational practices. Each category has several criteria and sub-criteria.

Project specifics include an evaluation of the project team, including the owner's experience in construction, the quality of the subcontractors, and a periodic (e.g., quarterly) evaluation of the contractor based on their financial statements. A current evaluation of the contractor's capacity and financial ability given the current work load is also considered, together with specific characteristics of the project and its scope. Also, contractual risks are evaluated to ensure that the contractor is familiar with the project delivery method and that the clauses in the contract are acceptable. Contractual risks includes an assessment of the contract form (standard verses owner wording) and the contract type. Contractual risks also includes an assessment of different contractual aspects such as payment clauses, warranty clauses, toxic and hazardous substances and materials, and many other factors to determine the contactor's obligations and responsibilities according to the contract. The contractor`s organizational practices evaluate the contractor`s practices in several areas, such as constructability, cost management, zero accident techniques, change management, procurement management, communication management, and quality management. Contractor's organizational practices include an assessment of the contractor's ability to carry out different management practices for the proposed project.

Due to the large number of evaluation criteria and the practical limitations of expert systems, a method of reducing the number of criteria was required. A questionnaire was developed and distributed amongst three senior surety brokers and two senior underwriters to determine the relative importance weights of the evaluation criteria in the decision-making process. Each respondent was asked to evaluate the importance of each criterion to the overall qualification of the contractor on a scale of 1-7, 1 being the least important and 7 being the most important. Criteria that had an average importance weight of less than 4.0 were eliminated, as recommended by the experts.

MODEL DEVELOPMENT METHODOLOGY

An expert knowledge-based model is proposed that is based on fuzzy if-then rules that relate the input (evaluation criteria) to the output (overall contractor project qualification). The model is constructed using knowledge from experts to incorporate experts' opinion under uncertainty. The use of fuzzy set theory provides a quantitative, mathematical technique to deal with imprecision, subjective information, linguistic expressions, and ranges of possible values. Fuzzy set theory is able to incorporate qualitative criteria into the decision-making process. Input criteria were quantified using linguistic variables such as poor, average, and good. Each linguistic variable was represented by a fuzzy set in which an element belongs to that fuzzy set to a certain degree of membership. Fuzzy sets are represented using membership functions.

The model development roadmap in Figure 1 shows the components of the proposed model, as well as the techniques used to develop each component the model. The membership functions will be estimated using genetic algorithms (GAs), while the rule base, which is the main component of the model inference process, will be determined using learning from examples. The rules' importance weights will be developed using artificial neural networks (ANNs). Finally, a sensitivity analysis will be conducted to determine the appropriateness of the aggregation method, defuzzification method, and the membership function shapes. The main components of the model development are described next.

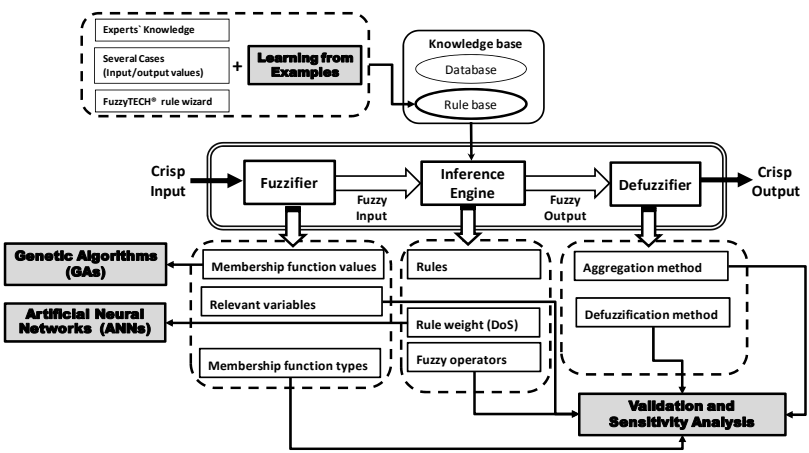


Figure 1. Contractor Qualification Model Basic Structure and Development Roadmap

Estimation of Membership Functions

Before gathering data to construct the membership functions, experts were consulted to determine the linguistic terms used to describe the input and output variables as well as possible numerical values that can be used to quantify them. Table 1 shows

examples of the input criteria, the linguistic terms, their corresponding numerical scale, threshold values (red flags) below which there is a cause for concern for the variable, and favourable values, as suggested by surety experts.

Genetic algorithms (GAs), which are considered random search techniques, have been applied to many different problems such as function optimization, routing problems, scheduling, designing neural networks, system identification, digital signal processing, computer vision, process control and machine learning (Goldberg 1989, Dorigo 1993, Tang et. al. 1996).

Table 1. Sample of Input Criteria for Qualifying Contractors and Method of Assessment

Input Name	Linguistic Descriptors	Quantification X-Axis Value	Red Flag	Favourable If
Owner Funding	Poor, Average, Good	Predetermined Scale 1-7	< 4	Higher
Owner Experience	Poor, Average, Good	0-15 Years	< 5	Higher
Overall (Subcontractors) Qualification	Unqualified, Qualified, Very Qualified	Predetermined Scale 1-7	< 4	Higher
Working Capital Trend	Poor, Average, Good	-16-16 Percent	< -10%	Higher
Tangible Net Worth Trend	Poor, Average, Good	-16-16 Percent	< -10%	Higher
Gross Profit Margin Trend	Poor, Average, Good	-16-16 Percent	< -10%	Higher
Debt to Equity Ratio Trend	Poor, Average, Good	-16-16 Percent	< -10%	Higher
Net Profit Margin	Low, Average, High	0-20 Percent	< 2%	Higher
Cash Flow	Unacceptable, Acceptable, Good	Predetermined Scale 1-7	< 4	Higher
Operating Line	Unacceptable, Acceptable, Good	Predetermined Scale 1-7	< 4	Higher
Work On Hand	High, Average, Low	Predetermined Scale 1-7	< 4	Higher
Project Type/Complexity	Poor, Average, Good	Predetermined Scale 1-7	< 4	Higher
Payment Clauses	Poor, Average, Good	Predetermined Scale 1-7	< 4	Higher
Warranty Clauses	Poor, Average, Good	Predetermined Scale 1-7	< 4	Higher

Researchers follow one of two approaches in applying GAs for fuzzy membership function estimation or optimization. The first approach involves starting from scratch (i.e., randomly assuming an initial solution/s) to reach the optimal solution (Arslan and Kaya 2001, Ross 2004). The second approach involves assuming an initial solution that depends on expert opinion regarding the membership function shapes or values (Wang et al 1998, Makrehchi et al. 2003). In the proposed approach, the initial population (solutions) that will be used in GA optimization will not be randomly generated. Rather, an initial estimation of membership functions will be done using the horizontal method (Pedrycz and Gomide 1998). A questionnaire has been developed to collect data to determine the initial membership functions of each criterion. The experts are asked to assess which values on the quantification scale of a given criterion belong to which linguistic terms used to describe the criterion. Their responses are used for the preliminary estimation of membership function using the horizontal method. Figure 2(a) shows an example of the estimated membership function for “project type/complexity” using the horizontal method.

According to Lorterapong and Moselhi (1996), linear shape approximations (i.e., triangular and trapezoidal) are the most practical shapes of membership functions in many applications. The next step in the proposed method of membership function generation is the transformation of the membership functions developed using the horizontal method above into triangular or trapezoidal shapes using interpolation. Figure 2(b) shows an example of the interpolation process for the estimated membership function of "project type/complexity" to get all the possible linear approximations. Using interpolation, there may be more than one solution that represents the calculated membership functions. The most appropriate shapes and parameters for input and output membership functions will then be selected and considered as the initial population for the genetic algorithm (GA) optimization stage. Table 2 shows an example of the resulting six solutions for membership functions for three input variables "Cash Flow", "Operating Line", and "Work on Hand", after the interpolation process.

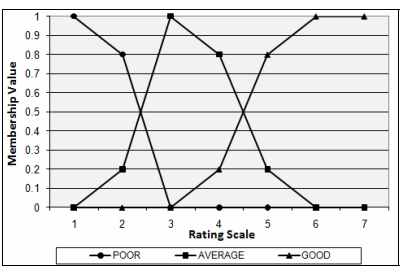


Figure 2(a). Project Type/Complexity Membership Function

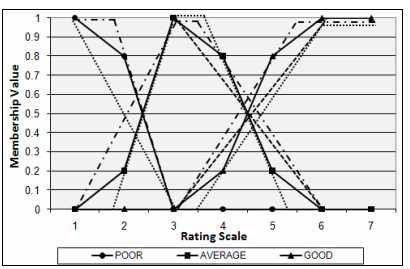


Figure 2(b). Interpolation of Membership Functions

The GA process will start with the initial population to conduct genetic algorithm operations (crossover and mutation) to generate a new generation of membership functions. A fitness evaluation function will be used to produce an objective value to measure the status of performance of each individual (solution). Depending on the fitness value, the decision of accepting or rejecting an individual will be made. Solutions with high fitness values will be used for generating a new generation. Then, the best solutions in the new generation (individuals) will be used to generate another generation, and so on, to reach the optimal or near optimal solution.

Table 2. Initial Solutions for Membership Functions

Solution No.	Current Evaluation																													
	Cash Flow												Operating Line												Work On Hand											
	UNACCEPTABLE				ACCEPTABLE				GOOD				UNACCEPTABLE				ACCEPTABLE				GOOD				HIGH				AVERAGE				LOW			
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
1	1	1	2.7	4	2	4	4.8	6	4	6	7	7	1	1	2.7	4	2	4	4.8	6	4	6	7	7	1	1	2.4	4	2	2.7	4.4	6	4	6	7	7
2	1	1	2	4	2.8	4	4.8	6	4.8	6	7	7	1	1	2	4	2.8	4	4.8	6	4.8	6	7	7	1	1	2	4	1.5	4	4	6.5	4.4	6	7	7
4	1	1	2.7	4	2	4	4	6	4	7	7	7	1	1	2	4	2	4	4	6	4	7	7	7	1	1	2	4.5	2	4	4	6	4	6.5	7	7
5	1	1	2	4	2.8	4	4	6	4.8	6	7	7	1	1	2.7	4	2.8	4	4	6	4	6	7	7	1	1	2.4	4	1.5	4	4	6.5	4	6.5	7	7
6	1	1	2.7	4	2.8	4	4.8	6	4	6	7	7	1	1	2.7	4	2.8	4	4.8	6	4	7	7	7	1	1	2.4	4	2	4	4	6	4.4	6	7	7

Several contractor project qualification cases / records will be collected, and experts will be asked to provide the corresponding overall qualification (output) values based on their initial assessment. These cases will be used to measure the fitness of each solution. Using qualification/assessment examples to develop the membership functions will allow for future calibration of the membership functions based on new cases.

Fuzzy Rules Extraction

The set of logical if-then rules that relate the input to the output are a useful representation of expert knowledge for a given area. Fuzzy if-then rules that use linguistic terms in both the antecedent (if part) and consequent (then part) can be extracted using one of two methods: (1) using an expert or a group of experts, who are capable of making decisions based on their extensive knowledge; (2) when the assistance of an expert is not available, using historical cases or databases (Del Campo 2004). A data-driven approach using learning from examples will be used to develop the fuzzy if-then rules for the proposed model using historical cases. The rule base will be extracted by detecting patterns in contractor qualification examples for specific construction projects, collected from experts' records, which contain values for the input (evaluation) variables and the corresponding output (overall contractor project qualification) values.

The proposed technique starts by determining the most appropriate linguistic terms to represent the crisp input and output values of the contractor qualification examples. As presented by Wang and Mendel (1992), this process will be done into two steps. Firstly, the membership degree of the input and output values in each linguistic term will be determined, as illustrated in Figure 3 for three input variables "Cash Flow", "Operating Line", and "Work on Hand" according to the contractor evaluation example data presented Table 3.

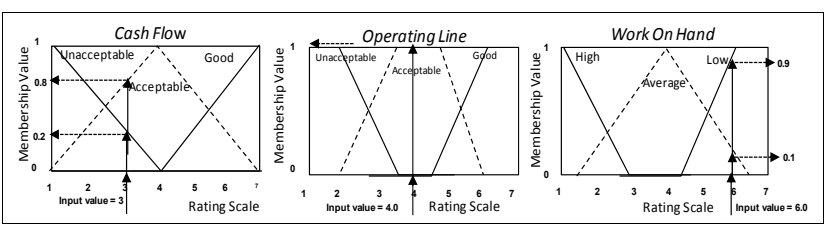


Figure 3. Example of Membership Degrees of Input Variables

Table 3. Rule Extraction Example

Input (Crisp Values)			Output (Crisp value)
Cash Flow	Operating Line	Work On Hand	Current Evaluation
3.0	4.0	6.0	4.5
Membership degree in each linguistic term			
Unacceptable = 0.2	Unacceptable = 0	High = 0	Poor = 0.1
Acceptable = 0.8	Acceptable = 1	Average = 0.15	Average = 0.9
Good = 0	Good = 0	Low= 0.85	Good = 0

Secondly, the linguistic term with the maximum membership degree for each input and output variable will be selected to generate the fuzzy rule, as illustrated in Table 3. In this example, the resulting rule would be: If *Cash Flow* is "Acceptable" and *Operating Line* is "Acceptable" and *Work On Hand* is "Low", THEN *Current Evaluation* is "Average".

Degree of Support of Rules

Artificial Neural Network (ANN) techniques based on back propagation will be introduced into the model to find the best rule weights or degrees of support (DoS). A back propagation network, which maps inputs through input membership functions and associated parameters and then through output membership functions and associated parameters to outputs, will be used to train and update the degrees of support (DoS) associated with the generated rules (Bousabaine 2001). The DoS will change through the learning process. The following example illustrates the proposed technique to estimate the rules' DoS for the same input and output variables presented in the previous section.

The set of rules related to this example are:

Rule 1; If Cash Flow is "Acceptable" and Operating Line is "Acceptable" and Work On Hand is "Low", THEN Current Evaluation is "Average".
Rule 2; If Cash Flow is "Unacceptable" and Operating Line is "Unacceptable" and Work On Hand is "Average", THEN Current Evaluation is "Poor".
Rule 3; If Cash Flow is "Good" and Operating Line is "Good" and Work On Hand is "Low", THEN Current Evaluation is "Good".

The approach to modify the rules' DoS is conducted in the following steps (Bousabaine 2001):

1. Calculate the value of each rule using Equation 1, as illustrated in Table 4.

$$\textbf{Rule Value}_i = \textbf{Rule DoS}_i * \textbf{Min. value}_i \quad [1]$$

where Min. value$_i$ is the minimum membership value of the input variables included in rule$_i$.

Table 4. Example of Determining Degrees of Support of Rules

Contractor's Current Evaluation Case	Cash Flow	Operating Line	Work On Hand	Current Evaluation			
	Inputs (Crisp Values)			Output (Crisp value)			
	3.0	5.0	6.0	4.5			
					Min. Value	DoS_{old}	Rule value
Rule 1	Unacceptable = 0.2	Acceptable = 1.0	Average = 0.15	Poor	= 0.15	* 0.8	= 0.12
Rule 2	Acceptable = 0.8	Acceptable = 1.0	Low = 0.85	Average	= 0.8	* 0.65	= 0.52
Rule 3	Good = 0	Good = 0	Low= 0.85	Good	= 0.0	* 0.5	= 0.0

2. Calculate the predicted output value of the contractor's current evaluation using Equation 2.

$$\textbf{Predicted Output} = (\sum \textbf{R}_{\textbf{Full}i} * \textbf{Rule value}_i) / \sum \textbf{Rule value}_i \quad [2]$$

where R_{Fulli} is the value on the rating scale that has full membership in the linguistic term of the output of rule$_i$.

Predicted Output = [(1 * 0.12) + (4 * 0.52) + (7 * 0.0)] / [(0.12+0.52+0.0)] = 3.44

3. Calculate the prediction error between the predicted output and the actual (i.e., target) value of the contractor's current evaluation using Equation 3.

Prediction Error = (Predicted output - Actual output) / Actual output [3]

where Actual output is the value of the contractor's current evaluation assigned by surety experts.

Prediction Error = (4.5 – 3.44)/4.5 = 0.236111

4. Fine-tune the degrees of support (DoS) of the rules using Equation 4.

$$\mathbf{Dos_{i\ new} = Dos_{i\ old} + LR * Prediction\ error * [(Dos_{i\ old} * Min.\ Value_i) / \sum Rule\ value]} \quad [4]$$

where $Dos_{i\ new}$ is the updated degree of support of rule *i*, $Dos_{i\ old}$ is the initial (or previous) degree of support of rule *i*, and LR is the learning rate (0.5 in this example).

In this example, the new DoS of the rules are calculated as follows:

$Dos_{1\ new} = 0.80 + 0.5\ (0.236111) * [0.12/(0.21 + 0.0 + 0.04)] = 0.822$
$Dos_{2\ new} = 0.65 + 0.5\ (0.236111) * [0.52/(0.21 + 0.0 + 0.04)] = 0.750$
$Dos_{3\ new} = 0.50 + 0.5\ (0.236111) * [0.00/(0.21 + 0.0 + 0.04)] = 0.500$

MODEL VALIDATION

The model will be validated using several unseen (historical) cases collected from surety experts. The validation error produced by the model will provide a clear indication of the ability of the model to generalize and extrapolate from the training data. Refinements to the model will be made, as necessary.

CONCLUSIONS

A framework for developing an expert knowledge-based model to help surety underwriters to assess project specifics, contractual risks, and contractor's organizational practices, for the purpose of bonding contractors for a specific construction project, has been described. Several artificial intelligence techniques were proposed for developing the model, to incorporate the best features of each. The model is currently being developed, tested, and validated for accuracy with participating surety brokers and underwriters.

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EFFECT OF CULTURE ON SELECTION OF DISPUTE RESOLUTION METHODS IN INTERNATIONAL CONTRACTS

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ABSTRACT

International construction projects provide opportunities for developing countries to advance in the global economy and for international firms to increase their profit and market share. Despite the attractive opportunities that international construction offers, there are many challenges and difficulties to moving into international markets. Many risks are associated with international construction, one of which is the risk arising from culture differences, and the way this affects how contract clauses are written. One of the very critical clauses affected by the cultural aspect is the dispute resolution clause. This paper discusses the different dispute resolution methods employed in international construction contracts and develops a model suggesting the use of specific dispute resolution methods depending on the culture characteristics. Finally, the model is used to develop testable propositions of the relationship between the dispute resolution methods and the characteristics of the culture studied. The propositions developed may eventually help in the selection of the appropriate dispute resolution method during contract formation.

KEYWORDS: International Contracts, Alternative Dispute Resolution Method, Culture Dimensions

GLOBALIZATION IN CONSTRUCTION

"Globalization'' is defined as a situation where political borders become increasingly more irrelevant, economic interdependencies increase, and national differences becomes more obvious due to dissimilarities in societal cultures and central issues of business (Ngowi et al. 2005). The first move of globalization in construction was in the appearance of international contractors as a result of the ease of movement of

goods/services across borders and communication advancements. These contractors entered the international market in many forms. Most remarkable was the oil-economic boom in the Middle East and North Africa that created huge construction demand. Also, the emergence of multilateral agreements between countries and between companies themselves (such as joint ventures and alliances) enabled firms to perform businesses in each other's countries (Ngowi et al. 2005).

International construction is defined as the industry where a company which is a resident in one country, performs work in another country to diversify and expand its market shares. Most of these companies are ones from advanced industrialized countries who perform work in newly industrialized or less developed countries (Dikmen et al. 2006; Ngowi et al. 2005). This provides the opportunity of utilizing the most up-to-date expertise and knowledge effectively (Chan et al. 2005). International construction work includes consultancy, contracting, equipment supply, construction products/materials and facility management (Dikmen et al. 2006).

Despite the attractive opportunities that globalization offers, there are many challenges to moving into the international markets. Many risks associated with international construction arise from differences in culture, economic conditions, specifications/standards, legal frameworks and productivity levels (Dikmen et al. 2006). To enter a foreign market, a company must evaluate all aspects affecting the project, should be cross-culturally competent and capable of managing in contrasting cultural dimensions (Chan et al. 2003). Many studies have been performed to identify and measure international risks, and to suggest mitigation measures. Some studied indicators of the market/project attractiveness such as availability of funds, market volume, economic prosperity and country risk rating. Others developed decision support tools that aim at facilitating such a critical decision (Dikmen et al. 2006).

Once the decision is taken to venture into international contracting, firms must be aware that the international contracts they will sign may be similar to their own domestic contracts, but will still include some major additional/modified clauses that address international issues. One of these very critical clauses is the Dispute Resolution clause. This paper discusses both the different dispute resolution methods (DRM) employed in international construction and culture dimensions that provide a framework for the effects of cultural differences on organizations. A model is then developed suggesting the use of specific DRM depending on the culture dimensions. Finally, the model is used to develop testable propositions of the relationship between the DRM and the characteristics of the culture studied.

CONSTRUCTION DISPUTES

International projects provide opportunities for developing countries to advance and for international firms to increase their profit and market share. A good working cooperative relationship among the involved parties is a must for these benefits to be realized. Firms should be able to understand and deal with differences in cultures, values, traditions and languages of the other party (Chan et al. 2006). They should know whether the legal system they will be operating under is similar or different

than their home country (Yates et al. 2007). Such comprehension will definitely affect the success of their businesses (Chan et al. 2006).

Different contractual factors, cultural backgrounds, legal and economic factors, languages, technical standards, procedures, currencies, and trade customs involved in international projects make projects more vulnerable to disputes. International construction disputes represent a significant number of disputes arbitrated in the international commercial arbitration accounting for almost 20 percent of all disputes referred to the International Chamber of Commerce (ICC) each year (Seifert et al. 2005). If not properly managed, disputes may lead to delay in projects, lower team spirit, increase project costs, and damage business relationships (Chan et al. 2005).

Disputes in international construction mostly occur for reasons such as parties' lack of knowledge and experience in construction law (such as conflicts of laws and jurisdictional problems), project management practices are not homogeneous (local vs. foreign) and/or differences in objectives (Chan et al. 2006, Chan et al. 2003). It has also been confirmed by many studies that the differences in the factors mentioned above have a huge effect on the causation and resolution of construction disputes (Chan et al. 2006, Chan et al. 2003). They generally affect the way the contract is set up and the selection of the DRM. Parties involved are concerned with the clarity of local laws and the contract's interpretation governed by these laws (Chan et al. 2003).

DISPUTE RESOLUTION METHODS

In the global arena, there are many forms of DRM adopted with their own particular characteristics (Chan et al. 2006). Techniques other than litigation are referred to as Alternative Dispute Resolution (ADR) techniques. Litigation is a dispute resolution government run system, involving judges and courts. In construction contracts, most contracts will not go for litigation unless other ADR techniques have been attempted first (Yates et al. 2007). Litigation is a very procedural process following many rules. Parties involved need solicitors and barristers to assist them as they are the only ones permitted to address the court, which implies a very expensive process. The judgment of the court is final and binding. Litigation is public as anyone can attend the trial, and no party has any say on the choice of the judge. Given that the construction disputes are mostly technical and judges taking decisions in such disputes usually lack the technical knowledge that may be required, litigation is not the best resort though sometimes becomes the only one (Construction Disputes Resolution 2009).

Most ADR processes offer disputants the option of determining the process they will use which is why outcomes become more satisfying and easier to comply with. More cooperation and less competition is involved compared to litigation. For this reason, ADR helps maintain good relationship between parties which becomes a key advantage in the construction industry where parties continue to interact, if not on the same project, at least in other future projects after settlement is reached (Construction Disputes Resolution 2009). In the context of large international projects where there are several parties of different nationalities involved, ADR avoids any difficulties of conflict of laws or jurisdictional problems that may arise as it allows the parties to

reach agreement as to how their disputes should be resolved taking into account the national and cultural differences (Chan et al. 2003). ADR has gained favor over litigation for its low cost, speedy resolution and lower procedural complexity (Chan et al. 2006). The forthcoming paragraphs briefly introduce some of the most commonly used forms of ADR in international contracts.

Mediation/Conciliation: It is a voluntary non-binding process where a mediator assists the parties in achieving a negotiated settlement. It thus gives the parties full control over how their dispute is to be resolved with the mediator helping the parties to explore various settlement options. However, at the end, it is up to the parties to decide whether any of the options suggested by the mediator will resolve the dispute (Construction Disputes Resolution 2009, Yates et al. 2007). Mediation features confidentiality and is designed to sustain a continuing strategic relationship between the parties involved (Chan et al. 2006). One of its major strengths is that the solution offered may not be in compliance with the respective contractual rights and obligations of the parties (Construction Disputes Resolution 2009). Unlike mediation, in conciliation, a conciliator recommends a settlement which is either accepted or not by the parties (Construction Disputes Resolution 2009, Yates et al. 2007).

Adjudication: In this process, a neutral adjudicator decides on a resolution of a contractual dispute between the parties within a predetermined time limit. If the contract so states, the decision is binding on the parties. The time limit for the decision is a very distinguishing characteristic of this process. However, the parties can still question the decision if not satisfied with it and seek a more lengthy detailed procedure. In this case, the party who the decision came in favor of will still enforce the decision by getting control of the disputed funds all through the subsequent dispute resolution procedure. Adjudication proves to be very economic and speedy though this might be at the expense of the decision thoroughness. This makes it most appropriate where time is of essence or where work is required to continue while awaiting the decision (Construction Disputes Resolution 2009, Martin 2003).

Dispute Adjudication Board (DAB): DAB was developed by the construction industry as result of the inadequacy of institutional arbitration to provide an efficient and cost-effective means of dispute resolution. It constitutes a panel of technical experts that works with a particular construction project who are familiar with the project's contract and progress, and adjudicate quasi-binding disputes that arise out of the contract. Thus parties avoid being subject to a suit in any one of the forum courts of the parties involved in the construction project reducing legal risks. In international projects, it is desirable to have DAB members of nationalities as those of the parties involved. Today, both the World Bank and the FIDIC (International Federation of Consulting Engineers) conditions have DAB replace arbitration as the primary DRM (Seifert et al. 2005). However, DAB is not binding and thus any of the parties can resort to any other ADR form (Yates et al. 2007).

Arbitration: It is usually used as an alternative to litigation with prior agreement of the parties (Construction Disputes Resolution 2009). International contracts usually

specify the location of the arbitration proceedings, since local jurisdictions regulate the arbitration process within their jurisdictions, and also specify the governing language (Yates et al. 2007). Its edge emerges from the fact that disputes faced in construction require the skills of the decision-maker to be more biased towards relevant technical issues, rather than merely legal issues. Arbitration is confidential compared to litigation (Chan et al. 2003, Construction Disputes Resolution 2009). The decision reached is final and binding, and is usually enforced through the courts of any jurisdiction, not necessarily the jurisdiction where arbitration was held. Such a characteristic made it of great attraction in international disputes as the loser may not have sufficient assets in the location where the arbitration took place and thus the decision may be enforced elsewhere (Construction Disputes Resolution 2009). However, the arbitration process ends with a win-lose situation where the arbitrator decides the outcomes and the parties lose the power to determine the outcome (Martin 2003). Though the most popular DRM, other DRM are sometimes favored as it is often overly formalized, time consuming and expensive (Seifert et al. 2005).

Expert Determination: In this case, the parties refer the dispute to an expert who has full authority to make a decision solely without any of the parties' consultation based on the expert's own knowledge. The decision is usually final and binding. This form is usually used in complex technical issues where the parties themselves may lack the technical expertise. It is considered a very cheap form of dispute resolution yet requires faith in the expert's competence (Construction Disputes Resolution 2009).

Hybrid Methods: Mediation-arbitration or med-arb links both mediation and arbitration where the parties start with mediation and then move to arbitration if no agreement is reached. Another hybrid method is mini-trial, in which trial and negotiation are linked to form a jury trial and a mini-trial. In the summary jury trial, a nonbinding trial is held before a mock judge and jury, after which the parties negotiate a settlement. In a mini-trial, a nonbinding trial is held before a three-person panel and is followed by the parties negotiating a settlement (Martin 2003).

Figure 1 presents a summary of some of the most common DRM and the escalating levels in hostility and cost associated with them. Note that the steps start with the prevention techniques which aim at preventing the dispute from occurring either by risk mitigation measures or creating a teamwork environment (Cheung et al. 1999).

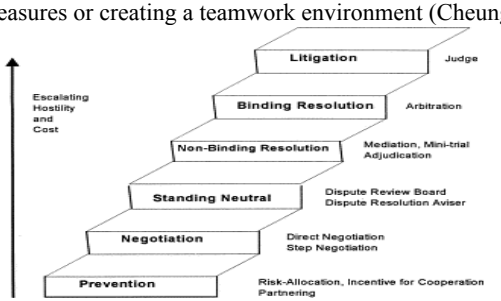


Figure 1: Construction Dispute Resolution Steps (Cheung et al. 1999)

CULTURE AND ITS DIMENSIONS

Having discussed the characteristics of the most popular DRM used and in an attempt to relate them to a cultural perspective, culture definition and its dimensions will be discussed in this section. Culture is defined differently according to the research field where it is being studied. In terms of an organization, Hofstede (1984) defines culture as the collective programming of the mind which distinguishes one group from another. In the construction industry, culture is about characteristics of the industry, approaches to construction, competence of people, and the goals, values and strategies of the organizations they work in (Kivrak et al. 2008). Every culture distinguishes itself from others by the solutions it chooses to certain problems. From the solutions chosen to problems arising from relationships with other people, the passage of time and from the environment, Trompenaar et al. (1999) grouped the ways in which values differ between cultures into seven dimensions. Dimensions seen to be linked to choice of DRM are discussed in the following paragraphs.

Universalism versus Particularism (rules vs. relationships): People in universalistic cultures believe that general rules, codes, values and standards take precedence over particular needs. The universal truth, the law, is considered logically more significant than human being relationships. Particularistic cultures view the ideal culture in terms of human friendship, extraordinary achievements and intimate relationships. The "spirit" of law is more important than the "letter" of law. The laws in particularistic cultures merely codify how people relate to each other. Dilemmas accordingly arise between legal contracts or loose interpretations, emphasis on globalism or localism and extending rules or discovering exceptions (Trompenaars et al. 1999).

Specific versus Diffuse (superficial or deep relationship involvement): Some cultures stick to the facts of the situation while others want to know people better before doing business. Interactions in "specific" cultures between people are highly purposeful and well-defined. Specific individuals concentrate on hard facts, standards and contracts. In diffusely oriented cultures, all the relationship elements are related to each other. Dilemmas arising include stressing facts or relationships, preference of data or concepts and bottom line or general goodwill. For example, in USA, the culture is more specific compared to UK which is more of a diffusely oriented culture (Trompenaars et al. 1999).

Affective versus Neutral (conceal or show emotions): In an affective culture people do not object to a display of emotions. Affective cultures may interpret the less explicit signals of a neutral culture as less important. In a neutral culture, it is incorrect to express feelings overtly. Neutral cultures may think the louder signals of an affective culture too excited, and over-emotional. In neutral cultures, showing excess emotions may erode the power to interest people. Dilemmas arising include detached or enthusiastic, long pauses or frequent interruptions and professional or engaged dialogues. For example, in USA compared to East Asia, the culture tends more towards being affective (Trompenaars et al. 1999).

Inner-directed versus Outer-directed: This factor explains the difference in perception as to whether people control environment or vice versa. The way people relate to their environment is linked to how they control their own lives and destiny. Internalistic people see nature as a complex machine which can be controlled with the right expertise. They do not believe in luck or predestination. Externalistic people see mankind as one of nature's forces, so they should operate in harmony with the environment. They do not believe that they can shape their own destiny. Dilemmas arising include driven by conscience or response to outside influence and creation of one's own strategy or diffuse with others (Trompenaars et al. 1999).

Sequential versus Synchronic Time: This factor describes if things are done one after the other or all together. Every culture has developed its own response to time. In a sequential approach, time moves forward in a straight line with one thing done at a time. Time commitments are a must and plans are rigid. In a synchronism approach, time moves round in cycles, with people doing several things at a time. Time is flexible and plans are easily changed to satisfactory complete interactions. Promptness depends on the type of relationship (Trompenaars et al. 1999). For example, British, Americans and Germans are considered to be sequential versus Asians, Latin Americans and Arabs which are more synchronic. If those two cultures work together in projects, significant problems may arise (Kivrak et al. 2008).

DISPUTE RESOLUTION METHODS AND CULTURE DIMENSIONS

Better understandings of different cultures help prevent and resolve disputes. In this paper, a model is developed suggesting the use of specific DRM depending on the culture characteristics/dimensions described above. Table 1 suggests a matrix to be followed on selecting various ADR methods during the contract formation stage depending on the characteristics of the culture involved. It can be seen from proposed matrix that each culture characteristic/dimension results in different choices of DRM.

Table 1: Culture Dimension-to-Dispute Resolution Method Matrix

Cultural Dimension	Litigation	Mediation/ Conciliation	Adjudication	DAB	Arbitration	Expert Determination
Universalism	x		x		x	x
Particularism		x		x		
Specific	x		x		x	x
Diffuse		x		x		
Affective		x	x	x	x	x
Neutral	x					
Inner-directed		x	x	x		x
Outer-directed	x				x	
Sequential		x	x	x		x
Synchronic	x				x	

In a culture characterized by universalism where law is considered logically more significant than human being relationships, litigation would likely be preferred over mediation/conciliation which may be contrary to a culture characterized by particularism. Extending this more, Figure 2 suggests a scale of preference of a specific DRM moving from a universalistic to particularistic culture.

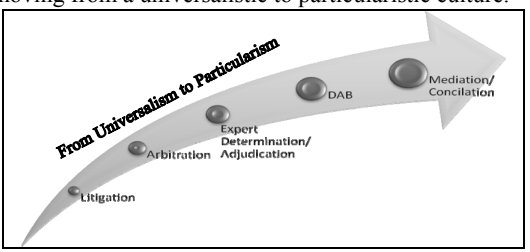


Figure 2: Scale of preference of dispute resolution methods moving from universalism to particularism

Specific and diffuse characteristics of a culture almost follow the same choice of DRM followed by universalism and particularism cultures. As both specific and universalism cultures concentrate on hard facts, standards and contracts while diffuse and particularism cultures are more relationship oriented. Since all DRM presented in the matrix above are of confidential private nature, litigation becomes the only DRM that would be preferred by an affective culture where being exposed to the public is acceptable versus a neutral culture where confidentiality is preferred.

Inner-directed cultures who believe nature can be controlled with the right expertise, will most likely be inclined towards DRM in which parties reach their own decisions rather than rely on a third party taking a binding decision for them. Accordingly, such cultures would prefer mediation/conciliation, adjudication and DAB. They may even go further to form their own hybrid DRM. Internalistic cultures, on the other side, would follow DRM where third parties take final binding decisions as litigation, arbitration and expert determination.

As for the time aspect described by the sequential versus synchronic cultures, sequential cultures appreciate the value of time, and thus would rather use DRM that are less time consuming such as mediation and adjudication. Synchronic cultures priority is the satisfactory completion and thus would prefer litigation or arbitration.

It is worth noting, however, that a culture is described by a mix of the dimensions mentioned earlier, and thus even though a cultural dimension may suggest a certain DRM, a second dimension may overshadow it recommending another DRM or suggesting hybrid DRM forms. Following the logic proposed in the matrix, the following testable prepositions of the relationship between the DRM and the characteristics of the culture studied are proposed:

P1: In a universalistic and/or specific culture, one of the following DRM will be chosen in the dispute resolution contract clause: litigation, adjudication, arbitration and/or expert determination.

P2: In a particularistic and/or diffuse culture, mediation/conciliation and/or DAB will be chosen in the dispute resolution contract clause.
P3: In an affective culture, one of the following DRM will be chosen in the dispute resolution contract clause: mediation/conciliation, adjudication, DAB and/or expert determination, while litigation will be chosen in a neutral culture.
P4: In an inner-directed and/or sequential culture, one of the following DRM will be chosen in the dispute resolution contract clause: mediation/conciliation, adjudication, DAB and/or expert determination.
P5: In an outer-directed and/or synchronic culture, litigation and/or arbitration will be chosen in the dispute resolution contract clause.

A practical example of the work proposed is the survey conducted by Chan et al. (2005), interviewing 40 DRM experts, which revealed that arbitration is the most popular DRM in China, followed by mediation, litigation, expert determination, adjudication, dispute, resolution adviser, dispute review board, mini-trial, and med-arb. It is seen how the ADR method with highest popularity –arbitration- involves formal processes yet overcomes litigation problems of dragging on for years with local law courts systems. Arbitration is formal enough to bind contracting parties in addition to being flexible enough to respect the Chinese nature of resolving dispute in private. The study also shows how mediation is the second most popular ADR method preferred in China mainly due to its private setting (Chan et al. 2005).

CONCLUSION & RECOMMENDATIONS FOR FUTURE RESEARCH

Construction disputes are an integral part of the construction process. An understanding of the various forms of DRM and their critical factors is of great value in handling disputes. Disputes frequently stop the project progress, and thus increase costs and evolve into major conflicts that affect the performance of the project (Kaklauskas et al. 2008). As parties of the dispute become aware of the advantages and disadvantages of one DRM over the other and their relation to the country they are operating in, they may use this knowledge to select the most suitable resolution method. Deciding on the appropriate DRM for international projects requires vigorous investigation due to the cross-cultural situation involved (Chan et al. 2003).

Since problems and disputes can occur in many different ways, times and locations, no one DRM fits all problems and disputes. Thus, this study becomes of great importance specifically to the international construction industry where factors affecting the dispute vary significantly depending on the host country. If the prepositions developed are supported by empirical verification using an international sample, it would be of great benefit to the construction companies operating overseas. It would help them negotiate the most adequate DRM to use when doing business. A case study comparing and analyzing the culture effect on choice of DRM in different countries would serve as an additional verification to the propositions presented in this paper. A content analysis of international contracts set up in different countries and DRM chosen would also offer a wider understanding of this study prepositions.

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GUIDELINES FOR A STANDARD PROJECT PARTNERING CONTRACT

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ABSTRACT

This paper calls for a project partnering contract that integrates the entire project team under a single multi-party document. A three-phase methodology study based on literature review, interviews with 21 senior industry practitioners, and subsequent associated analysis was utilized in order to meet the goal and objectives of this study. Under this research, a series of principles and guidelines were highlighted whereby the owner, contractor, suppliers, and manufacturers collaboratively work together under the same terms and conditions. Thus, the owner has to deal with only one integrated contract which substantially reduces the risk of gaps or overlaps between the different roles and creates duties of care between all team members. A partnering contract would never, on its own, change the culture and environment of the construction process and thus, strategic partnering should be promoted not only at project specific activities but at all organizational activities. It is perceived that that this research would hopefully lay basis and foster legal professionals towards drafting of the first standard U.S partnering contract, which should help in developing a more effective and efficient contracting environment.

KEYWORDS

Construction, Project Management, Supply Chain, Partnering, and Project Delivery.

INTRODUCTION

Partnering is the establishment of a team approach for mutual beneficial resolution for the ongoing difficulties and problems that might arise on a construction project. As quoted in Levin (1998), the associated general contractors (AGC) defines partnering as “attempt to establish working relationships among the parties through a mutually-developed formal strategy of commitment and communications. It also attempts to create an environment where trust and teamwork prevent disputes, foster a cooperative bond to everyone’s benefit, and facilitate the completion of a successful

project". Partnering was used in the projects carried out by the US Army Corps of Engineers since the 80s of the twentieth century (Harmon 2003).

Partnering could provide a substitute to the undesirable known pattern of the construction industry where each party solely think of his own interest at the expense of other parties and the project itself (Cheng and Li 2004). Previous research highlighted the key success characteristics of any partnering relationship to include trust, team working, no blame culture, transparency in relation to costs, risk allocation and sharing; integrated delivery teams involved from the earliest stage of the project, long term relationships, and continuous improvement based on performance measurements (Lynn and Hancher 1990, Brown 1994, Larson 1995, Ellison and Miller 1995, Conley and Gregory 1999, Lazar 2000, Cheng and Li 2002, and Anvuur and Kumaraswamy 2007).

A list of possible challenges to successful partnering might include: (1) delays in team formation which result in losing the added benefits of early involvement of contractors, suppliers, and manufactures in the construction process; (2) lack of genuine commitment on the part of any partnering team member which results in an atmosphere of suspicion and uncertainty where ideas are not shared and problems are not brought to other team members' attention; (3) failure to attain documented mutual understanding in the work environment which results in wrong interpretation, missed deadlines, and wasted resources; (4) lack of clarity and openness in treatment of cost of risk, profit, and joint risk management which result in undermining the whole essence of the partnered approach; and (5) failure to align partnering agreements with individual contractual relationships/processes whereby the contracting parties will revert to their contracts at the first sign of trouble to only protect corporate self-interest (Harback et al 1994, Bates 1994, Puddicombe 1997, Lazar 1997, Brooke and Litwin 1997, Chan et al 2003, Mosey 2001, and Tang et al 2006)

Contracts reflecting traditional procurement patterns are generally unsuitable for partnering because they promote hierarchical levels of contracting and fragmentation and do not allow for integrated delivery (Grajek et al 2000 and Mosey 2001). Thus, a partnering contract must create a regime in which risk is shared as opposed to simply allocated (Tang et al 2006). Allocating risk, no matter how carefully done, does not prevent the unwanted protective and defensive attitudes in the construction industry. Accordingly, in an integrated team, while the management of the risk should be allocated amongst the team to whoever is best placed to manage it; the risk itself should be properly and fairly shared (Crane et al 1997 and Crane et al 1999).

OBJECTIVES

This paper aims to set guidelines for a single multi-party project partnering contract whereby the owner, contractor, suppliers, and manufacturers collaboratively work together under the same terms and conditions. Thus, the owner has to deal with only one integrated contract which substantially reduces the risk of gaps or overlaps between the different roles and creates duties of care between all team members. It is perceived that that this research would hopefully lay basis and foster legal professionals towards drafting of the first standard U.S partnering contract, which should help in developing a more effective and efficient contracting environment.

METHODOLOGY

A three-phase methodology was utilized in order to meet the goal and objectives of this study. First, the author carried out literature review of the reasons behind success and/or failure of partnering arrangements in construction projects. Second, the author conducted structured survey about the needed requirements to promote the partnering concept in the construction industry through a standard contract. Third, the output of phases one and two was analyzed to put hands on the basic principles for establishment of a standard partnering contract that integrates the entire project team under a single multi-party contract and covers the construction processes.

Structured Survey

In order to carry out phase two of the aforementioned methodology, an industry survey was tailored to assess the opinions and beliefs of construction professionals in connection with the needed requirements to promote the partnering concept in the construction industry through a standard contract. The survey comprised two sections. The first section embraced five demographic queries regarding the respondent's profession, years of experience, and prior partnering industry practice. Section two comprised twelve questions that were formulated based on the revised literature, the government/industry review of procurement and contractual arrangements in the UK construction industry (Latham 1994), and the British standard partnering contract (Mosey 2001). While question one featured a five point likert-scale, the other eleven questions were structured as open-answer questions to provide the respondent with more room to highlight the reasoning of his logic, which provides more in-depth analysis of the survey results (Wackerly et al 2002). The survey was either completed by the respondent and sent back to the author through e-mail and mail communications or filled by the author during phone calls and personal interviews with the respondent

It is worth mentioning that counting the respondent's answers on section two required answers on section one that proves: (1) at least 15 years of experience in the construction industry and (2) at least one partnering practice on a medium/large scale project either domestically or internationally.

The survey was carried out between October-December 2008. Initially the survey was sent to 37 industry professionals through e-mails where 2 follow-up e-mails were sent afterwards at 2 week intervals. A complete response was received from 29 respondents representing 78.3% of the targeted professionals through e-mail, phone call, or personal interview. However, 8 responses were disregarded for insufficient industry experience or partnering practice. The minimum acceptable size to represent the population was calculated using the empirical method defined by Wackerly et al (2002) where:

$$\text{Sample Size (n)} = [\{(4) * (\text{Range of Population} / 4)^{2}\} / \{25\}] \quad (1)$$

In this regard, the range of population was determined to be equal to 37 and thus, the minimum sample size is calculated as 14. Accordingly, it is statistically acceptable to utilize the received 21 responses as the basis for this study. The 21 respondents covered 5 professions that are in direct relation with the matter of construction project management where 42.8% are contractors, 33.3% are project

managers/architects/engineers, 9.5% are owners, 9.5% are arbitrators/lawyers, and 4.9% are college professors. Also, 80.9% had experience of 25 years or more and 19.1% had experience between 15-25 years. Lastly, all respondents had participated or witnessed a partnering activity in a medium/large scale construction project either domestically or internationally.

RESULTS AND ANALYSIS

Based on the carried out survey as well as the associated literature, it is perceived that the success of a standard project partnering contract is pillared on a set of interconnected guidelines that should be borne in mind by industry practitioners and associated legal drafters.

Project Environment

100% of the respondents emphasized that an effective partnering contract should prioritize the project environment. Successful projects, and in particular successful partnered projects, are heavily dependent on relationships established between team members (Thompson et al 1999). The obligations on the partnering team members are to work together and individually in sense that ensures that creation of a partnering team does not affect the obligations of each individual team member to fulfill its agreed role and responsibilities. All contract clauses should state clearly the values of trust, fairness, and mutual co-operation within the scope of each party's agreed role, responsibilities, and expertise (Eom et al 2008). Thus, the partnering contract should describe a performance task force that is composed of individuals representing all core partnering team members who are tasked with reviewing and stimulating the progress of the project. Though the partnering team nominate the members of this task force, the team should stay responsible for ensuring that the task force perform its agreed and required functions with due diligence. It is essential that this task force is an effective working body that fosters communication on site and can even meet at short notice if required. In this regard, this task force should operate: (1) as a brake on unilateral decisions such as terminations; (2) as the recipient of early warnings from any partnering team member; (3) as an objective assessor of key performance indicators; (4) as an impartial review body in the event of disagreements; and (5) as one level in the problem-solving and dispute resolution procedure (Thompson et al 1999). Moreover, and in order to promote collaboration environment between partnering members, the decisions of the task force in all of the aforementioned matters should be by consensus rather than majority vote. **Project Manager**

76.2% of the respondents indicated that the partnering contract should promote the role of an independent project manager. The project manager should organize all meetings of the task force, the partnering team, and any partnering workshops. The project manager's role is not only administrative, he should also supervise value engineering, value management, and risk management exercises. The project manager should be the only party entitled to give instructions to the contractor, although the contractor has a right to object if any such instruction is contrary to the partnering documents or demonstrably not in the best interests of the project (Harmon 2003). The project manager also assesses valuations of the contractor's work, any

proposed changes that their effect on time and cost is not agreed between the owner and the contractor, and any claims submitted in accordance with the contract for additional time and money arising from events outside the contractor's control. Lastly, the project manager should confirm project completion and rectification of defects. The most important point is that the contract should expressly clarify any restrictions on the authority of the project manager, or otherwise this authority will be completely unrestricted. In all cases, it should be noted that any discretion of the project manager under the partnering contract must be exercised fairly and objectively between partnering team members (Anvuur and Kumaraswamy 2007).

Partnering Advisor

To promote the collaborative partnering environment, 90.5% of the respondents stressed that the standard contract should recognize the role of a partnering advisor. The partnering advisor should be available to provide partnering team members with advice and support in relation to their relationships and operation under the project. The duties of the partnering advisor could include documenting the progress of the partnering relationships through reviewing specialist contracts and drawing up any joining agreements, pre-possession agreements, and commencement agreements. Other expected responsibilities could include the provision of fair and constructive advice to the partnering process through attending meetings as the task force or partnering team members may consider appropriate and providing assistance in the solving of problems and the avoidance or resolution of disputes (Latham 1994). Realizing all these duties, the partnering advisor needs to be an individual with demonstrable experience in any suitable discipline that is right for the role required on the project (Brooke and Litwin 1997). It should be noted that the partnering contract should owe the duty of care and fees associated with the advisor to all partnering team members in order to establish credibility and reduce the need for second opinions (Lazar 2000). Also, the contract should prohibit the said advisor from representing an individual partnering team member in any project related disputers in order to avoid conflict of interests (Lynn and Hancher 1990).

Design process

71.4% of the respondents suggested that the partnering contract should lay basis for an integrated design process that addresses work activities prior and after commencement of work on site. This design process should recognize that the partnering team, including the contractor, is formed at the earliest opportunity so that they can look at alternative outline design solutions on a collaborative basis (Larson 1995). Under the said process, the duties of a lead designer and other associated design members are described clearly in a services schedule. This development setting is expected to encourage maximum contractor and specialists input (Thompson et al 1999). In this regard, value engineering exercises could be brought into that process at appropriate stages and that all designs will be tested regularly against the owner's budget for the project. It is noted that the responsibility for designs rests with the party who prepared them, and with those parties who contributed to them. Also, the contract should clearly assign responsibility for obtaining planning permission and other relevant approvals as well as provisions for

owner comments or approvals and the overriding time constraints for delivery of the project. It should be noted that these design guidelines should be open to any amendments required by the partnering team members or specific project conditions.

Partnering and Project Schedules

61.9% of the respondents highlighted that the proposed contract could recognize the issues of partnering and project schedules. The two schedules should be binding on all partnering team members. On one hand, the partnering schedule should govern all activities leading from signature of the project partnering and commencement agreements. This schedule should be closely tied to the aforementioned integrated design development process and associated consultant services schedule. Moreover, it should indicate periods of time identifying obstacles outside the control of partnering team members including grant of planning, site acquisition, availability of funding, and the like. It should be noted that while developing the partnering schedule, partnering team members need to be realistic about the time they require for their contributions to the partnered process (Glagola and Sheedy 2002). On the other hand, the project schedule timetable governs realization of the project after signature of the commencement agreement and should be firmed up to reflect the periods finally agreed for completion of the project. Also, the project schedule should state where any activity of the contractor is dependent on another partnering team member or if a project involves work in occupied properties or there are complex pre-conditions to particular activities, and provide for appropriate lead-in periods. It should be noted that the project schedule should not include method statements or other matters that are internal to the business operation of a particular partnering team member (Wilson et al 1995).

Suppliers and Manufacturers

100% of the respondents emphasized stressed that in order to promote the effectiveness of the partnering process, it is important that key suppliers and manufacturers are selected at the earliest possible opportunity. A standard partnering contract should provide a competitive selection processes to complete the supply chain needed under the contract proceedings. In this regard, the contractor will invite tenders from proposed specialist suppliers and manufacturers such that the project manager will critically evaluate these tenders on the basis of best value that is consistent with the objectives of the partnering team (Herback et al 1994). Moreover, it is crucial to develop a suitable specialist contract for supplies and manufacturers who will be part of the partnering team or not. This contract should recognize the interests of owners, contractors, and their subs in order not to inflate prices, with the cost increases passed directly on to the owner (Crowley and Karim 1995).

Prices and Profits

66.6% of the respondents emphasized that the partnering contract should identify at the outset the contractor's profit, central office overheads, site overheads, and the like. It should also highlight any payment agreed to be made for contractor's services prior to signature of the commencement agreement. Moreover, the contract should envisage an agreed maximum price at the time of signing the commencement agreement including firm prices for each specialist supplier or manufacturer wherever

possible, with any remaining risk contingencies closely analyzed by the partnering team. It should be noted that the agreed maximum price can be subject to variation to reflect agreed changes and claims arising from specified unforeseeable events (Lynn and Hancher 1990). On a further note, the partnering contract should specify profits to be on a lump sum basis rather than a percentage in order to avoid any vested interest in escalating costs (Grajek et al 2000). Accordingly, profit should be kept separate from central office and site overheads and should not increase as a result of invisible benefits such as trade discounts or bargains. On the other hand, profit could be increased as a result of agreed incentive payments.

Incentives

85.7% of the respondents suggested that the anticipated partnering contract should realize set of payment incentives that promote and enforce the collaborative attitude between team members (Tang et al 2006). First, it is important to recognize the potential for shared savings against expected capital expenditure and shared added value added in terms of matters such as improved quality, lower maintenance costs, and longer life expectancy. In this regard, the partnering contract should indentify a formula between partnering team members for the division of savings achieved while: (1) making sure that those who are paid a fee for their work do not hold back their best ideas in the hope of gaining an additional benefit through shared savings; (2) shared savings are only calculated against a robust figure rather than an early budget estimate; and (3) ascertaining whether the added value can be guaranteed sufficiently for the partnering team member who made the proposal to justify receiving their additional reward (Tang et al 2006). Second, the partnering contract should realize an incentive that bridges between payment and target key performance indicators. Liquidated damages deal with this issue but without a corresponding bonus for early completion. In this regard, it is unlikely that these damages will be seen as a motivator of best practice, it is more likely that they will encourage pre-emptive claims and a defensive attitude by a contractor seeking to ensure that they are not levied (Wilson et al 1995 and Tang et al 2006). Another payment related incentive could be calculated according to the achievement of zero or minimum defects at project completion or during the defects liability period, or to the achievement of zero or minimum accidents on site (Bates 1994). Third, the partnering contract should include the partnering team in the operation of the build facility through engagement in the ongoing repairs, maintenance, and a range of related services. This team's vested interest in minimum operating costs is a powerful incentive for good quality procurement. Fourth, the contract should open windows for further partnering in prospective projects on the basis of strategic alliances (Tang et al 2006).

Changes

100% of the respondents asserted that like any standard form of contract, the partnering contract should set a clear mechanism for management of changes for the mutual benefit of the partnering team. Any partnering member can propose a change to the owner and it is then for the owner to implement the formal change procedure. The contractor can object to a change that it considers contrary to the partnering

documents or otherwise damaging to the project, but otherwise must put forward in advance an evaluation as to the cost and time implications of the proposed change (Harmon 2003). The owner can then determine whether it wishes to proceed with the change and whether or not it agrees with the contractor's evaluation. On small changes, the owner can override the requirement for an advance cost and time evaluation if it is confident that these issues can be dealt with after the event (Harmon 2003). Any disputed evaluation would pass firstly to the project manager to be considered on a fair and reasonable basis and then, if the parties cannot reach agreement through the hierarchical dispute resolution procedures (Levin 1998).

Problems and Disputes

100% of the respondents indicated that the partnering contract should provide a structured approach to problem solving and dispute resolution with the intention of keeping problems and disputes under the control of partnering team members. This is attained through the use of a problem solving hierarchy whereby individuals within partnering team members are given a limited period of time to resolve any problem with their opposite numbers in other partnering team members (Cheng and Li 2002). If they fail to do so, then automatically the problem is passed up the line to the next most senior named individuals in each organization. If a problem is not solved by this means, it is referred to the task force with a view to achieving an agreed resolution influenced by those task force members not directly involved in the problem itself. If the task force fails to achieve a consensus resolution, then the contract provide for conciliation, mediation, or some other form of alternative dispute resolution that can be facilitated by the partnering advisor. All of these mechanisms should be, of course, without prejudice to the partnering team members' statutory right to refer a dispute to arbitration or litigation (Puddicombe 1997 and Harmon 2003).

CONCLUSIONS AND RECOMMENDATIONS

A modern project partnering construction contract should include: (1) duties of fairness, teamwork, mutual cooperation and shared financial motivation; (2) clearly defined roles and duties in a fully integrated document; (3) agreed allocation of risks for each project with changes priced in advance; (4) flexibility as to payments with clear payment entitlements; incentives for exceptional performance; and (5) mechanisms for avoidance of conflict and speedy dispute resolution. Also, partnering contracts should promote effective risk management strategy through: (1) identifying risks and their likely cost; if possible, (2) eliminating or reducing risks and their costs; (3) insuring risks where affordable and appropriate; and (4) sharing or apportioning risks according to which partnering team member or members are most able to manage them.

In order to materialize an efficient and effective partnering environment, training should be materialized in order to promote culture change and develop long term strategy. Partnering training should commence with senior managers, followed by providing training for staff engineers and estimators, internal and external auditors, corporate finance, and other associated departments. This should facilitate a common understanding of proposed partnering strategies for providing real support and pro-active involvement in reducing bureaucracy and finding innovative ways of

procurement in the firm. Subsequently, it is advisable each firm initiate contacts with its potential partnering team members for prospective future projects. These communications should remove perceived commercial sensitivities by allowing each member the opportunity to develop its own strategy for the introduction of strategic partnering, according to the individual company culture and policies, and negotiate them afterwards with other potential members in a calm environment that emphasizes sharing experiences and resolution of problems without losing any commercial edge. Subsequently, a partnering team could be formulated between associated members on the aforementioned basis of the foreseen standard partnering contract.

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Implementation of a Decision Support System for Commercial Evaluation and Selection of Equipment Suppliers

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Abstract

This paper describes the results of an implementation of a decision support system to aid analysis and selection of engineered equipment suppliers in the early stages of capital projects. Procurement of equipment is a complex process which requires the evaluation of multiple suppliers against project targets. This analysis is usually performed manually, is time consuming, and certain tradeoffs may be overlooked. A technique to support procurement decisions with complex tradeoffs among key variables has been missing. The results of this research take significant steps to fill this gap. The system integrates historical data, market assessment, and supplier bid information to support evaluation of tradeoffs among cost, schedule, quality, shop load, and transportation variables. Validation was performed with two recent selection cases. Data from commercial bid tabs was imported into the system and results were presented and compared against three EPC firms' final recommendations. The decision support system provides rapid evaluation and comparison of several supply alternatives, thereby improving the consistency and quality of commercial analysis in the early phases of capital projects.

1. Introduction

Major equipment ties up a large proportion of construction costs, has long lead times, and is usually associated with the acquisition of complex or specialized technology (CII 1999). Major equipment is engineered and fabricated specifically for the project (e.g., tanks, heat exchangers, pumps). Engineering, manufacturing and delivery of these items are very uncertain and may disrupt construction schedule. As a consequence, procurement planning for engineered equipment is critical and needs to start during the early stages of capital projects, mainly Front End Loading and conceptual design.

Our research was motivated by the following issues: 1) Procurement process complexity and lack of tools: Procurement of long lead engineered equipment is a

complex process which requires the evaluation of several suppliers as well as schedule and budget targets. This analysis is usually performed manually, is time consuming, and allows that certain tradeoffs may be overlooked. Therefore, there is a need to develop computer-based tools to support and speed up the work of procurement managers in better understanding the tradeoffs involved in the selection of engineered equipment suppliers. 2) Supply chain constraints: mounting global demand for oil and gas, energy, and infrastructure has stressed the supply chain over the last few years, and various constraints need to be taken into account when planning the execution of projects. Suppliers were out of shop capacity, and there was also a capacity shortage to transport materials around the globe, especially ocean freight and rail transportation. Substantial increases in lead times and price escalation were a direct consequence of this scenario. Procurement has clearly become a more complex process and commitments need to be done much earlier in the capital project lifecycle. 3) Market data is not electronically integrated to support procurement decision making: To survive in such a complex and dynamic scenario, firms need to identify sourcing alternatives, reduce supply risks and improve scheduling and cost performance. Knowledge of market conditions is essential to supporting early planning and supplier selection decisions; however, getting, keeping, and analyzing updated market data is hard. Most firms executing industrial projects have either rich data on market forecasting information and/or historical data on supplier performance. However, available data is commonly found in different paper files archived inside procurement managers' drawers or stored in firms' information systems. As a result, data is currently not integrated to support analysis and decision making.

This paper describes the results of an implementation of a decision support system to aid analysis and selection of engineered equipment suppliers in the early stages of capital projects. First, we present a brief literature review on decision aid methods for supplier selection in construction. Second, we describe the current supplier selection process implemented in the studied EPC firms. From this description, we identify opportunities for implementation of our decision support system. Second, we discuss the software which was tested in two case studies. Finally, we present the findings of this implementation and our conclusions.

2. Decision Aid Methods for Supplier Selection

Decision aid methods are very useful tools used to support managers making complicated selection decisions. There are a number of techniques and software products that have been developed in operations research area that can also aid solving selection problems in construction. Analytic Hierarchy Process (AHP) and Multi-attribute Utility Theory (MAUT) are examples of common techniques that have been implemented in construction to solve various types of problems (see Elmisalami et al. 2006, Shapira and Goldenberg 2005, Skibniewski and Chao 1992). However, very little has been published on methods to aid managers making selection decisions on suppliers or supply chain configurations. Jiang et al. (2005) have shown the potential use of AHP to support supply chain selection. These authors proposed a framework based on the Analytic Hierarchy Process for ranking different supply chain configurations.

Bernold and Treseler (1991) presented a vendor analysis system that is based on the best-buy concept. A vendor-rating approach to secure the best buy in construction was proposed and analyzed. According to these authors, benefits of the formal vendor-analysis and rating system include the standardization of evaluation criteria, which provided consistency and transparency. The best buy approach allows users to consider and weight their preferences; however, it does not provide the capability to identify the optimal vendor based on project and procurement targets.

The decision support system proposed in this study has to provide an objective and rapid method for tradeoff analysis to compare alternatives against real targets, and to support analysis of quantitative criteria. AHP and MAUT do not support these purposes, especially the first one. The Aspiration Interactive Method (AIM), a technique used in the operations research area, on the other hand, provides useful information to help decision makers learn about the tradeoffs among criteria considered in the selection of alternatives from large sets of available choices (Lotfi et al. 1992). The idea is to adjust aspiration levels of the objectives -which are used as targets for decision makers – and obtain the feedback regarding the feasibility of the aspiration levels. As these aspirations are adjusted, the nearest solution changes. Weights are generated by the aspiration levels and the nearest solution is determined by calculating a score for each alternative and ranking them according to the attainment levels against the set of aspiration levels. Azambuja et al. (2009) provided a comprehensive example for the selection of pump suppliers. In the next section, we explain the current selection process implemented in the studied EPC firms.

3. Mapping the Selection Process of Engineered Equipment Suppliers

The three EPCs that participated in the validation phase described a very similar – if not the same – process to select engineered equipment suppliers. Figure 1 illustrates the overall process they use to select these suppliers.

During late front end loading phase (FEL), firms usually prepare an approved suppliers list for the project. This list includes suppliers from both EPC and Owner individual lists. These companies look at their previous purchase orders and the current market for nontraditional suppliers which fulfill their minimum requirements. Managers commented that an initial list with 80 suppliers is not uncommon. Once the list is evaluated, EPCs issue request for inquiries to several suppliers (approximately 20 to 30 suppliers). Suppliers then send information regarding expected lead times, costs, specifications, and interest in participate in the bidding phase. After gathering all this information, EPCs prepare a short list of suppliers which will be requested to send a formal quotation for evaluation (5 to 10 suppliers). According to procurement managers, coming up with a short list of suppliers is a very complex task because of the number of alternatives available at this point of the process.

Finally, after receiving the quotes, EPCs prepare technical and commercial bid tabs for analyzing and recommending the supplier. Technical bid tab is assessed and validated by the engineering department to ensure suppliers are technically capable of producing equipment according to the specifications. The commercial bid tab, which includes data on lead times, costs, and previous performance, is prepared and analyzed together with technical recommendations by the procurement department.

Typically, commercial bid tabs are presented in spreadsheet format. A final recommendation is based upon analysis of both tabs.

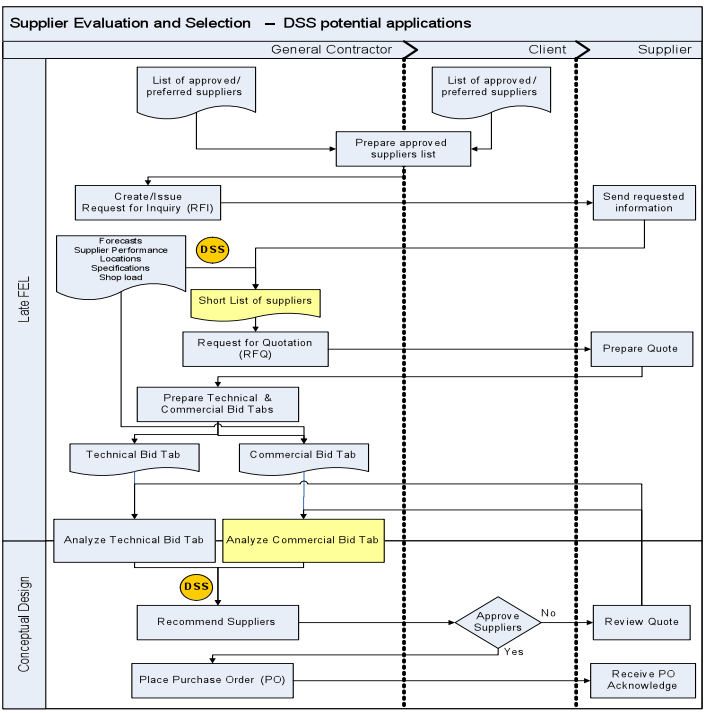


Figure 1: Supplier selection process

According to the studied firms, there are two main potential uses for the decision support software: 1) Help EPCs narrowing down the approved suppliers list in order to come up with an appropriate short list. 2) Support commercial bid tab analysis before final supplier recommendation.

Figure 1 also illustrates where the system fits in the overall supplier selection process. The potential application and implementation for achieving those two purposes depends upon how EPC firms organize their information. EPC-1 for example can use the system for both purposes since information is often available and organized to support analysis during the preparation of the short list. EPC-2 and EPC-3 still need to organize their supplier information – which is available in their computer systems – before thinking about using the tool to identifying which suppliers should be shortlisted.

All EPCs can use the system to analyze commercial bid tabs. According to EPC-1, the software can help procurement managers identifying an optimal or realistic decision based on existing data. EPC-2 and EPC-3 also commented that the

software fits very well this purpose. EPC-2 emphasized the support offered for analyzing tradeoffs of commercial bid tabs and justifying their final supplier recommendation to clients. Basically, this company needs a tool to communicate the reasons why they selected a certain supplier out of the long list of suppliers. Likewise, EPC-3 highlighted that the software can support intelligent analysis of current data in the bid tabs. The procurement director also recognized the use for short listing based on analysis of their historical data. He said the company wants to move towards this direction, however they are not ready yet.

The two case studies illustrate the kind of support our software can provide for evaluation of current data, which are included in commercial bid tabs, aiding procurement managers justifying their final recommendation.

4. Decision Support System

A decision support system which integrates market data (forecasting, current bid or historical) on supplier performance with procurement targets to aid equipment supplier selection has been developed. The application has been implemented in Visual C#.NET as a Windows Form Project, in the form of simple and intuitive forms, with Microsoft Access as the back-end database. The database stores information about equipment, suppliers, logistics partners, and fabrication and transportation information (e.g. lead times, costs, shop load utilization, fabrication, shipment, and quality performance).

Users need to choose one type of equipment, a project geographic location, and input schedule milestones and target costs associated with the equipment and its transportation. Users also need to input their desired supplier performance attributes, such as shop load utilization, on time fabrication, on time shipment, and quality. Based on users' inputs, the database is queried to find all the suppliers who match users' requirements. Figure 2 shows a screen capturing the valid suppliers.

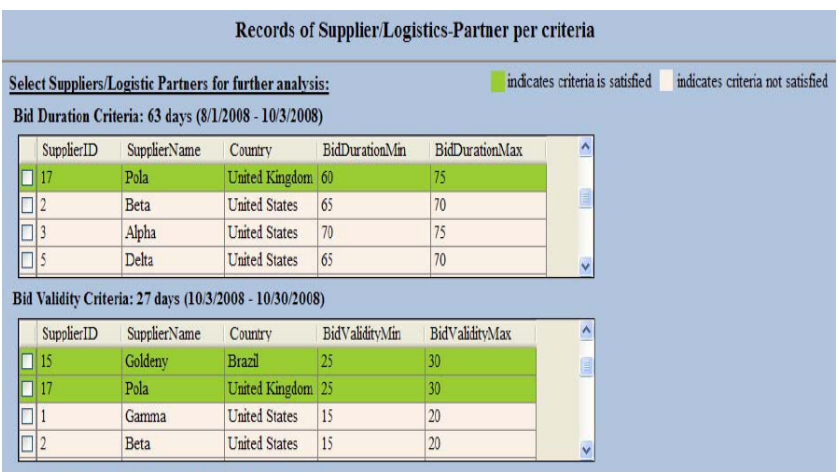


Figure 2: Evaluation of valid suppliers

Even though it was considered very useful, this list of alternatives still did not provide support for ranking and selecting valid suppliers. Identification of best suppliers is still complex given the large amount of information presented to managers. It was needed to develop a method to guide users in the identification of the nearest supply alternatives based on their desired targets. This was done via the AIM method. AIM uses the users' inputs and a set of optimization objectives to intelligently assign weights to different parameters used in the selection processes. The result of the method is represented as a graph and values for different criteria are shown in a data table which shows how each parameter affects a supplier rank (see Figure 4). This component of the application aids managers in quickly ranking and evaluating a set of suppliers based on the values of their inputs. Moreover, managers can identify the ranking of their preferred suppliers against the other available suppliers. Finally, they can rapidly perform what-if analysis based on real data stored in the database. A change in the input targets also triggers different solutions, and different suppliers might become better options according to these new set of targets. Results of AIM analyses are automatically generated by the system. Users just need to inform their targets to generate different scenarios and analyze tradeoffs.

5. Implementation Findings

This section describe the results obtained using the software to evaluate two actual selection cases. The first case details the selection of two fired heaters. The second case reports the selection of a compressor for the same project. Data from commercial bid tabs was imported into the system and results were presented and compared against three EPC firms' final recommendations. In this section we describe in details the selection of fired heaters. We start with an overview of the scenario and the results suggested by the software. After reporting this information, we compare the suppliers suggested by the software against the ones actually awarded by the EPC firm. All EPCs recommended their preferred suppliers based on the same information that was provided via commercial bid tab.

After assessing the commercial bid tab, we were able to build the case scenario for inclusion in the software. Targets or aspirations for this case are illustrated in figure 3. Tables 1 and 2 summarize bidders' data which was stored in the database. Table 1 presents information on material and fabrication while table 2 lists information associated with transportation criteria.



Figure 3: Aspiration levels for selection of fired heaters

Table 1: Bidders information on Material/Fabrication

MATERIAL/FAB	Bidder 1	Bidder 2	Bidder 3
Location	USA	Asia	USA
Bid Validity (days)	30	30	30
Material Costs (USD)	4,331,050	3,843,541	4,303,541
Material Escalation (%)	+ 2 at PO	0	0
Fabrication lead time (weeks)	70-76	61-67	71-77
Shop load utilization (%)	80	85	75
On time fabrication (%)	85	92	96
Quality	3	2	1

Table 2: Bidders information on transportation

TRANSPORTATION	Bidder 1	Bidder 2	Bidder 3
Transportation mode	Inland Freight (Truck or Barge)	Ocean	Inland Freight (Truck or Barge)
Transportation Costs (USD)	73,000	512,000	226,500
Escalation (%)	0	0	0
Transit time (weeks)	2-4	3-5	1-3
On time Shipment (%)	90	85	80

Figure 4 illustrates the overall ranking of bidders for both material/fabrication criteria (top of the figure) and transportation criteria (bottom of the figure). These results indicate that Bidder 3 is ranked the top supplier for material/fabrication criteria (AIM =1), followed by Bidder 2 (0.621), and Bidder 1 (0.245). Bidder 3 however is the worst ranked supplier for transportation (0.333). Bidder 1 is the supplier with best overall score for transportation (1). This figure allows a first assessment of tradeoffs involved in the decision.



Figure 4: Overall AIM ranking – Fired Heaters

Managers can also rapidly assess how each bidder performs in each criterion. Figure 5 illustrates other specific tradeoffs the software provides to users.

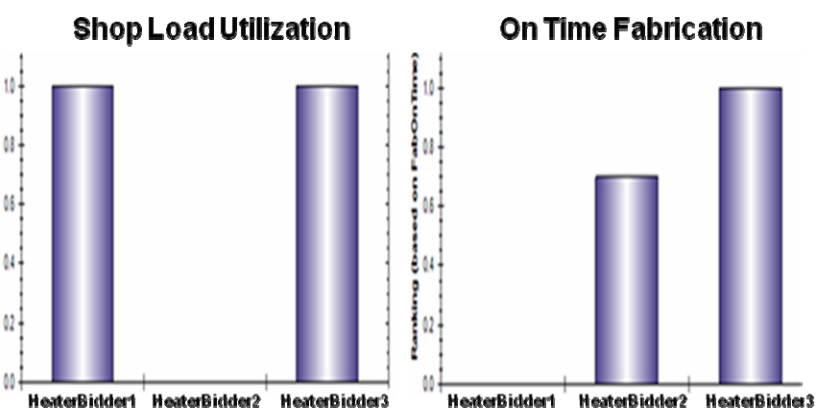


Figure 5: Material/Fabrication tradeoffs – Fired Heaters

Procurement managers were very satisfied with the tradeoff analysis they were able to visualize. The option for separating material/fabrication from transportation was based on feedback gathered in the early phases of the software development.

6. Comparison of Actual Recommendations vs. Software Results

Table 3 describes the solutions suggested by the software and each EPC. The main reasons for the recommendation are also summarized. This information allows the comparison of software solutions against actual solutions recommended in the real cases.

EPC-1 is the firm which provided the cases and served as a baseline for comparison. EPC-2 and EPC-3 selected the bidders after evaluation of the commercial bid tab summary data and description of scenarios provided by the researcher during the validation meetings. EPC-2 and EPC-3 selected bidder 3 for case 1 (Heaters) and bidder 2 for case 2 (compressor). In the first case, managers selected a domestic supplier because of their negative experiences with international suppliers (costs of inspection, expediting, coordination meetings) and also because bidder 3 presents the best quality rating. In the second case, they evaluated bidder 2 and mentioned that material plus transportation costs were good. Therefore, decision was cost driven.

Table 3: Supplier recommendation - DSS vs. EPCs

	Case 1 Fired Heaters	**Reasons for selection - Heaters**	**Case 2 Compressor**	**Reasons for selection - Compressor**
DSS	Bidder 3	AIM Ranking	Bidder 2	AIM Ranking
EPC 1	Bidder 1	Location (logistics costs), Warranty, technical capabilities	Bidder 2	Secure fabrication, discount, keep schedule, same project team
EPC 2 and EPC 3	Bidder 3	Location (coordination and logistics costs), Quality	Bidder 2	Material + Logistics costs

In summary, managers clearly ignored tradeoff analysis of the available parameters in their actual selection. Even though there was some choice disagreements in the heaters case, managers appreciated the system and highlighted that it appears to fit in their selection process. They also commented that graphic visualization of tradeoffs provides more transparency to the data of their bid tabs, enabling quick identification of potential awkward values that may be provided by bidders.

7. Conclusions

This research presents a systematic approach that can be used to assess and select equipment suppliers. A consistent, useful, and applicable tool to support procurement decisions has been missing. The results of this research take significant steps to fill this gap. A computer-based tool which integrates firms' data with the selection approach was implemented to demonstrate its applicability to two actual cases. The validation indicated that the approach was easily understood by the target audience and it adds value to the overall supplier selection process. All firms that participated in this research do not have objective methods to carry out this analysis and recommend their suppliers. AIM provides such capability and can play a significant role in the selection of equipment suppliers.

The decision support tool provides rapid evaluation and comparison of several supply alternatives, improving the quality of procurement plans, speeding up the time managers spend carrying out commercial analysis, and supporting recommendation of suppliers in the early phases of capital projects. We understand that technical assessment is very important and, in some cases, can guide the decision for the best supplier. However, technical analysis is responsibility of engineering staff. The target users of this system are experienced procurement managers who need to carry out commercial assessment of the suppliers before coming up with their final supplier recommendation. The system proposed in this research is very useful to support such purpose.

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Interaction of Processes and Phases in Project Scheduling Using BIM for A/E/C/FM Integration

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Abstract: Current construction practice is very fragmented and is built upon a culture of adversarial roles; the different processes are carried out by various stakeholders who are not contractually responsible to each other and who many times are brought into the project after all major decisions have been made. The information exchange between the different parties is very limited. Building Information Modeling (BIM) is a tool that can foster project integration on different levels, because it can facilitate information exchange, access to real time information, and information gathering among project members. One specific application that can demonstrate how BIM can be used to integrate the team, the processes and the project phases is the use of BIM for the scheduling process. This paper defines Architecture, Engineering, Construction, and Facility Management (A/E/C/FM) integration, describes how BIM can enable project integration using the specific example of scheduling throughout the project using a preliminary model that leverages the capabilities of BIM, not only for 4D visualization, but also to generate and manage the schedule.

Keywords: AEC+FM Integration, BIM, Scheduling, Project Management.

Introduction

The construction industry has several characteristics that are preventing it from achieving desired levels of performance in terms of productivity, quality, safety, cost, schedule, sustainability and so on. The process and the supply chain are very fragmented; the project is divided into separate phases which usually are performed by different teams. Even within each phase the different activities are performed by different companies which are not contractually responsible to each other. Within these fragmented teams the communication is very poor, and the exchange of

information is kept at minimum; therefore, the project information is dispersed, is not accurate and sometimes is not current (O'Connor 2009, Zaghloul and Hartman 2003, Tang 2001, Sullivan 2009, Skal 2005, Rooney 2006). The AEC+FM integration could help on overcoming most of those issues that are preventing the industry to achieve the desired standards. According to Eastman (2008) BIM is a process that fosters integration, because it allows the entire team to work under a common model, therefore the information exchange is smoother and the information is very current. In addition BIM is based on parametric objects that allow not only storing geometry information, but also storing other parameters or attributes of the object.

The schedule is regarded as the transition between the design and the actual construction of the project. It is a very important tool that plays different roles at the different stages of the project. In addition most of the times it is developed by different team players. Many times the preliminary schedule developed during the planning phase is not reflected on the construction schedule and is not finally accomplished at the end, therefore some projects are nor on time and in budget. The scheduling process should be an integrated continuous process, which first accurately helps on the definition of the duration of the process and subsequently in the feasibility of it; that later lead the procurement and construction process; and that finally serve as a control mechanism to develop a successful project.

This paper presents a brief background on BIM and the use of BIM for scheduling, gives a framework of what AEC+FM integration is, proposes an integrated approach to scheduling using BIM, and finally presents some conclusions.

BIM and Scheduling

The concept underling BIM emerged in the early 1970's when the industry started to use intelligent CAD systems (Eastman 2008), and it has evolved ever since. There are different definitions of BIM; Eastman (2008) defines it as process that uses parametric objects to generate a model, those that are defined by the rules embedded in them. According to Smith and Edgar (2008) BIM is a "digital representation of physical and functional characteristics of a facility". It is a model that integrates all necessary facility graphic and non-graphic information. According to Kymmell (2008) BIM is a project and process simulation, where simulation is a single coordinated and integrated entity that contains all the information required to plan and build a project. BIM simulates the project in a virtual environment that allows making adjustments to the project before it is constructed.

A BIM consists of 3D models of components with attached required information, and links among the models, components and information. Some of the information contained in the model is physical, about the nature of the object including dimensions, localization with relation to other objects. Other information is parametric information about the object that makes it an intelligent model. In addition BIM allows the creation of a composite model that collects various models of different components of the building; the composite model shows the total project for visualization and coordination (Eastman et al. 2008; Kymmell 2008).

The use of BIM for scheduling purposes has been addressed by various researchers and software development companies from different perspectives. The different approaches found in academic and in industry driven literature have been

divided in two main groups: first the use of the model to generate the schedule as part of BIM; and the link of external information to BIM for visualization.

Use of the model to generate the schedule as part of BIM

Tulke and Hanff (2007) proposed a model to calculate task duration using BIM. Then use task duration, objects and rules to generate the schedule. They state that duration could be directly supported by selecting quantities from the model, creating a bill of quantities that could be completed with manually added quantities, and using a productivity factor. The objects and the quantities are stored in a relational database. Using a standard query language the scheduler could select the quantities on task level. Based on BIM properties the scheduler could select the quantities that satisfy certain restrictions, and could store the selection query for a certain task of the schedule. Thus, the relationship between activities and the model is established creating a rule based linking. According to their model one software application creates the bill of quantities and other software application creates the schedule. The information from these applications and the rules are stored in the project database.

From the industry perspective there are software companies that are currently offering applications to generate and manage the schedule based on BIM. VICO Control technology creates a building model that encompasses geometry, location and activities related to each building element. In order to calculate the schedule or the estimate the model objects are linked to a recipe that contains the description of materials, labor and resources required for a specific building component, the recipe consists of one or more construction methods. The steps followed for generating the schedule are: first is to connect the geometric data to the recipe, next is the semiautomatic generation of the schedule based on the links of the information in the recipe and the model components, and then the creation of zones that describe where the tasks are to be performed. This results in a work breakdown structure that contains the quantitative information of the project by zone, which is the base for the schedule. Task durations are calculated from quantities from the methods and resources, then are assigned to a work breakdown structure. The 3D elements in the work breakdown structure are connected to the tasks and cost resulting in a 5D model used for simulation and analysis. The main problem associated to VICO Control is that the model has to be created on the same software; therefore it is not using the design model (Kymmell 2008).

Link of the model to an external schedule for visualization

Currently, most of the scheduling applications found in the industry associated to BIM, are tools and applications for 4D representation and visualization. External schedule programs are linked in one direction, therefore it is possible to change the data from the scheduling software in the model, but it is not possible to update the schedule with model changes, therefore the schedule has to be updated separately (Kymmell 2008). 4D is a mechanism to digitally link 3D building elements with time information from a construction schedule. One important advantage is the visualization of different construction sequences to determine the optimal one or to determine the most appropriate layout. 4D can be used for technical presentations to

communicate how design and construction are going to be phased, or to review the construction progress (Kymmell 2008; Rundell and Stow 2007; Wooley 2007).

There are two different approaches to 4D, the first one is automated solutions with dynamically linked schedule elements and the second is a manual solution with architectural visualization tools that manually link elements to timeframes. The only viable way of broadly implementing this technology in the construction industry is by using automated relational databases that integrate existing design files and construction schedules. BIM can be used to associate any resource database with elements in the 3D model. In addition information embedded in the model such as productive content can be linked to a resource database, and quantities can be extracted from the model (Rundell and Stow 2007; Wooley 2007).

AEC+FM Integration

Though an extensive literature review, the authors found that there are three main approaches to AEC+FM integration. Some authors suggest that the main factors that influence integration of the project are open information exchange, access to current information in a timely manner, and improved communication. From this perspective a tool such as BIM could help to improve the performance of the project (Eastman 2008, Schwegler et al 2001, Sun and Aouad 2000, Tang 2001, Sullivan 2009). Other authors affirm that the integration of the project should be defined in terms the culture of the project and make an important emphasis on the team work relationships. From this perspective team building plays a major role (Tang 2001, Sullivan 2009, Rahman and Kumaraswamy 2004). Other authors state that the most important factors in project integration are related to risk allocation, reward structure and establishment of common goals. From this perspective the contracting and the project delivery method are essential (Tang 2001, Sakal 2005, Sullivan 2009, Rooney 2006, Rahman and Kumaraswamy 2004, Zaghloul and Hartman 2003, Matthews and Howell 2005).

In order to achieve truly project integration all of the factors mentioned above should be undertaken. It is necessary to assemble a team composed of the owner, architect, engineers, specialty consultants, general contractor, major subcontractors, major suppliers, users, and facility managers; early in the process. It is necessary that the team has well defined common goals, reflected on a fair reward structure and on a shared allocation of risk. In addition it is necessary that the team has an open constant communication, and that the complete information is always available to those members of the team who needed. The processes have to be continuous instead of fragmented, and the project tools should be used throughout the project.

These changes should be led to a large extent by the owner, because they should select the delivery system that will be used and should set the culture of the project. It is necessary to change the contracting and reward structure towards a structure that rewards the achievement of common goals in the best interest of the project, and not individual local optimization. These changes are not going to be possible while the team selection, contracting and reward are based on a design bid build (DBB) project delivery method. Because in DBB the selection criteria is based only on costs and the contract wording rewards only the individual performance and does not allow innovation. Moreover most team members come on board when major decisions have been made and most of their knowledge input has been lost.

The proposed system is based on the integration of several processes in order to generate the schedule of a project from a building information model and to allow the visualization of a 4D model. The main idea is that the schedule can be created directly from the project model, created by the design team in any BIM software that is based on IFC classes; therefore it will be a continuous tool that will be updated as the project is developed. Thus a more accurate schedule can be created starting at the schematic design phase and will evolve with the project. In addition there will be just one schedule throughout the project that will include the activities and the ideas of all the project members. The model should be developed by the design team, including the project requirements from the owner, the user and the facility manager. Then, the model encompassing the project information is used by the project management and the construction team to calculate a very accurate schedule from the first stages of the project; they would not need to wait until each design phase is finalized. Even though the users and the facility manager do not play a direct role in the development of the schedule; all their input is included as part of the model.

Using a non proprietary language, the system will extract some basic data from the design model in order to generate a bill of quantities, these quantities will be linked to work packages that will be generated from a standard work breakdown structure and from user input having the activities and sequences of those activities, then the work packages containing quantities will be linked to standard productivity data in order to calculate the duration of the activities. A first schedule is calculated according to activities, duration and sequences, then the schedule is optimized taking into consideration resources availability, cost and time constraints, finally the optimized schedule can be visualized in different chart representations or through a 4D model, and the chart of resources is generated. The system can be updated in several parts of the process and as the activities are linked to the quantities, and the quantities are linked to the model, the whole system will automatically update. The user can update the 3D model, the activities and sequences in the work packages, the resource, time and cost constraints, and the actual schedule with real conditions data.

System Architecture

An ideal model for the scheduling automation system would be based on the client-server architecture, as seen in Figure 1.

A client-server architecture is one in which the different processes are divided into different layers. A three tier; client, application server and database is proposed for the system under consideration. The client will consist of the graphical user interface where the initial 3D model and final 4D model with the schedule could be viewed. This is where a user can make changes, update design or any variable, or a manager can go inside and approve the changes. The second tier will consist of applications to model the design, the proposed work package builder, a rule engine which runs the rules on the work package or on the schedule generated and a scheduler which works on the work packets and the user input data to generate an optimized schedule and a 4D model. The third tier consists of the database layer. This is where all the project data which comprises the 3D and 4D models are stored.

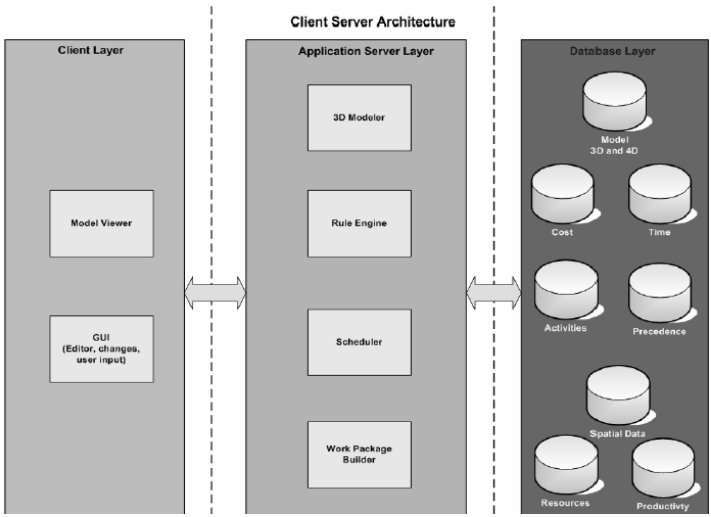


Figure 1. Layered architecture approach for the automation of scheduling activities

Methodology and Process Flow model

The processes involved for the automation of scheduling could be basically broken down into extracting the required information from the 3D model, generating the work-packages from extracted data and then shaping a schedule by integrating and optimizing the extracted data with external project specific information and implementing this in the form of a 4D model. The processes are presented in the flow diagram of Figure 2.

Processes

BIM Analysis: A 3D model is the starting point for any BIM enabled process. The 3D model is assumed to be already in place from the design. For the scheduling automation process, a separate 3D model is not generated, but it is proposed to use the existing model which will contain the details about the attributes, properties, and a set of rules. Before starting the scheduling process it is necessary to make sure these minimum required data are present in the BIM. Data from the model will be used for two further processes, for quantities extraction and for generating the work packages. The outputs of this process used for quantities extraction are, element tag, element spatial location, geometry, materials, and equipment. The outputs used for work package generation are spatial location of the elements within the project and element tag. The source of information is the BIM (geometry, materials, equipment, element tag, and spatial location), as seen in Figure 3.

Extract quantities: This is an external process that uses as input element tag, geometry, materials and equipment information from the model. It could be part of BIM, however we are trying to have as less information stored in BIM as possible, in order to make the system with reasonable processing requirements and easy to

handle. In addition to the quantities extracted from BIM, the application will allow user input in order to add quantities that are not present in BIM or quantities that are wrong because of interoperability issues during the extraction process. The process consists on performing the takeoff from the model using elements and materials or equipment, producing as output the bill of quantities in terms of Masterformat divisions, material or equipment, location, and measurement unit. The sources of information for this process are the BIM (element tag, spatial location, geometry, materials and equipment) and user input (elements that are not in the model and correction to extraction errors), as depicted in Figure 3.

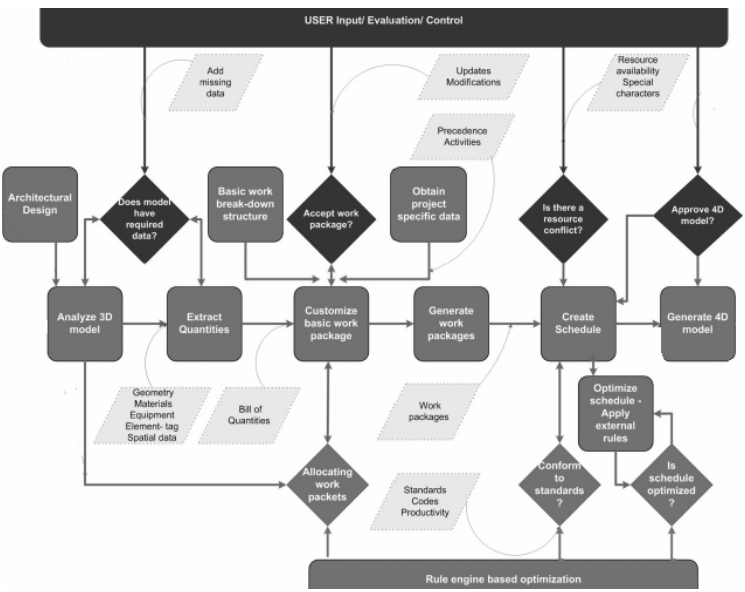


Figure 2. Process flow diagram for the proposed system

Generate work packages: This is an external process that seeks to organize the quantities into workable activities and to assign to those activities sequences. The process has several inputs, first the bill of quantities from the extract quantities process (Masterformat divisions, material or equipment, location, and measurement unit), and second the customized work packages from customize work packages process. The customize work package is a process that uses a standard work breakdown structure in terms of Masterformat divisions and based on the project type, as base of work packages, and allow user input to customize those basic activities according to the project specific needs. The process uses project specific information fed by the user (precedence knowledge and sequences rules) and element tag and location within the project to determine the sequence of those activities.

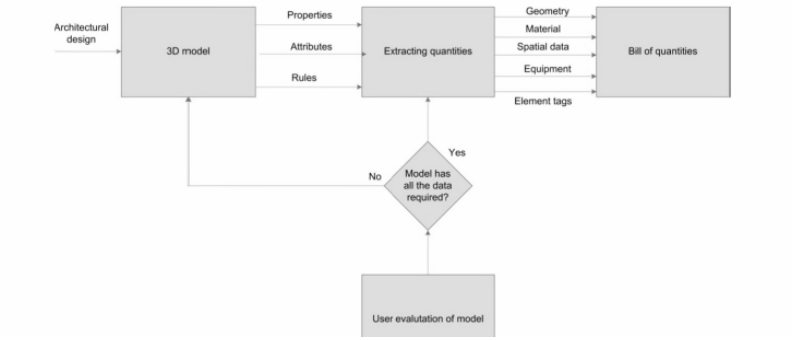


Figure 3. Analysis of existing model and extracting of quantities

The "generate work package" process links customized work package information including sequences to the bill of quantities information according to Masterformat divisions. The outcomes of this process are the work packages (activities) with quantities and sequence information. The sources of information for this process are BIM (element spatial location and tag), user input (modifications of work breakdown structures, sequencing rules), external information (standard work breakdown structure) and extract quantities (bill of quantities), as observed in Figure 4.

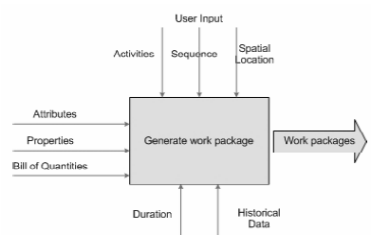


Figure 4. Generating the work package

Create schedule: This is an external process that seeks to calculate the schedule in an optimal way according to different constraints through an iterative process. In the first iteration the process uses the work packages with associated quantities and sequences, and external productivity information to calculate the duration of each activity and subsequently to calculate the schedule using as only constraints duration and sequences of the activities. In the subsequent iterations the optimization of the schedule takes place. The optimization schedule takes the calculated schedule (work packages, sequences and duration) and runs on them external rules for optimization purposes. Standards and codes are applied and user evaluation is included in this process. Through the user evaluation process resources availability, cost and maximum length of the project are used to optimize the schedule. This should be an iterative process so that the final schedule is optimized for various factors like resources, cost, time, etc. based on the user preferences and the project needs. The output of create schedule process is the optimized schedule. Figure 5 shows the

sources of information for this process: generate work-package (work packages), external information (productivity), external rules (codes and standards), and user input (resource availability, cost and time constraints).

Generate 4D model: The optimized schedule is received and from that a 4D model is generated by combining the schedule with the 3D model. Figure 5 also shows how the 4D model forms the basis for different types of scheduling visualization, according to the user preferences (Gant Charts, CPM chart, linear chart, etc.), 4D model visualization and produces resources charts. This process also allows the input of user changes to update the schedule. The sources of information for this process are BIM (3D Model), create schedule (optimized schedule) and user input (updates).

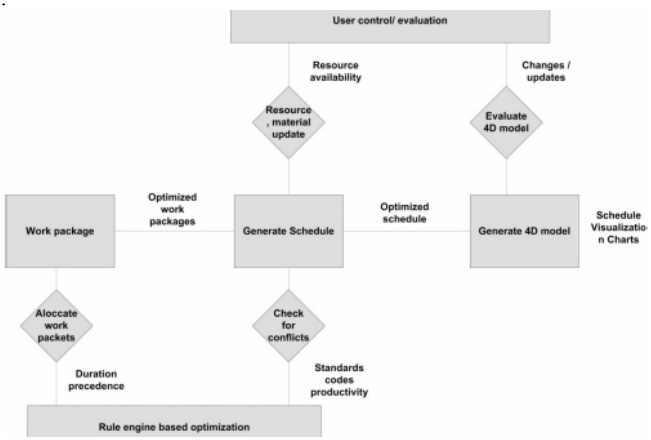


Figure 5. Generating an optimized schedule and 4D model

Conclusions

AEC+FM integration is essential to improve the overall performance of the construction industry. To achieve integration it is important that the project teams rethink the way construction projects are being developed. There are many factors that influence the integration of the project, and all are important in order to achieve truly integration; however, many of those factors converge in the need to improve project communication and information exchange. BIM is a tool that can foster integration because it not only improves project communication and information exchange, but also creates a platform that serves as a framework for collaboration. One of the applications of BIM that could really improve the performance of the project is related with the use of BIM to generate and control the schedule. Using BIM for scheduling purposes can help to generate a unique schedule for the project team from the design model that can be automatically updated as the project evolves. Therefore the schedule will reflect more accurate the duration of the project and will serve as a decision making tool.

Acknowledgments

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MODEL FOR LEGAL PRINCIPLES OF COMPENSATION FOR ERRORS IN BILLS OF QUANTITIES: A LAW AND ECONOMIC ANALYSIS

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ABSTRACT

Due to their complexity, construction contracts frequently encounter contract modification disputes, especially, the compensation claims for errors in the bills of quantities under lump sum contracts. The prevailing standard contract forms such as Joint Contracts Tribunal's Standard Building Contract with Quantities (JCT SBC/Q) often contain provisions for the adjustment of the lump sum price if there are errors in the bills. However, undesirable outcomes are often observed under current practice. By developing a game theory model, this paper investigates the contracting parties' strategic interactions and analyzes the differential efficacy of alternative legal principles of compensation for errors. Based on this model, we derive the legal principles that may reduce opportunism incentives and minimize transaction costs. The principles suggest that claims for error compensation should pass the test that the errors are not obvious ex ante to the eyes of professionals. Prevalent standard forms under which the compensation is granted regardless of the nature of errors violate the derived principles and deserve further investigation.

1. Introduction

The lump sum contract is probably the most common type of contract used in the construction industry. It is often applied to government projects (Keyes 2004). A lump sum contract giving the selected contractor an incentive to limit costs may be an optimal contract (McAfee and McMillan 1986).

Under the lump sum contract, the plans and specifications are prepared by the project owner, usually via the architect/engineer (A/E), in advance of invitation to bid. Subsequently, the value of the various work items is to be established through bidding procedure. The sum of all the values to be paid shall be fixed as the price stated in the contract. Even if additional works are encountered during the course of performance, the lump sum price in its original spirit will not be adjusted. This is the interpretation derived from the Inclusive Price Principle of English Law (Wallace 2004).

Unfortunately, things in practice are not as simple as that in principle. Specifically, the documentation of a lump sum contract may include a set of bills of quantities, prepared by quantity surveyors to prescribe the details of particular work items with quantities. Errors or omissions often exist in the bills of quantities for construction projects (Adrian 1993). The contractor accordingly requests contract

modification and additional payments for the errors while discovering the errors during the course of performance. The prevailing standard contract forms nowadays, for example JCT SBC/Q, often contain provisions for the adjustment of the lump sum price if there are errors in the bills. Any error or omission in the bills shall be corrected and deemed to be a variation. In other words, the owner under JCT SBC/Q should compensate the contractor for the quantity difference due to errors in the bills. The result is opposite to the Inclusive Price Principle.

As such, it remains to be an extremely controversial puzzle of whether under a lump sum contract, the contractor should be granted remedy for discrepancy between the quantities stated in the bills and the as built quantities. If the owner subsequently agreed to increase the fixed price due to the quantity difference, when may the modification be justifiable and enforceable? A variety of theories and practices keep competing with one another on this issue.

Economic analysis evaluates legal rules by the structure of incentives they established and the consequences of people altering their behavior in response to those incentives (Friedman 2000). Comparing among the various equilibrium behaviors of the owner and bidder respectively under different legal rules enables us to assess those effects of the laws from the standpoint of economic efficiency. From the perspective of law and economics, we develop in this study a refinement of the contract modification rules that address issues on quantity differences under construction lump-sum contracts. The contracting parties' strategic behaviors under alternative modification rules are to be examined in our study.

In section 2, we go through a brief discussion of the problems of contract modifications and quantity differences under construction contracts in order to highlight significance of the issues addressed in this paper. Section 3 describes the model and analyzes equilibrium strategies of contracting parties under alternative legal rules. Section 4 draws conclusions and shows the optimal legal rule that governs the contracting parties' strategic behaviors in dealing with potential errors in the bills. Our analysis concludes that the contract modification rule under which the enforceability of a promise to pay additional amounts for errors in the bills of quantities is contingent upon the nature of the errors can discourage opportunistic behaviors between the contracting parties and achieve economic efficiency.

2. Problems of Contract Modifications and Quantity Differences under Construction Contracts

2.1. Enforceability of Contract Modification That Grants Additional Payments

The issue on additional payments for quantity difference of the construction contract is relevant to the contract modification law. In light of the traditional common law, pre-existing duty rule governs the enforceability of the modification of contract. The Rule provides that modifications of a contract not supported by "fresh consideration" would be unenforceable such that extortion or coerced modification would not be encouraged (Patterson 1958). A promise to make additional payment for which the promisee is already under the original contract to do is without consideration, examplified in the leading judgment from the British High Court in Stilk v. Myrick, 170 E.R. 1168 (1809). However, there have been many exceptions developed by

some courts to circumvent the pre-existing duty rule. For example, contract modifications may be held enforceable because of mutual rescission, waiver, additional consideration, unanticipated circumstances, economic duress, and so on (Graham and Peirce 1989).

In addition, there is even statutory "erosion" of the pre-existing duty rule. Article 2-209 of the US Uniform Commercial Code provides that an agreement modifying a contract within this Article needs no consideration to be binding. The official comment states that modification made thereunder must meet the test of good faith imposed by this Act. The effective use of bad faith to escape performance on the original contract terms is barred, and the extortion of a modification without legitimate commercial reason is ineffective as a violation of the duty of good faith. In other words, a legitimate commercial reason and good faith may constitute the legal basis for the enforceability of contract modification in disregard of the lack of fresh consideration.

Furthermore, the Restatement (Second) of the Law of Contracts § 89 also provides an exception for the preexisting duty rule. A promise modifying a duty under a contract not fully performed on either side is binding if the modification is fair and equitable in view of circumstances not anticipated by the parties when the contract was made.

It appears that the pre-existing duty rule has been undermined in a general sense. Nonetheless, the question whether those legal terminologies substituting the pre-existing duty rule, like "extortion," "good faith," "economic duress," "opportunistic threat," and so on, can be given a meaningful and objective definition still remains unresolved. The legal principle needs to be further refined for the specific type of contract and issue.

2.2. Debates on Remedy for Errors in Bills of Quantities

As introduced in the previous section, the major standard forms grant the contractor a special remedy for errors in the bills. For example, the Joint Contracts Tribunal's Standard Building Contract with Quantities (JCT SBC/Q) is one of the most common standard contracts used in the construction industry of UK and also adopted by international contracting parties in many other countries. In principle, the contract price is set on a lump sum basis with monthly interim payments. The owner at the stage of tender provides the contractor with drawings and bills of quantities. The price data filled by the contractor in the bills of quantities are mainly for the purpose of valuing variations. The owner and contractor are equally bounded by the rates stated in the bills of quantities once the contract is concluded (Rycroft and Ndekugri 2002).

Clause 2.14.1 of JCT SBC/Q directs that "if in the Contract Bills…, there is …any error in description or in quantity or any omission of items…, the departure, error or omission shall not vitiate this Contract but shall be corrected so that it does provide that information." Clearly, JCT SBC/Q grants compensations to the contractor for the errors in the bills of quantities, despite of the nature of errors in the bills. The contract modification of additional payment agreed by both parties is justifiable and enforceable under JCT SBC/Q. It is widely accepted among scholars and practitioners that the owner should be obligated to prepare the bills of quantities in accordance with standard method of measurement. It should be the owner's

responsibility for the accuracy of the bills. The owner should assume the risk of its errors in bills of quantities.

Nevertheless, the opposite opinion claims that a requirement to use a standard method does not thereby constitute a warranty of accuracy of the bills (Thornton 2007). Traditionally, by the virtue of lump sum, the total price of lump sum contract cannot be altered, except for variations of the project occurring during the course of the performance. Any contractual documents showing work items and unit prices exist merely for the purpose of valuing such variations. Any bills of quantities found in association with lump sum contracts have no legal effect beyond their use in the valuation of variations and, in some cases, as a basis for interim payment. Indeed, such bills may not even perform these functions, and may simply be used as a guide issued to bidders in the tender phase so as to reduce the time and expense of the estimating process required to arrive at the "Lump Sum." In an old English jargon, such bills "do not form part of the contract", and the contract remains essentially a "Lump Sum" contract (Wallace 1975).

Wallace further explicated that claims brought by the contractor for errors in the bills "are essentially without merit, because either (a) the contractor has noticed the 'error' in the Bills when pricing, and if he intended to claim was stealing a march on both the employer and his competitors in tendering an apparently lower price or (b) he has not noticed the 'error', in which case his prices will in any event have included for the process or contingent expenditure involved." He suggested that the successful bidder should be contractually obliged to disclose the detailed make-up of its tender prices before the contract is signed such that bills of quantities could perform the function of permitting an accurate comparison of tenders, or precise measurement or valuation of variations or interim payment (Wallace 1975).

However, even if the contract law imposed compulsory obligation on the contactor to disclose the detailed make-up, those figures would be easily manipulated and distorted if the contractor's incentive of exploiting its private information was not properly removed. Practically, such a proposal might not be able to properly resolve the problem.

Basically, the bills of quantities are intended to be simply a guide to allow the price to be determined. Mistakes in the bill descriptions or quantities are unlikely to be remedied as a legal rectification of the contract to reflect the true intention of the parties. It is more likely than not, that the common intention will be that the tendered price should prevail, rather than a price revised to account of the errors (Atkinson 2000). Therefore, the contractor's obligation to perform the whole work for the lump sum price will disentitle him from claiming additional payment for increases in the quantities (Dorter 1991). Given the early precedents of England, contractors would diligently peruse contract terms prior to executing a lump sum contract and ensure that their rights and obligations are clearly spelt out (Xavier 2002).

Thornton further explored the Inclusive Price Principle of English law introduced in the authoritative textbook, the 11th edition of Hudson's Building and Engineering Contracts. The principle provides that work that is indispensably or contingently necessary for completion should have been included within the contract price. Since for most construction contracts, there would always be some element of uncertainty about the extent of work and the final price prior to completion of the

work, the design process would never have been fully completed at the time the contract is made. Therefore, any indispensable or contingent work must be carried out at the contractor's own expense and will not qualify for additional payment (Thornton 2007). Thornton tried to argue the irrationality of passing the risk of paying for unascertained indispensably or contingently necessary work onto the owner. However, he drew the conclusions without giving clear analysis to the distribution of risks. Especially, the inefficiency led by the owner's strategic behavior did not obtain substantial consideration.

2.3. Bidding Strategic Behavior

Contractors are potentially able to enjoy greater profits from unbalanced bidding although it is also possible that it may give cause for them to incur additional risk. Contractors have the advantage over owners in this regard by having available to them their own private information about their estimates of a project's cost. Owners do not have access to this same information, which makes it far more difficult for them to determine the existence and the extent of any possible loading in any item prices.

One of the methods of unbalanced bidding was to exploit errors in the planned quantities. A contractor having done a field investigation might discover that quantities of some items during construction will exceed the estimates in bills of quantities. This contractor would benefit if they were to load up the prices of those underestimated items, and load down the prices of others, in which it could still win the contract with the same tendering bid (Cattell, Bowen et al. 2007).

Some claimed that the bidder's exploitation of its private information of production volume need not cause losses to the owner because a correct bid, based on correct volumes specified in the bills, would have reflected a higher bid price (Missbauer and Hauber 2006). Others proposed a procedure to adjust the unit prices offered by the winning bidder for managing the unbalanced bids (Wang 2004). However, the very information asymmetry between the owner and contractor results in rent seeking behavior with net costs and, thus, economic inefficiency. The efficiency cannot be attained unless the applicable rule provides the parties with appropriate incentive to move. This reality should not be overlooked.

As such, our prime issue of concern is the consequences of relevant legal rules and the efficiency of risk allocations. We focus on the ex ante incentive and bidding strategic behavior of the parties under alternative contract modification rules. A theoretical game model is developed to evaluate the efficacy of the contractual rules.

3. The Model

However, as we will analyze in the following sections, the contractor's opportunistic behavior can be encouraged under the provisions of JCT SBC/Q. On the other side, the Inclusive Price Principle may not achieve efficiency and minimize transaction costs at the stage of contract tendering.

3.1. Setup of the Game

Consider an owner who is developing a construction project under the traditional procedure of procurement and engages the A/E in producing the tendering documents,

including drawings, specifications and bills of quantities that itemize the detailed project works. Inevitably in practice, there is always possibility that an error of quantity deficiency for any specific work item exists in the bills of quantities. If the owner wants to lessen the deficiency, the higher cost needs to be invested in the design management. Otherwise, the owner may use the lower efforts in design management and allow the greater deficiency in the bills of quantity.

Subsequently, the owner publishes the tender documents and invites bidders to bid for the contract. The lump-sum price scheme is to be applied for all the works to be performed under the contract. Bidders are required to allocate and submit the unit price for each work item described in the bills of quantities. Bidders build up the total price of their own bids based on the unit prices times quantities (Wang 2004).

In practice, an experienced contractor will conduct a basic procedure for bid preparation prior to submitting its bid, including examination of the drawings, specifications and bills of quantities provided by the owner, site visit, calculation of the bid price, and so on. Some errors in the bills of quantities may be discovered by the bidder through such basic procedures for bid preparation; thus, the owner estimated quantities are inconsistent with those taken off by bidders. We call such an expected difference the obvious error, which is professionally noticeable by experienced contractors from their basic bid preparation. Otherwise, if the owner estimated quantities are exactly consistent with those taken off by the experienced contractor from the basic bid preparation, the discrepancy between the estimated and actual quantity, is considered as the latent error, which is not professionally noticeable by experienced contractors from their basic preparation, and entails further detection to be discovered in addition to the examination in the basic bid preparation process.

With the private information of the quantity deficiency, the bidder chooses to either reveal whatsoever discovered or use unbalanced bidding strategy. While revealing those errors discovered, the bidder requests the owner to correct the deficiencies, in which the quantity of the specific work item in the bills will be modified and the lump sum price will be adjusted accordingly. The adjustment involves in a re-examination process of the bills of quantities, in which a cost is to be incurred by the owner.

Alternatively, while concealing whatever errors discovered, the bidder uses unbalanced bidding strategy and attaches to the underestimated work item a skewed unit price, rather than the bidder's actual unit cost.

Finally, during the performance of the contract, the contractor will reveal any and all the errors, which have not been corrected before contract awarding, and request contract modification compensating for those quantity deficiencies.

As such, this article uses a simple theoretical model to evaluate the various legal rules: when is the contract modification that compensates for errors in the bills of quantities justifiable? We first focus on obvious errors in section 3.2, and then turn to latent errors in section 3.3. We shall compare the effects of different legal rules on the strategic behavior of the owner and bidders and the corresponding transaction costs incurred by both parties in preparing or examining the bills. This analysis aims to derive the contractual rule under which the opportunistic behavior may be eliminated and the transaction cost minimized.

3.2. The Obvious Errors

In this section, we address the obvious errors possibly existing in the bills of quantities, which may be discovered through the basic procedure for bid preparation.

First, attention is given to the parties' equilibrium behaviors under which the legal rule allows contract modification that compensates for errors in the bills. For instance, JCT SBC/Q provides that errors will be corrected and treated as variation in the execution of project. To put it in other words, the contract modification due to the existence of errors in the bills may be justifiable and expected when the errors are discovered during the course of performance. The contract price should be increased in accordance with the unit price previously broken down by the bidder and set forth in the contract documents.

The owner determines the level of efforts invested in the design management, in which a cost is incurred by the owner. The bidder chooses from: (1) concealing the obvious errors discovered and submitting unbalanced bids, or (2) revealing the obvious errors and requesting correction.

Because the legal rule grants compensation to the contractor for obvious errors in the bills of quantities, the bidder has an incentive to exploit their private information for seeking extra profit from the compensation. To conceal obvious errors discovered and to submit the unbalanced bid evidently is the strictly dominant strategy of bidders.

Given the bidder's strategy, the owner will choose a level of effort in the design management to minimize its total expenses on the project. However, the first-best condition which requires the owner expending nothing in the design management cannot be accomplished. Moreover, the opportunistic behavior of bidders to exploit their private information cannot be completely eliminated. Given any level of the owner's cost for design management, bidders have no incentive to disclose whatever obvious errors discovered through the basic procedure for bid preparation. Bidders always attempt to submit unbalanced bids and subsequently claim for modification of the contract price during the performance of work. The owner faced with the claim has difficulty to demonstrate that the unit price previously quoted by the contractor was manipulated and skewed since the bidder's cost structure is unverifiable. Therefore, such kind of claim would incur significant dispute costs and jeopardize the cooperative relationship between the owner and contractor. The opportunistic behavior may even impede future transactions and result in economic inefficiency.

Second, we now turn to the legal rule forbidding contract modification that compensates for errors in the bills. Similar to the Inclusive Price Principle, the contractor is not entitled to compensation for quantity differences due to the errors in bills. If bidders did not reveal the errors and requested for correction before submitting their bid, they shall take full risks relating to the accuracy of work quantities once both parties have signed the contract. In other words, the court sticks to the pre-existing duty rule, in which contract modification does not justify itself under the Inclusive Price Principle. The existence of errors in the bills does not create any fresh consideration.

Thus, the bidder will suffer a significant loss from choosing to concealing obvious errors discovered and submit the unbalanced bid without obtaining compensations after completion of project. Submitting unbalanced bids does nothing

good to the bidder. Therefore, it is the bidder's strictly dominant strategy at the tendering stage to reveal whatever errors discovered and request rectifying the underestimated quantities.

On the other side, the owner tends to reduce the efforts and the contract quality since the owner need not compensate for any errors in the bills of quantities. Notwithstanding, the effort level injected by the owner in design management will not decrease too significantly although. Whenever bidders bring the request for correction of the bills, the owner incurs a cost in relation to re-examining the bills of quantities, which is increased by any decrease of the owner's effort in the design management. The lower the efforts in design management used by the owner, the higher the rectification cost incurred.

Accordingly, the owner will choose the level of its design effort at which the cost in correcting the obvious errors may be balanced. At the same time, the decision of the owner will be optimal and satisfy the first-best condition. Most of all, this rule completely eliminates the incentive for bidders to exploit their private information and use unbalanced bidding strategy. In addition, this model induces the owner to use the optimal level of efforts in the design management.

To end this section, it can be found that the legal rule forbidding contract modification that compensates for errors in the bills delivers bidders an ex ante incentive to reveal obvious errors discovered through their basic process of tender preparation and request rectification before submitting the bid. The owner accordingly will use its optimal effort in the design management, in which the total cost of transaction is minimized. Therefore, the greater net gain and efficiency may be achieved by distributing the risk of obvious errors to bidders and forbidding the contract modification.

3.3. The Latent Errors

Following the same framework for analysis as the previous subsection, we first address the parties' equilibrium behaviors under the legal rule that allows contract modification that compensates for latent errors in the bills.

In order to discover those latent errors and submit unbalanced bids, the bidder needs to conduct further investigation in addition to its basic process of preparation for the bid. Otherwise, the bidder may choose to simply submit the balanced bid without expending in further investigation of latent errors.

As is usually the case when the minimum effort to be used in detecting latent errors is greater than the excess profit obtained from unbalanced bidding, taking unbalanced bidding strategy cannot be worthwhile. The additional cost may be too significant for bidders to detect the latent errors for using unbalanced bidding strategy. There is no chance for bidders to take advantage of the owner. Under such circumstance, the legal rule that allows contract modification that compensates errors in the bills of quantities brings bidders no incentive to use unbalanced bidding strategy. Given bidders' strategy, the owner will expend nothing in the design management, and the first-best condition may be satisfied as well.

To evaluate, the legal rule that allows contract modification that compensates errors in the bills of quantities cannot induce bidders to expend more in detecting latent errors in the bills. Although the latent errors cannot be discovered and corrected

at the tendering stage, the owner will subsequently compensate the contractor the exact cost overrun for the erred work item, and no extra profit will be sought by the contractor. In addition, this appropriate amount of compensation provides the owner with an incentive to invest at the efficient level of reliance (Miceli 2002). As a result, the total cost of the transaction may be minimized under such a rule.

Second, under the legal rule forbidding contract modification that compensates for errors in the bills, the bidder has two choices: (1) to expend in further investigation of latent error and request correction before submitting the bid, and (2) to simply absorb the cost for the deficiency without expending additional efforts in discovering latent errors. In order to avoid taking the risk of cost overruns, the bidder will choose to invest in detecting latent errors and request modification of the bills at the tendering stage.

On the other side, the owner considers whether to invest design management efforts in reducing latent errors so as to balance the cost incurred in correcting the bills upon the bidder's request. When the minimum effort to be used is too significant, the owner will simply choose to expend nothing in managing latent errors but awaiting the bidder's request for correction.

From the long-term point of view, the contractor, however, will incorporate into the lump-sum price a premium that quantifies the risk of latent errors in bills of quantities. The owner will have to pay a higher price in order to have the contractor bear the risk of difference in work quantities. The uncertainty will impede potential transactions and cause further loss of efficiency to the industry.

Moreover, having predicted bidders' behavior, the owner might consciously create, by itself or via the designer, latent errors in the bills. The opportunism on the side of the owner shall also be taken into account, especially in which the potential errors faced by the parties are latent. As Browning and Cohen pointed out, for the culture of construction industry, especially under the lump sum price scheme, "not only is the information on which the contractor is to base his price inadequate but the client then seeks to transfer as much of the risk as possible onto the contractor" (Browning and Cohen 1998). It is implied that the strategically rent-seeking behavior of contracting parties is so real and evident. There may be an incentive for the owner to skew the bills and to specify work quantities that are different from the values actually estimated (Missbauer and Hauber 2006). Insisting on the Inclusive Price Principle while addressing latent errors in the bills of quantities may result in the owner's strategic distortion of the bills and, thus, inefficient allocation of resources. Instead, enforcing the compensation for the latent errors may economize on the transaction costs and maximize the total gain of both parties.

To conclude, enforceability of contract modification that compensates for errors in the bills shall be contingent upon the nature of the errors. Bidders shall be compensated for the errors in the bills, provided, however, that the errors have been found to be latent. The economic efficiency may be achieved by applying such a contingent legal rule.

4. Conclusion: A Contingent Contractual Rule

As argued by Rooke, Seymour et al., while the bidders' opportunistic behavior can be seen as a rational response to the underlying profit and economic conditions in this

industry, such interactions have been embedded in the culture (Rooke, Seymour et al. 2004). The inefficiency arising from opportunism in the construction industry is such conspicuous and significant. Therefore, it is vital to examine the relevant institutions, which influence human interactions and the resulting transaction costs. Our objective is to analyze the strategic behavior of the owner and bidder in response to different contractual rules that determines the additional compensations for errors in the bills under lump sum contracts, and then evaluate the economic efficiency of the rules. Eventually, efficiency may be realized when circumstances provide sufficient incentive for those with bargaining strength to alter institutions in the efficient direction (North 1990).

This paper concludes that the contract modification rule under which the enforceability of a promise to pay additional amounts for errors in the bills of quantities is contingent upon the nature of the errors can discourage opportunistic behavior between the contracting parties. We conceptualize the errors in the bills into two categories: obvious and latent errors. From the standpoint of economic efficiency, we show that a contingent rule under which contract modification compensating for errors in the bills is justifiable only if the errors are latent discourages opportunistic behavior of the parties without causing inefficient transaction costs. If the contractor conceals the obvious errors in the bills of quantities without requesting correction before submitting its bid but claims compensation for the errors during the performance of contract, then the claim for compensation is unjustified. A promise of the owner to pay additional amount therefor may be presumed to be a coerced modification and is unenforceable. Instead, if the contractor discovers the latent errors during the performance of contract, then the contract shall be modified to compensate the contractor for the errors at the rate of charge incorporated into the bills of quantities.

On the one hand, forbidding contract modification compensating for the obvious errors eliminates the incentive for bidders to do unbalanced bidding. Bidders will be induced to truthfully report to the owner for rectification without exploiting its private information. At the same time, the design quality would be preserved at the optimal level of the owner. Otherwise, allowing and enforcing the contract modification compensating the bidder for the obvious errors in the bills induces bidders to submit unbalanced bids and leads to a relatively high design cost incurred by the owner in response to bidders' opportunistic behavior.

On the other hand, while the errors existing in the bills are latent, allowing and enforcing the contract modification that provides compensation to the contractor prevents the owner from manipulating the bills of quantities and causes none of the parties to expend unnecessary costs in examining the bills. Neither party would be worried about the opportunistic behavior that might be adopted by the other party. As a result, the contingent rule under which contract modification compensating for errors in the bills is justifiable only if the errors are latent may achieve efficiency by discouraging opportunism and minimizing transaction costs.

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Assessment of Direct Work Utilization at the Workface in the U.S. Construction Industry (1972-2008)

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Abstract

Direct work percentage based on work sampling of construction projects measures the effectiveness of labor utilization at the workface, often exposes excessive traveling and idle time in the execution of construction activities, and reflects, to a large extent, the soundness of detailed crew level planning. This paper presents the findings from a series of productivity studies that were conducted on 123 construction projects involving 69 general contractors in the Austin, Texas area during the period of 1972-2008. Analysis of these work sampling studies indicate that there is a slight decrease in the direct work percentage and a slight increase in support work ratio during the period of 1972-2008. However, this trend cannot be justified at a statistical significance level. Nevertheless, it is reasonable to conclude that direct work ratio has been stagnant over the last four decades. The average direct work ratio is around 45% in that period and direct work ratio shows no statistical significant difference among different types of projects. The research concludes that labor utilization at the workface indicates that craftsmen are doing productive work less than half the time that is being observed. It is recommended that contractors employ significantly greater planning resources to ensure a larger percentage of direct work.

Introduction

Successful renovation and delivery of the United States infrastructure urges the need for improvement in construction productivity. This challenge is amplified considering the current economic conditions. Nevertheless, after a century of sporadic advances in equipment, tools, materials, and methods, it is widely agreed that the US construction

industry still faces a low rate of productivity growth (Arditi and Krishna 2000; Allmon et al. 2000; Goodrum and Haas 2004; Rojas and Aramvareekul 2003). However, the quantification of this rate of productivity improvement at the industry level has been in a state of flux because of little consensus on appropriate productivity metrics (Eastman and Sacks 2008).

Instead of assessing the construction productivity as a whole, this research focuses on the crew time utilization that is a part of construction productivity measurement. At the project level, construction productivity is typically defined as the input effort divided by the output quantity. The input effort is often based on man hours; while the output quantity is usually collected in a variety of ways, such as estimated percent complete, physical measurement, and so on. However, the measurement of productivity in construction projects is often based on the reversed definition—input/output, which is more convenient for the purpose of cost control. From the point of view of productivity improvement, either definition makes it clear that effective utilization of craftsman time at the workface is an integral part of onsite construction productivity improvement. The effectiveness of crew time utilization is commonly measured using the means of direct work ratio. While a few large construction companies periodically assess their own direct labor utilization, there has been no comprehensive direct work assessment across dimensions as time, project type, organization type, activity type, and crew size.

This research analyzed a set of productivity studies that, in part, examined direct work utilization on 123 construction projects by the means of work sampling. This comprehensive assessment of crew time utilizations at the workface enhances the understanding of the industry trend of direct work percentage, evaluates the adverse impacts of certain behaviors, such as traveling and idle time, on direct work utilization, and reflects the effectiveness of crew level planning in the construction industry over the years.

Review of Data Collection Methodologies

Productivity improvement is a complex proposition because there are a multitude of factors affecting the productivity performance of any onsite operations. It is the complexity of productivity improvement that accounts for the emphasis upon onsite data collection to foster understanding of the degree of impacts of such factors on productivity. The productivity studies that are reported in this paper use work sampling as one of the primary onsite data collection methods to studying direct labor utilization at the workface.

Work Sampling

Work sampling measures how time is utilized by the labor force. In the work sampling technique, observations of what each worker is doing at a particular instant are recorded. The activities of workers are typically divided into the predetermined categories, such as direct work, support work, and idle time (Oglesby et al 1989). In practice, different contractors may use different categories. In general, work sampling gives information about time spent on activities and therefore provides indirect information about productivity. Most companies focus particular attention on their

crafts' direct work rates, which is a percentage of time spent on direct work during all working hours, and they do so by implementing programs and processes to increase their direct rates as much as possible in order to improve their site's productivity. However, direct work time does not necessarily correlate with unit rate productivity (Thomas 1991). In other words, a high percentage of direct work time would not always indicate an equally high level of unit rate productivity because of variation in skill levels of the workers sampled, work methods and types of tools and equipment used. Even considering these constraints, many companies consider work sampling as an important diagnostic tool for measuring productivity performance at the workface.

Research Background

The research reported in this paper is a part of a stream of onsite productivity studies that were conducted on 123 construction projects in the Austin, Texas area during the period of 1972-2008. Figure 1 shows the distribution of these projects over the years. In addition, the composition of these projects in terms of project type is shown in Figure 2. These projects involved 69 different general contractors, which represent construction companies at different sophistication levels.

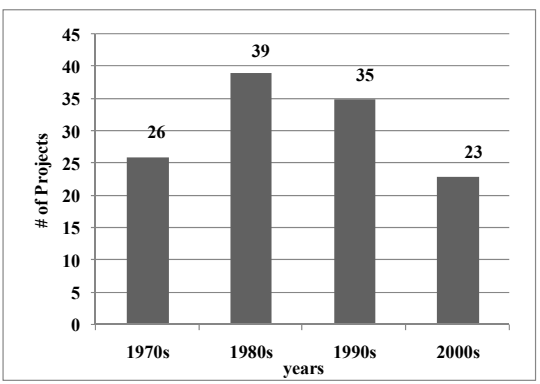


Figure 1. The Distribution of the Projects Over the Years

The purpose of these studies is two folded. The first purpose is to assess the effectiveness of labor utilization through work sampling, activity rating, and method studies. The second purpose is to evaluate onsite safety practices. The results of these studies provided a unique and rich dataset that can be leveraged to study the trend of direct labor utilization and safety practices in the U.S. construction industry. Specifically, the focus of this research is on assessing the direct labor utilization by analyzing the work sampling data that are accumulated in these studies.

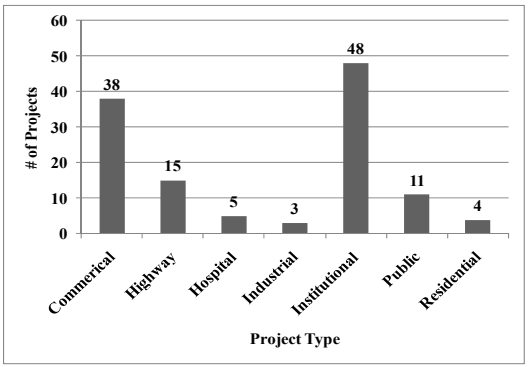


Figure 2. The Composition of the Projects based on the Project Type

It is worthwhile to note that work sampling and activity rating have been implemented in many different ways in the past. Therefore, a brief description of the systems used in this study is provided as follows. First, there are two work sampling schemas that were used in the 40-year study period. The productivity studies that were conducted in the period of 1972 to 1984 simply use two categories—direct work and nonproductive work—for work sampling. The required minimum sample size in these studies was set to 800 at that time. Then, starting from 1986, six predetermined categories were used in work sampling and remained present. These categories are direct work, transport, travel, instruction, personal time, and delay. In analysis, these categories are also often combined into three major categories including direct work, supportive work, and idle time. Figure 3 shows the mapping between the categories that are used in different periods of studies. In essence, these six categories are an expanded version of three-category system used in the early studies (Figure 3). In addition, the required minimum sample size was increased to 2000 because of the increasing number of large projects (>100 labor forces) involved in these recent studies. Second, the Five-Minute Rating has been utilized as the primary activity rating method throughout the course of the reported productivity studies in this research.

Data Analysis and Discussion

The collected work sampling data from these productivity studies is analyzed in this section. The purpose is to investigate the trend of labor utilization over the years and to characterize the patterns of labor utilization across the factors such as project type. As discussed in the research background, the work sampling techniques used in these productivity studies have evolved over the thirty six years. This development contributes to the fact that the data collected in the recent studies yield more detailed information than the data collected at the early times does. Consequently, the data in certain work sampling categories, such as supportive work, can be only analyzed according to different study periods, while others, such as direct work, can be analyzed across the whole productivity study period.

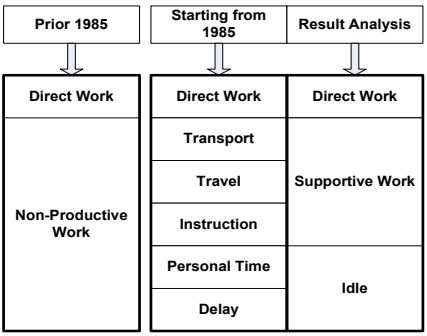


Figure 3. The Categories used in Work Sampling in Different Study Periods

The Chronologic View of Labor Utilization

Direct work ratio measures a critical aspect of craftsman performance at the workface. Figure 4 shows the chronologic view of direct work ratios of the projects that were studied over the last thirty six years. Accordingly, it becomes clear that this ratio has been stagnant without showing signs of improvement. Even worse, the ratio shows an overall declining trend though such a trend cannot be justified at the statistically significant level. Aside from the trend of direct work ratio, it was found that the average direct work ratio of all these projects is 45.4% with a standard deviation of 9.66%. The large deviation also partially explained the difficulty of statistically justifying the declining trend.

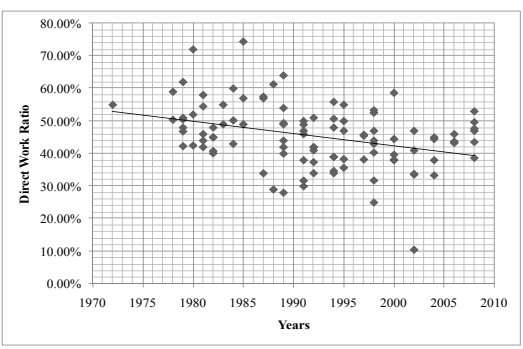
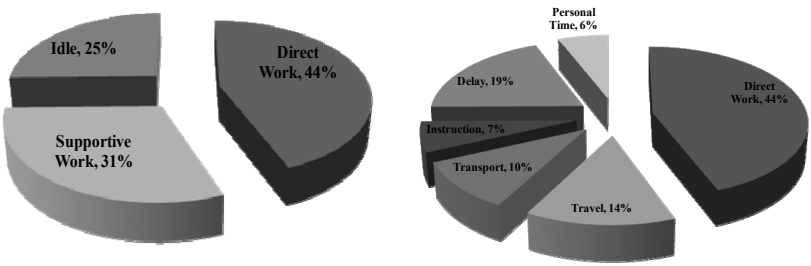


Figure 4. The Chronologic View of Direct Work Ratio (1972-2008)

Besides the direct work ratio, the analysis of other labor utilization categories is focused on the productivity studies that were conducted after 1985. This is because only after the year of 1985, the detailed six-category work sampling was adopted in

the productivity studies. These recent studies (1985-2008) allow the composition of labor utilization to be analyzed at a much detailed level. According to Figure 5a, it can be noted that in the studied projects craftsmen spent the average 44% of time in direct work, the average 31% of time in supportive work, and 25% of time were idle. The standard deviations for these average values are 9.66%, 8.93%, and 7.01% respectively. A further breakdown of these major categories along with the percentage values is shown in Figure 5b. Specifically, it was found that in average craftsmen spent 13% of their time in traveling, 10% of their time in transport, 7% of their time in instruction, 6% of their time in personal time, and 19% of their time in idle.



(a) (b)

Figure 5. The Composition of Labor Utilization at the Workface (1985-2008)

To analyze the trend of labor utilization at the workface using the more recent work sampling schema, the results of work sampling in every studied project are plotted in Figures 6, 7, and 8. It can be noted that the labor utilization at the workface in these projects displays great variability. In terms of the overall trend, each of these categories, including direct work, support work, and idle, displays contrasting patterns. More specifically, the unproductive portion of labor utilization (idle) displays a relatively flat trend. At the same time, the supportive work ratio in these studied projects is gradually increasing while the direct work ratio is declining over the years. In addition, the increase of supportive work ratio in the period of 1985 to 2008 also indicates that craftsmen have been spending increasing time at the workface in transporting, traveling, and instructional activities, which in turn reflects inadequate crew level planning in increasingly complex construction projects.

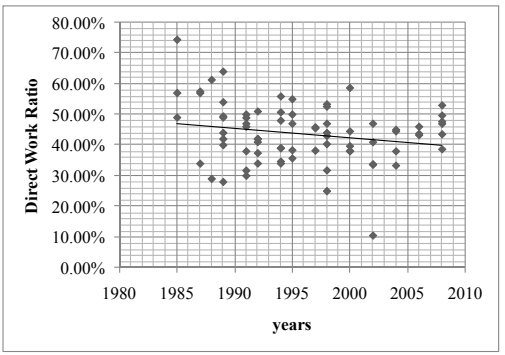


Figure 6. The Chronologic View of Direct Work Ratio (1985-2008)

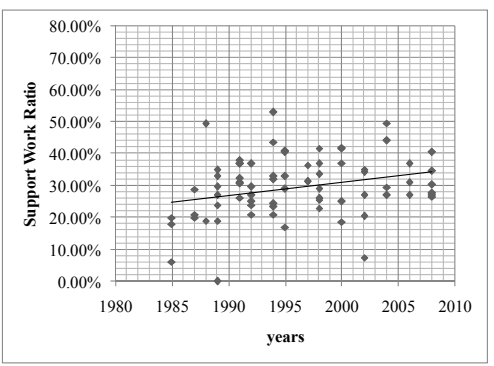


Figure 7. The Chronologic View of Supportive Work Ratio (1985-2008)

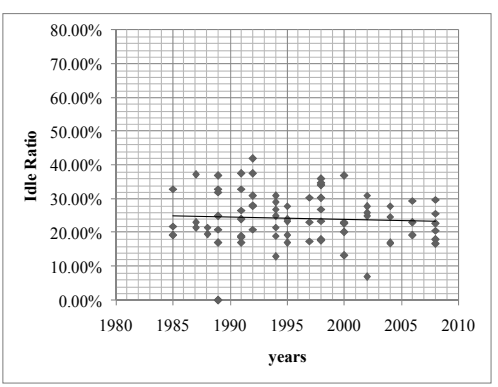


Figure 8. The Chronologic View of Idle Ratio (1985-2008)

Direct Work Ratio vs. Project Type

Based on the characteristics of the studied projects, these projects can be classified into seven categories. They include commercial, public, highway, hospital, industrial, institutional, and residential. The average direct work ratio for each type of projects is calculated and summarized in Figure 9. The result shows that hospital projects have the lowest direct work ratio among all type of projects. This outcome is largely correlated with the complexity of hospital projects. Conversely, commercial projects have the highest direct work ratio, 51%, according to the analysis results. The increased modularization and repetition of the same work in commercial projects (office, hotel room, and store) may contribute to such high performance. It is worthwhile to note that most of the projects that were studied in this research fall into the categories of institutional, commercial, and governmental. Therefore, the average direct work ratio of these types of projects should be considered as most reliable as compared to other types of projects.

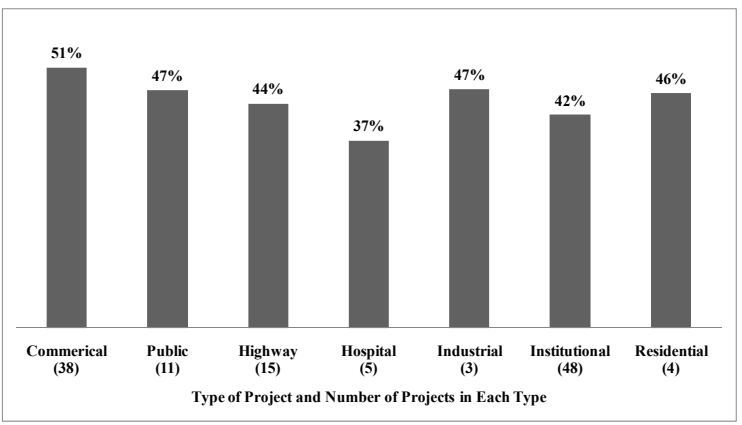


Figure 9. The Average Direct Work Ratios in Different Types of Projects

Direct Work Ratio vs. Size of Workforce

In Figure 10, the direct work ratio of a project is plotted against the size of workforce utilized in that project. It should be noted that only projects that have information about the size of labor force are displayed in Figure 10, and the size of workforce is determined from the peak manpower that was utilized in the study period. The plot shows no strong correlation between the size of workforce and the direct work ratio.

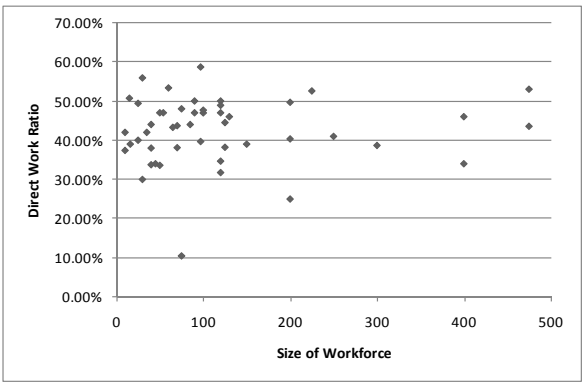


Figure 10. Direct Work Ratio vs. Size of Workforce

Direct Work Ratio vs. Contractor Type

The contractors who performed the construction work for the studies projects are divided into two major categories—regional contractor and national contractor. Then, the average direct work ratio of both categories is plotted in Figure 11. The result indicates that the national contractors perform worse than the region contractors in terms of direct work percentage. However, such difference in direct work ratio between these types of contractors is not statistically significant.

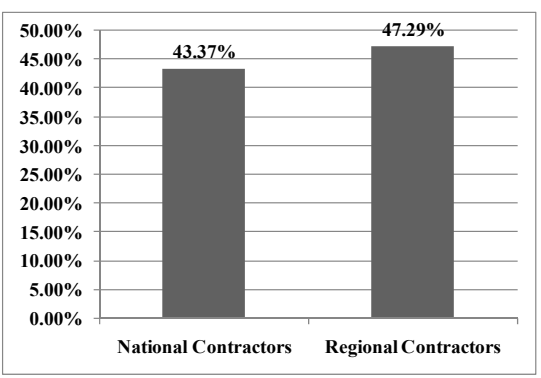


Figure 11. Direct Work Ratio vs. Contractor Type

Conclusion and Recommendations

This research analyzes the pattern of crew time utilization at the workface based on a unique set of productivity studies that investigated a variety of construction projects in the Austin, Texas area. The research results indicated that direct work ratio has

slightly decreased in these projects and support work at the workface has increased. Overall, craftsmen are doing productive work less than half the time that is being observed. This observation may offer some explanations to the stagnant productivity rate in the construction industry. In addition to the trend of direct work ratio, this research shows that there is no correlation between project type or size of workforce and direct work ratio. An interesting observation is that in these studied projects the local contractors perform better than the national contractors in terms of direct work ratio. This result may be caused by the fact that in many cases the work performed by the local contractors is less complex than the work performed by the national contractors, and they employ their own labor from job to job. Overall, the average direct work ratio in the projects that were studied in this research is higher than what were reported in other studies (Thomas 1991; Liou and Borcherding 1986). This may be due to the fact that these earlier studies focused on industrial projects, which is typically more complex than most of the projects included in this research.

It is evident from this research that labor utilization at the workface can be improved by the site leadership and little emphasis on crew-level planning is adversely influencing direct work and productivity in the construction industry. It is recommended that contractors employ significantly greater planning resources to ensure a larger percentage of direct work.

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Bi–level Framework for Measuring Performance to Improve Productivity of Construction Enterprises

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Abstract

The construction industry has experienced profound changes that have forced construction enterprises to utilize performance measurements to improve their productivity. Current performance measurement frameworks (such as the Construction Industry Institute [CII] Benchmarking and Metrics program [BM&M]) mainly focus on the project level. In addition, many construction companies apply company-level performance measurement frameworks (such as the Balanced Scorecard [BSC]) that fall short in addressing particular issues and do not give a multifaceted measurement. An exploratory research was conducted to build bi-level performance measurement framework to improve construction enterprises' productivity. The proposed framework consists of two subsystems: company subsystem and project subsystem. The company subsystem is organized around the Balanced Scorecard (BSC). The project subsystem is organized around the nine knowledge areas of *Project Management Body of Knowledge (PMBOK)*. The configuration of the viable system model (VSM) is utilized to enhance the model's implementation. This formulation process was followed by a structured interview and a case study to highlight potential adoption of the framework. Results show that the proposed framework can be vital in improving productivity of construction enterprises.

Introduction

Construction productivity improvement is stagnant and poses a deep threat to the industry, yet it is imperative for construction enterprises' success because of a highly competitive business environment. Construction enterprises are characterized by the simultaneous implementation of various projects and control of multiple input resources, so performance measurement models and systems are vital (Yu et al 2007).

Construction performance measurements have been limited to financial analysis, which fails to represent general business progress (Robertson 1997). Contemporarily, the development of more comprehensive measurement frameworks and systems are essential for improving construction enterprises.

Currently, several performance measurement frameworks have been applied by construction companies on the company level. The Balanced Scorecard (BSC), established by Kaplan and Norton (1992, 1993, 1996), abandoned the traditional approach of concentrating on financial data, and focused on four general perspectives: financial, customer, internal business and innovation and learning. Quality Awards Models (QAMs), e.g. European Foundation for Quality Management (EFQM) Excellence Model, have been applied as a practical tool to Total Quality Management (TQM) implementation (Bou-Llusar et al, 2008). The Key Performance Indicators (KPIs) framework was launched in the United Kingdom (UK) as a Best Practice Program based on Egan's *Rethinking Construction* (1998).

On the project level, the construction industry mainly focuses on indicators like schedule, cost, quality and safety. The Benchmarking and Metrics program (BM&M), Construction Industry Institute (CII), has exerted a major influence on projects' performance (CII 2001; CII 2002; CII 2003; CII 2006). It defines project performance norms, develops a common series of metrics, and sets up a benchmarking database and a web-based evaluation system (Lee et al. 2005; Park et al. 2005).

The construction literature includes some examples of integrating the different frameworks (Robertson 1997; Bassioni et al 2005; Yu et al 2007). However, the lack of a multifaceted measurement is a universal limitation to these frameworks. These "gaps in knowledge and practices" demand a more integrated framework (Bassioni et al 2004).

To overcome this gap, an exploratory research was conducted on the bi-level performance measurement. This paper integrates both company and project subsystems into one comprehensive, viable, and systematic framework for construction enterprises. Viable System Model (VSM) (Bititci et al 1997) is incorporated into the proposed framework to integrate different systems on different levels. VSM includes five subsystems, system 1 (operational units), system 2 (supervisory system), system 3 (tactical management system), system 4 (developmental system), and system 5 (boss system). The formulation of the proposed model will be illustrated in the following section. System validation and an illustrative case study will be offered to highlight potential adoption of the framework. Finally, conclusion and future work will be presented.

Framework Formulation

The proposed framework contains two subsystems: company and project subsystems. Each one plays an equally vital role in the entire framework and exerts mutual influence on the other.

Subsystem on Company Level

The subsystem on company level is based on the BSC framework with basic characteristics of VSM (Figure 1). *Leadership*, at the top of the framework, serves as *System 5* (boss system) and it sets a construction enterprise's vision and mission, and formulates organizational strategies. *Operation manager* serves as *System 3* (tactical management system), and translates a company's vision and strategies into targets and priorities. Being highly flexible in its mission, *Operation manager* also controls the plan's operations and implements any changes.

The four perspective boxes of the BSC framework are applied below *operation manager*. The financial perspective, which represents shareholders, serves as *System 2* (supervisory system). The indicators of the financial perspective, like profitability and cash flow, provide guidelines to the operational business units. The customer perspective generally represents the market and the internal business perspective represents productivity, and both perspectives serve as *System 1* (operational units) focusing on productions and services. Construction enterprises are required to fulfill various functions, such as project construction and operation, contract obtainment, procurement, and client services. Performance measurement on this level is the performance advancement foundation of the whole company subsystem. The innovation and learning perspective serves as *System 4* (developmental system) focusing on identifying performance disadvantages and pointing out potential improvement. An environmental perspective is added to the company subsystem to

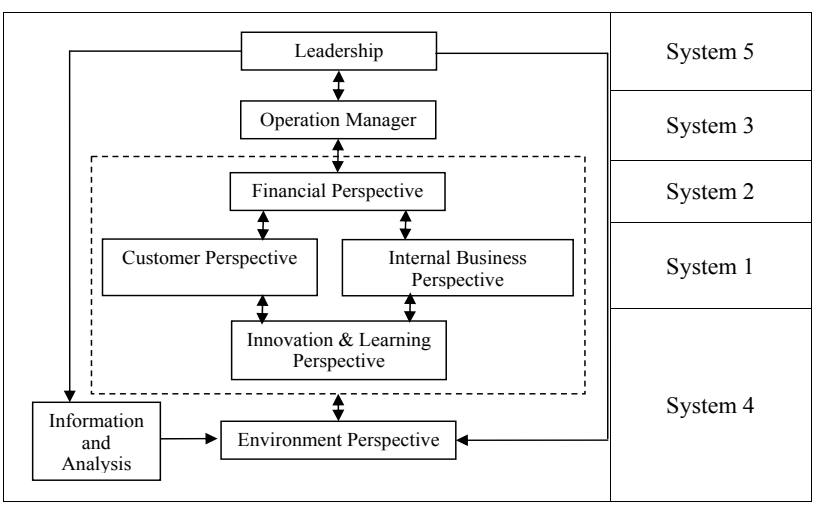


Figure 1. Subsystem on company level of the bi-level framework

represent an extension of the current BSC by including important organizational factors like suppliers, partnership, competitors, etc. It also serves as a part of *System 4*

(developmental system) because its connection with the external environment will assist a construction enterprise in realizing its performance disadvantages and prompt actions to reduce them.

To support the whole structure of the framework, deployment is designed (arrows in Figure 1) to serve as two main types of activities: 1) translating strategies, targets and priorities from the prior system to the latter system; and 2) getting feedback from the latter system to adjust to the objectives and operations of the prior system. To assist deployment with operating the whole system, *Information and analysis* has been entrenched into the company subsystem, which serves to collect data for the operation of the company subsystem and adjust for continuing promotion.

Subsystem on Project Level

The nine-knowledge-area framework of *Project Management Body of Knowledge* (PMBOK) (PMI 2004) is applied as the basic structure for the project subsystem. The nine knowledge areas were summarized from the practices of project programs, and qualified performance in these areas is indispensable for project success. Therefore, the project subsystem is organized based on the PMBOK framework, and also possesses the basic characteristics of a VSM as the company subsystem (Figure 2).

Project plan, defined and organized from contracts and drawings of a project, serves as *System 5* (boss system). The nine management areas of the PMBOK are arranged after the *project plan* and divided into four portions. I*ntegration management* serves as *System 3* (tactical management system), translates the plan into phase targets and adapts to changes during the project lifecycle. *Integration management* in a construction project mainly executes the entire project management and control changes, thus it provides support to other management areas. The other eight areas serve as *System 2* (supervisory system) and *System 1* (operational units). *Time, cost,* and *quality management* exert main influences on the performance of construction projects and are arranged directly before *project result*. *Scope* and *human resource management* start in the early phase of construction delivery, and the *communication, risk and procurement management* are indispensable during the construction phase. Performance measurement in these nine areas promotes efficiency of construction project programs and controls their operations and executions.

Project result serves as *System 4* (developmental system), since project results provide qualitative and quantitative results to analyze. Therefore, it is possible to discover technical, operational or communication problems and overcome negative performance through the adoption of advanced construction technologies or management efforts.

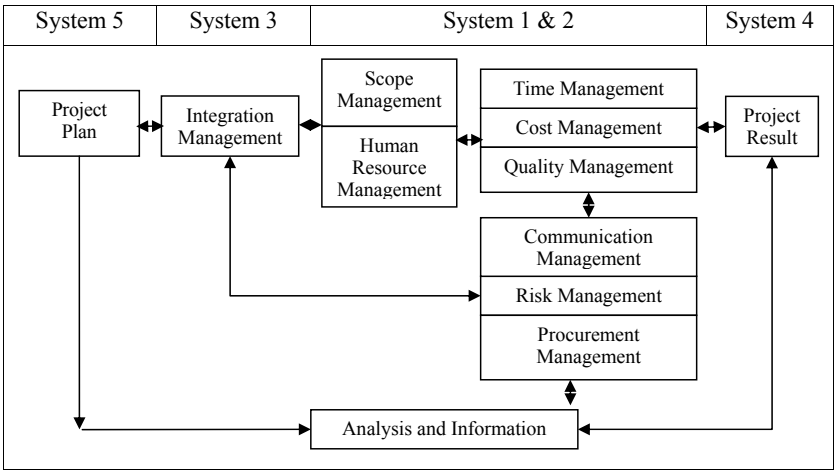


Figure 2. Subsystem on project level of the bi-level framework

Information and analysis is also applied in the project subsystem to support the process of performance data collection and project control.

System Validation

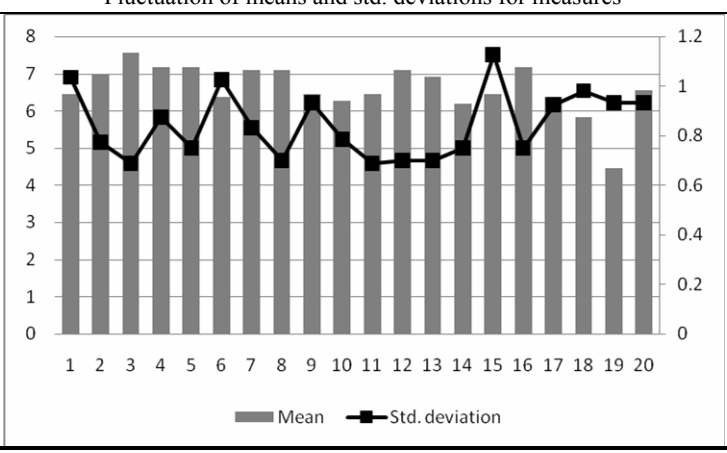
To validate the proposed bi-level framework, a structured interview was carried out with 11 experts from industry and academia, who average over 20 years experience in performance measurement. The descriptive statistics for the raw data were analyzed using SPSS Statistics v17.0© and the interview results follow:

1. The majority of the experts believe profit is the most important indicator of greatest concern for companies. Moreover, the BSC framework is deemed as the most widely used and accepted performance framework by the interviewees. One pointed that BSC's compatibility enhances its application with other performance methods.
2. Most experts believe that it is necessary to organize the framework into two subsystems, because performance on both company and project levels is important for construction enterprises. A couple of experts viewed the project should be a part of company level management, an opinion shared by Kagiouglou et al. (2001). Besides, all the experts believe it is appropriate to apply the PMBOK into the performance measurement, but several of them pointed out that the nine aspects should be weighted to identify the priorities for project management, or the measurement processes may be out of proportion.
3. For the company subsystem of the bi-level framework, different measures in different perspectives were rated by the experts from 1 to 8. Means and standard

Table 1. Interview results of measures on company level

Perspective	Measure	Mean	Std. deviation
Financial	1. return on capital	6.45	1.0357
	2. cash flow	7.00	0.7746
	3. profitability	7.55	0.6876
	4. reliability of performance	7.18	0.8738
Customer	5. customer focus	7.18	0.7507
	6. market share	6.36	1.0269
	7. quality of service & work	7.09	0.8312
Internal business	8. employee focus	7.09	0.7007
	9. business efficiency	6.45	0.9342
	10. manager competence	6.27	0.7863
	11. standard communication	6.45	0.6876
	12. safety/loss control	7.09	0.7007
innovation & learning	13. Human resource training & development	6.91	0.7007
	14. organization competency	6.18	0.7508
	15. informatization	6.45	1.1282
environment	16. partnerships and suppliers	7.18	0.7508
	17. competitor	6.36	0.9244
	18. society/environment impact	5.82	0.9817
	19. policy/law of government	4.45	0.9342
	20. risk control	6.55	0.9342

Fluctuation of means and std. deviations for measures

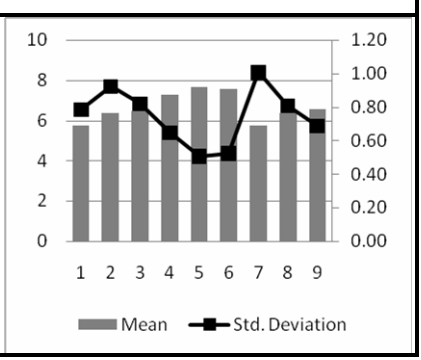


deviations of the data are presented in table 1 and they show divergent results. For the financial perspective, *profitability* receives the highest common attention (highest mean and lowest std. deviation). The measure of *return on capital* has relatively high standard deviation, showing that opinions are divergent on its importance. For the customer perspective, *customer focus* received more concerns from the interviewees. For the internal business perspective, personnel value and employee rights are emphasized, with more focus on *employee and safety*. For the innovation and learning perspective, personnel factors (*human resource training & development*) again enjoy more attention. Ratings on *informatization* present the highest standard deviation, reflecting one opinion that it can be "too much financial or technique burden, especially for small sized companies." The measures for the additional environmental perspective have very divided ratings. Several interviewees asserted that the environmental perspective is not necessary, but their rating for the measures of *partnerships and suppliers, competitors and risk control* are relatively high (all above 6).

4. For the project subsystem of the bi-level framework, the nine management areas were also rated by the experts also from 1 to 8. Based on the results of means and standard deviations showing in Table 2 they also show different priorities. Project *time, cost* and *quality* management are consistently viewed as most critical. *Communication* management, though receiving less focus on average, presents high standard deviation, indicating opinions on its importance are greatly divergent. The expert who rated it as 4, the lowest of all, maintains the view that communication management should be categorized as a part of integration management and it is difficult to measure. However, several experts confirmed its importance due to it being one key solution to address construction and engineering complexity.

Table 2. Interview results of areas on project level

	Mean	Std. Deviation
integration	5.73	0.79
scope	6.36	0.92
human resource	6.45	0.82
time	7.27	0.65
cost	7.64	0.50
quality	7.55	0.52
communication	5.73	1.01
risk	6.36	0.81
procurement	6.55	0.69



Illustrative Case Study

This case study illustrates the potential adoption of the bi-level framework into business practice. A real estate construction company was selected, due to its current performance difficulties, and the bi-level framework is applied to analyze these problems and provide potential solutions. The target enterprise for the case study is a leading real-estate company focusing on designing, constructing and transacting high-profile branded commercial properties in a metropolis in China. This company has approximately 1000 employees and, due to its international collaboration and an economic boom, the company has maintained high profits during the last five years. However, because of the changing business environment, the annual turnover in 2008 declined by 50% and the net profit has been cut 80% compared to 2007. The company generally uses the KPI model and focuses on financial indicators and internal business processes.

The serious decrease in business has forced the company to rethink their methods for performance measurement. After collecting sufficient information, the bi-level framework is applied to the target company to analyze company operation and projects in 2008. On the company level, the analysis shows that the leaders of the company should set the development of new markets as an additional strategy or objective to increase its ability to face environmental changes. Also, the enterprise must establish a more efficient and feasible management system with emphasis on risk analysis and control. On the project level, project planning must be careful and consider factors like project type diversity and market diversity. Also, the project manager should be trained to improve their execution ability.

The case study shows that the bi-level framework is an applicable measurement system that could be utilized to provide deep and integrated insight and to analyze the performance of a construction enterprise. Its detailed measures help the enterprise identify problems and improvements on both company and project levels.

Conclusions and Future Study

In an effort to improve the productivity of construction enterprises, this proposed paper presents an innovative bi-level performance measurement framework that combines both company and project subsystems, and the VSM is built in to enhance the integrity. The company level subsystem is guided by *leadership* and coordinated by *operation managers.* The following structure is organized around the BSC framework, and an additional environmental perspective is included to provide more insight for external influences. *Information and analysis* is also embraced to support the operation of the subsystem. The project level subsystem is directed by *project plan* and structured around the nine management areas of PMBOK. *Integration management* is defined as the tactical system to coordinate the other areas of management. *Information and analysis* is also incorporated to assist data collection and control project progress.

A structured interview was conducted to validate the bi-level framework, and a

case study was applied to test its practical application potential. The positive results confirm that this bi-level framework offers construction enterprises a comprehensive and integrated system to measure performance on both the company and project levels. The following research will concentrate on investigation of the detailed implementation of this framework. Once the framework has been observed in operation, the authors intend to identify key areas for empirical study and further refine the framework.

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Causes of Variation in Construction Task Starting Times and Duration

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Abstract

Variation in construction task starting time and duration can impact overall productivity performance, yet their root causes often remain unclear. In this research, variation is defined as the difference between what was planned and what actually happened. This paper examines the variation in starting time and the duration of construction tasks while considering 50 productivity factors. The 50 factors were divided into eight categories: prerequisite work, detailed design / working method, labor force, tools and equipment, material and components, work / jobsite conditions, management / supervision / information flow, and weather or external conditions. A nationwide survey involving craft workers, foremen, and project managers was employed and serves to offer valuable insight on the causes and impacts of variation. The findings will help construction project managers and field managers identify the common risk factors, focus on the root causes of variation in planning phase, develop effective strategies to reduce variation, and improve project

Introduction:

Variation almost always exists in the construction work process and it inevitably can have a significant impact on labor productivity, yet the root causes of variability often remain unclear. Ballard et al. (2003) argued the first line of defense advocated by lean construction is to reduce variability in an effort to reduce waste and ultimately increase productivity performance. Thomas et al. (2002) examined the impacts of variability in work flow and daily construction productivity using a factor-resource model to depict the resources and disruptions that affect productivity. They concluded that reducing variability of daily productivity is correlated to improved performance. They considered variability associated with the overall categories, such

as congestion, sequencing, weather, and rework, but did not explore further into these categories to identify the root causes of variation.

The lack of in depth understanding of the root causes of variation and its impact on labor productivity directly and indirectly lead to difficulty in controlling variation, decreased reliability of the construction work plan, and decreased productivity performance. Therefore, the objectives of this research are to:

- Objective 1: Determine the general causes of variation on starting time and duration of construction tasks based on opinions/perceptions of project managers, foremen, and workers – examine any differences in opinions/perceptions.
- Objective 2: Identify the most prevalent factors in terms of the variation of task starting time and task duration.
- Objective 3: Compare penalties associated with not reducing variation, from the perspective of project managers, foremen, and workers.

Literature Review:

The first step to addressing the topic of variation is to define it. There are several different definitions of variability or variation as it pertains to labor productivity. Rilett (1998) defined variability as the variance associated with a component or end product specification in construction projects. Tommelein et al. (1999) defined work flow variability as the standard deviation from an expected average. Radosavljevic and Horner (2002) defined variance in construction labor productivity as standard deviation, a measure of dispersion from the mean. Thomas et al. (2002) calculated variation of productivity as the average of the absolute value of the difference between daily productivity and the baseline productivity. Howell et al. (2004) measured variability of work flow by comparing the tasks assigned (those tasks that "will" be done), to those completed (i.e. what "did" get done). Percent of Plan Completed (PPC), the ratio of the number of tasks 100% completed to the number of tasks planned, is used to indicate work plan variability. Koskela (2000) defined variability as random variation in the processing times or arrival of inputs. For this research, 2 types of variation are defined 1) the variation of construction task starting time: the difference in planned task starting time and actual task starting time, and 2) the variation of construction task duration: the difference in planned task duration and actual task duration. This definition follows that used by Howell et al. (2004) while it breaks variation of entire tasks into task staring time and duration. Howell and Ballard (1994) discussed the importance of reducing variation to stabilize work flow. They argued that reduced variation, coupled with bottom-up planning, provides a better means to match work objectives in terms of what "should" and "can" be accomplished from an operational standpoint. Their research was focused on the planning phase of an operation and did not examine root causes of variation in detail, nor did it consider variation from the perspectives of different position levels (i.e. laborers, foremen, and project managers). Howell et al. (2002) showed that reducing variation in work flow will improve performance. They demonstrated that reducing variation to improve planning reliability from 50% to 70% can theoretically increase

productivity by 30% (i.e. from 50% to 65%). This research provided useful insight on the importance of variation; however, the authors also stated there was a need for empirical and quantitative analysis in future research. Thomas et al. (2002) examined the impacts of variability in work flow and daily construction productivity. They considered variability associated with congestion, sequencing, weather, and rework; however, there is a gap in knowledge as they did not explore further into these categories to identify the root causes of variation.

A significant amount of research has been performed in reference to factors affecting construction productivity. An extensive literature review was conducted to develop a thorough baseline of factors to consider when examining variation. Due to space limitations, only the most recent publications are discussed in any detail. The other authors included in the literature review were: Borcherding and Gardner (1981), Thomas and Yiakoumis (1987), Herbsman and Ellis (1990), Thomas and Sakarcan (1994), Portas and AbouRizk (1997), Somnez and Rowlings (1998), Rojas and Aramvareekul (2003), and Liberda et al. (2003). Dai et al. (2009) implemented a nationwide survey involving nearly 2000 craft workers to examine the impacts of 83 different productivity factors. Factors involving tools and consumables, materials, engineering drawing management, and construction equipment were identified as having the greatest impact on productivity from the craft workers' perspective. Kimpland (2009) divided the top factors into two categories; internal and external. Lack of foreman planning and communication skills, cultural resistance to change, poor communication between foremen and project managers, and lack of technical training at the craft level were the top internal factors. Poor quality of plans and specifications, slow responses to questions, unrealistic schedule demands from the customer, and lack of qualified foremen and craft workers were the top external factors. Based on literature review, 50 factors were identified to study the root causes affecting construction task variation for starting time and duration. The selection of the 50 factors was based on the following 3 procedures: 1) removing factors that only suitable for specific projects and tasks; 2) combining similar factors and factors under the same category (for example, hard hat, safety vast, safety net were combined as personal protective equipment); and 3) grouping the 50 factors into 8 main categories: prerequisite work, detailed design, labor force, tools/equipment, material and components, work/jobsite conditions, management/supervision/information flow, and weather or external conditions.

Methodology:

In order to answer the research questions, a questionnaire survey was developed. The survey was employed nationwide to collect the desired information pertaining to the variation of task starting times and duration. It involved craft workers, foremen, and project managers and consisted of three parts. In the first part, respondents provided background information such as their trade, position, size of their company, whether they work for a union or not, and their level of experience. The second part of the survey involved rank ordering the eight overall categories (previously identified) based upon how much they contribute to the variation of task starting times and task

duration times. The third part of the survey, respondents indicated how many weekly hours of variation, in terms of task starting times and task duration, they experienced due to each of the 50 individual factors.

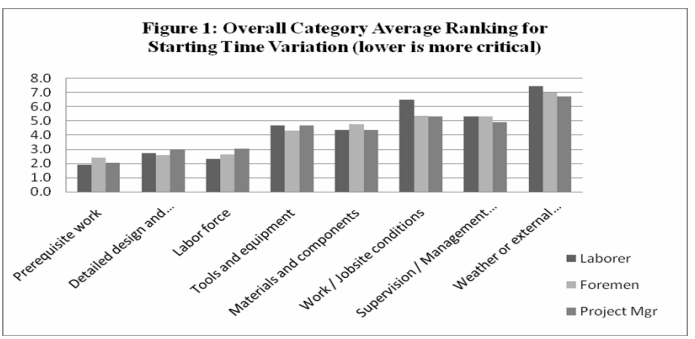
Careful attention was given to several potential problems area regarding errors associated with surveys. To mitigate measurement errors due to language barriers, the survey was translated to Spanish as many people in the construction industry speak Spanish as their primary language. A pilot study was conducted with a local construction company to reduce potential measurement errors due to weaknesses in the wording of questions and/or the lack of requisite instruction for respondents to answer the questions. Both the online version and the paper version utilized the same format to minimize any error due to the mode of data collection. The survey was distributed with the assistance of 22 US Army Corps of Engineer district offices, which are located throughout United States to address problems with coverage areas. These districts oversee all construction that is performed for the Corps of Engineers; thus, they are in contact with a large number of construction contractors. These are civilian contractors performing public work under a government contract. Thirty six district offices were contacted in the summer of 2009 and 22 agreed to assist with distributing the survey to their contractors. About five weeks (23 July – 30 August 2009) were allotted for the survey to be distributed, taken, and returned.

Survey Response and Analysis:
Fifty percent (11/22) of the districts responded to the survey with 84 online responses and 28 hard copies returned by mail. Of these 112 responses, 13 were not used in the analysis because they were either incomplete or the responses contained extreme outliers. Project managers made up 55% of the responses, followed by laborers with 25% and foremen with 17%. The remaining 3% of the respondents did not identify their position. Subcontractors and general contractors respectively provided 68% and 24% of the responses, with the remaining 8% unspecified. Thirty four percent of the respondents were associated with four or more trades. Twenty seven percent were associated with concrete, 16% with piping or plumbing, 8% with mechanical or HVAC, and 8% with earthwork. The remaining 7% was split among electrical, steel, roofing, drywall, or unspecified trades.

Objective 1:
Laborers, foremen, and project managers all rank ordered the eight overall categories in a very similar fashion both in terms of starting time variation and duration variation. Figures 1 and 2 illustrate the overall ranking, where smaller values represent a greater contribution to variation. Prerequisite work, detailed design / working method and the labor force were the top three categories influencing starting time variation. It is interesting to note that while laborers, foremen, and project managers all consistently regard prerequisite work as the top category to start tasks, project managers and foremen regard detailed design and working method as #2 and labor force as #3, while laborers rank labor force as #2 and detailed design as #3. The reasons may be that different groups of people focus on their roles and therefore think

their roles have a higher impact. Compared with laborers, project managers and foremen need to spend a large amount of time and effort to clarify detailed design and develop the working method. Therefore, they both agree this category should rank #2 and is more important than labor force.

Labor force, supervision / management / information flow, and materials / components represented the top three categories in terms of contribution to task duration variation. Again, while laborers, foremen, and project mangers consistently rank those categories as the top 3, laborers rank laborer force as #1 and project managers rank supervision/management as #1. Laborers believe that materials and component rank #2 and supervision/management rank #3 in terms of affecting variation in task duration. The reason is that by the time the task gets started; laborers probably already know the work method. It is likely that they may find a wrong size or wrong type of material only after they start work and it can significantly affect task duration.



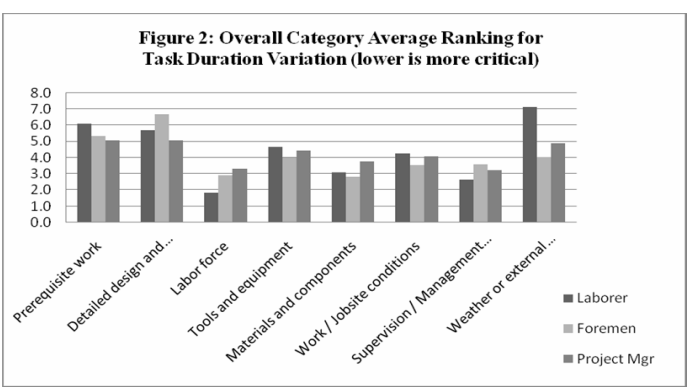


Figure 3 provides an overall picture of the individual categories and captures the total weekly variation (starting time + duration) based on the perceptions of laborers,

foremen, and project managers. It is apparent the magnitude of variation increases as the scope of responsibility increases, which is to be expected. The responses of laborers reflect those categories that impact their individual tasks or those of their crew. Foremen are responsible for several crews; therefore, it is not surprising the overall magnitude of variation increases when considering it from their perspective. A similar explanation holds true for project managers.

It is interesting to note the apparent discrepancy between Figures 1 and 2 and that of Figure 3. The labor force was one of the top categories in both Figures 1 and 2, yet it ranks in the bottom half of the categories when considering the total average weekly variation represented in Figure 3.

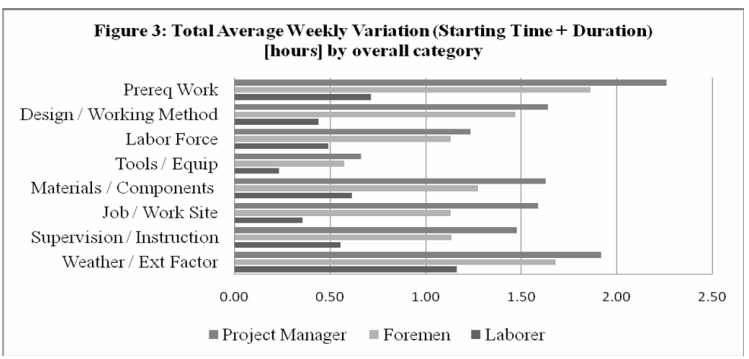


Figure 3: Total Average Weekly Variation (Starting Time + Duration) [hours] by overall category

The weather category is similar as weather is ranked relatively high (not as significant) in Figures 1 and 2, yet it is one of the top categories when examining Figure 3. The difference between the three figures may represent the respondents' perception of severity and frequency. Figures 1 and 2 represent the severity of the impact of variation for each category; not necessarily how frequently the variation occurs or how long each variation last, whereas Figure 3 represents the frequency and length of variation experienced on a weekly basis.

Objective 2:

In order to determine the most prevalent factors causing starting time variation, the 50 factors were rank ordered three times (once by each of the three duty positions – laborer, foreman, and project manager) based upon the amount of variation they caused. These rankings were then consolidated, while capturing the top five factors according to each duty position, to identify the top overall factors contributing to starting time variation. Table 1 contains these top eight factors. Although ordered slightly different, the top three factors in the view of laborers, foremen, and project managers was the same. It should be noted that the first and third factor are essentially the same; the question pertaining to turnaround time was included in two areas of the survey. There is a difference in the perceptions between laborers and that of the foremen and project managers. The laborers state needing guidance or

instruction from their supervisor and people arriving late and/or leaving early are the 4th and 5th highest causes of starting time variation; however, the foremen and project managers don't have the same perception as foremen rank those two factors 10th and 11th respectively. Project managers' perspectives differ by an even greater amount as they rank those two factors 20th and 16th respectively. There is not a significant difference between the perceptions of the foremen and project managers with regard to starting time duration as all of their top five factors are ranked within the overall top six factors.

Table 1: Top eight factors affecting starting time variation based on the responses of laborers, foremen, and project managers.

No.	Factor	Laborer Responses		Foremen Responses		Project Manager Responses	
		Hrs/Wk	Rank	Hrs/Wk	Rank	Hrs/Wk	Rank
1	Turnaround time from engineers when there is a question with a drawing	1.04	2	1.65	2	2.97	1
2	Completion of previous work (i.e. work before you isn't done yet)	1.44	1	1.62	3	2.64	2
3	Wait to get answers to questions you have about the design or drawing	1.00	3	1.79	1	1.95	3
4	Obtaining required permits for the work to begin	0.50	7	1.29	5	1.35	5
5	Quality of documents (errors in design and/or drawings)	0.54	6	1.00	9	1.48	4
6	Rework being required due to the quality of previous work	0.44	9	1.29	4	1.31	6
7	People arriving late and/or leaving early due to illness, injury, family or personal reason, etc.	0.58	5	0.97	11	0.93	16
8	Need guidance/instruction from supervisor	0.70	4	0.97	10	0.90	20

A similar approach is used with examining the variation of task duration. The nine most prevalent factors are shown in Table 2. There was more discrepancy in perspectives when examining the task duration variation than there was with the starting time variation. The laborers stated, as they did with starting time variation, that needing guidance from their supervisor and people arriving late and/or leaving early are the 4th and 5th highest causes of task duration variation. Once again, the foremen and project managers didn't have the same perception as foremen ranked those two factors 12th and 15th respectively. Project managers' perspectives differed by an even greater amount as they ranked those two factors 26th and 19th respectively. There is another difference in perception to illustrate when considering the sixth overall factor - rework. Rework is in the top five factors for both the foremen and

project managers, but is ranked 15th in the view of the laborers. The only indication of a significant difference in perspective between the foremen and the project managers is with respect to the seventh overall factor - worker/crew skill level. The project managers rank this as the 4th most important factor affecting task duration variation. The laborers have it as 9th (still in their top ten), but foremen rank this 17th.

Table 2: Top nine factors affecting task duration variation based on the responses of laborers, foremen, and project managers.

No.	Factor	Laborer Responses		Foremen Responses		Project Manager Responses	
		Hrs/Wk	Rank	Hrs/Wk	Rank	Hrs/Wk	Rank
1	Wait to get answers to questions about the design or drawing	0.74	1	1.68	1	1.96	1
2	Turnaround time from engineers when there is a drawing question	0.54	2	1.24	3	1.93	2
3	Completion of previous work (i.e. work before you isn't done yet)	0.40	7	1.29	2	1.81	3
4	Socializing (talking with fellow workers)	0.54	3	1.15	8	1.42	6
5	Weather impacts (excessive heat, cold, wind, rain, etc.)	0.50	6	1.18	5	1.23	11
6	Rework being required due to the quality of previous work	0.24	15	1.24	4	1.49	5
7	Worker/crew lack of skills/experience to perform the task(s) being asked of them	0.32	9	0.76	17	1.58	4
8	People arriving late and/or leaving early due to illness, injury, family or personal reason, etc.	0.52	5	0.76	15	0.93	19
9	Need guidance/instruction from supervisor	0.52	4	0.88	12	0.81	26

Although there are some perceptual differences between laborers, foremen, and project managers, the overall factors are consistent with previous research. Dai et al. (2009) found engineering drawing management to be one of the top three areas that affects productivity. Kimpland (2009) found poor quality of plans and specifications and slow responses to questions to be the top two external factors impacting productivity. In this research, waiting to get answers back / turnaround time for questions pertaining to the design or drawing and the quality of the design documents were also among the most prevalent factors for variation.

Objective 3:
There are two key points to emphasize when considering the results of this research and the previous discussion. First is the impact variation in starting time and task duration has on productivity. The laborers claim they experience 4.5 hours (determined from Figure 3) of total variation during an average week. This represents over a 10% loss in available hours when assuming a 40 hour work week. Considering the project managers' responses, we find a total average weekly variation of 12.4 hours, which can account for a 30% loss in available hours. The second key point has to do with the importance of information flow up and down the chain of command. The significance of a two hour variation in a task starting time may be significantly different for a laborer, foremen, and a project manager. For a laborer, the overall result may just mean a delay of two hours. For the project manager, the two hour variation could have second order effects. For example, the task that experienced the variation may have been a critical activity and the fact it was delayed by two hours may affect several other activities as well. This is why information flow is essential and there needs to be a mechanism in place to identify the critical information requirements (i.e. what does the project manager, foreman, etc. really need to know) and ensure people at all levels understand these.

Conclusions
Previous research has not done been conducted in terms of splitting the variation between starting times and duration. This research identified prerequisite work, detailed design / working method, and the labor force as the top three categories influencing starting time variation. In terms of task duration variation, the labor force, supervision/management/information flow, and materials/components were the top three categories. The most prevalent individual factors for both task starting times and duration were turnaround time for questions about the design or drawing and completion of previous work. The results of the research indicate a problem with schedule reliability and an inability to ensure laborers have correct design drawings in order to do their work. Strategies that involve collaborative planning among all levels of responsibility will significantly reduce or eliminate these problems by creating a more reliable schedule. Collaborative planning will also reduce or eliminate the number of questions about the design as these questions will be answered during the design process if the end users are involved during the planning.

One of the limitations of this study is that it was based on perceptions of those who took the survey. Although 50% of district offices that received the survey responded, the results may not represent the construction industry in general. The survey was sent to US Army Corps of Engineer district offices, which means that all the respondents were currently working on public projects. Additional survey forms have been sent to private construction companies to gain a perspective of those working on private projects. These results will be analyzed and included in future research.

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Comparison of Construction Labor Productivity between U.S. and China

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Abstract

One of the main entry barriers faced by U.S. construction firms for entering the booming Chinese construction market is the acquisition of accurate labor productivity data in China. The accuracy of labor productivity data can mean the difference between the success or failure of the construction projects. Due to the sheer diversity and complexity of international construction practices, minimal research has been performed on comparative labor productivity between U.S. and China. Research is currently being conducted to assist U.S. construction firms in competing in the Chinese market. The U.S. labor productivity data is obtained from *RS Means* while the Chinese labor productivity data is collected on-site in Chongqing, China (Chongqing is the largest and most populated municipality of China's four provincial-level municipalities). Comparative review of collected productivity data d will help enhance U.S. construction firms' competitiveness in the Chinese market and improve their project management capabilities in China.

Introduction

In 2007, U.S. construction spending totaled $1.25 trillion, with over 7 million employed, contributing $611 billion or 4.4% to the gross domestic product (GDP) (AGC, 2009). As for China in 2008, direct Chinese construction spending contributed a total of Renminbi (RMB) 1,707 billion yuan (US$250 billion) or 5.7% to the total GDP of RMB 30,067 billion yuan (US$4.4 trillion), up 7.1% over the previous year (see Figure 1) (NBS, 2009). The construction industry is an important sector for both countries' economies. Investment in plant and facilities, in the form of construction

activity, provides the basis for the production of products and the delivery of services (Chapman and Butry, 2009). It is clear that the industry has an impact on nearly every aspect of the economy and is vital to the continued growth of the country's economy. Therefore, construction project performance has always been an important concern of project owners, constructors, management professionals, and design professionals. Project cost and schedule performance depend largely on the quality of project planning and work area readiness preparation – the resulting productivity of the work process made possible in project execution (Picard, 2004). Labor productivity has always been one of the greatest risk factors and source of cost and schedule uncertainty to owners and contractors alike.

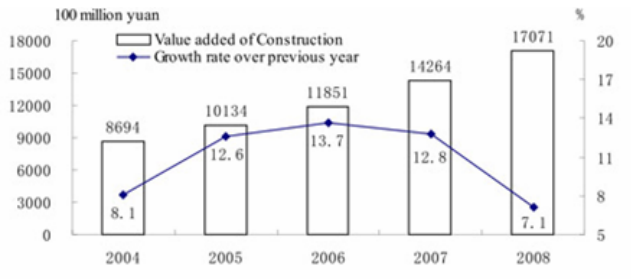


Fig. 1. Value-added of construction industry of China and its growth from 2004 to 2008 (NBS, 2009)

In both the developed and developing countries, with U.S. and China as specific examples, the construction industry has played a fundamental role in the process of economic development. As construction is a labor-intensive industry, small and medium sized businesses are the mainstay of some segments of the construction sector in the countries' economy. Construction is also diverse with respect to matters relevant in competition policy. Competition in the construction sector is usually highly localized, but the competition for the award of some large projects can be national or even transnational in geographic scope. For U.S. construction firms entering the booming Chinese construction market, the entry barriers derive from the possibility of the U.S. construction firms having to acquire the technology, the accumulation of experiences from previous Chinese construction, and the achievements reached by research and development of Chinese constructors.

Minimal work has been done on the labor productivity comparisons between U.S. and China due to limitation of data and the complexity of international standards. As project particularity in the construction industry results in product heterogeneity, it is impossible to produce homogeneous products of construction works through mass manufacturing (OECD, 2008). Therefore, in large part due to its impact on competitiveness and its influence on the success of the project, construction firms in the U.S. and China need to take a detailed look at the productivity of its workers.

Chinese Construction Industry

In China, the construction industry has played a powerful role in sustaining economic growth, in addition to producing structures that improves industrial productivity and quality of life over the recent years. According to the Engineering News-Record (ENR) Top 225 Global Contractors 2008, there are four Chinese construction firms are ranked in top ten and a total of fourteen Chinese construction firms are ranked in top one hundred in the world, compared to only nine were ranked in top one hundred in 2000. As for the ENR Top 225 International Contractors, China has become the country with the highest number of contractors being ranked in 2007 with 51 firms, compared to only 34 in 2000. The difference between the ranking of the Top 225 Global Contractors and the Top 225 International Contractors is that the global contactors are ranked by its construction contracting revenue both at the home country and abroad, and the international contractors are ranked by the revenue generated only outside its own home country (Huang, 2009). Table 1 shows the number of ranked Chinese construction firms between 2000 and 2007.

Table 1. Number of Chinese construction firms ranking between 2000 and 2007 (Huang, 2009)

	The Top 225 Global Contractors					The Top 225 International Contractors				
Year	1-10	11-50	51-100	101-225	1-225	1-10	11-50	51-100	101-225	1-225
2000	0	4	5	8	17	0	2	7	25	34
2001	0	5	6	8	19	0	4	9	27	40
2002	0	5	5	8	18	0	3	12	28	43
2003	0	5	6	8	19	0	5	8	34	47
2004	0	8	5	9	22	0	4	5	40	49
2005	2	5	5	11	23	0	3	9	34	46
2006	4	3	4	14	25	0	2	12	35	49
2007	4	4	6	13	27	0	4	9	38	51

Source: ENR–The Top 225 Global Contractors and the Top 225 International Contractors (2000-2007).

Today, many projects in China are constructed by various local firms as well as joint ventures between Chinese and U.S. companies. Given the involvement of the Chinese companies in almost all construction projects, a trade war could dramatically reduce opportunities for U.S. construction firms. However, at this time, the China's National Housing Reform provides enormous opportunities for U.S. firms. According to the U.S. Embassy in Beijing, China expects to build between 486 million and 549 million square meters of floor space annually in the first 20 years in the 21st century. U.S. firms will surely have a major role to play because Chinese firms often lack experience with large-scale projects such as skyscrapers, and many new building technologies, equipment and materials which come from U.S. In this regard, to satisfy project owners and funding agencies and to fulfill specifications, it is imperative for U.S. firms to obtain the immediate data on construction cost and productivity which needs to be readily available for cost estimating, bidding and scheduling purposes.

Meanwhile, the construction activities in China are generally more labor intensive, physically demanding, and time consuming comparing to the extensive mechanization of construction in a highly developed U.S. construction industry. It is widely known that labor productivity is extremely difficult to measure due to the heterogeneity of the construction industry's products and inputs (Koehn and Ahmed, 1998). There is also no common definition of labor productivity in the industry. Even when definitions are consistent, approaches to measuring input and output vary so greatly that valid comparisons between projects in the U.S. and China are almost impossible. As a result, the most important element associated with the efficient operation of a project in the U.S. and China remains in labor productivity, which is quantitatively the most abundant but unstudied resource in both countries' construction industries. Furthermore, there is a need for better measurement approaches that apply more specifically to the work at the task level.

Definitions of Construction Productivity

In the U.S. construction industry, productivity is being defined as "to measure the effectiveness with which management skills, workers, materials, equipment, tools and working space are employed at, or in support of, work-face activities, to produce a finished building, plant, structure or other fixed facilities at the lowest feasible cost" (Oglesby et al., 1989). Dozzi and AbouRizk (1993) defined labor productivity as measured at an activity level, and because construction activities are normally labor intensive, productivity at the activity level is frequently referred to as labor productivity, which measures the input as labor hours and the output as installed quantities. As shown in the equation below, labor productivity is the ratio of the quantity of input to the quantity of output.

$$\text{Productivity} = \frac{\text{LaborHours}}{\text{CompletedWork(Unit)}}$$

When it is defined in detail manner, the labor productivity is measured in actual work hours per installed quantity and the lower productivity values indicate better productivity performance (Park et al., 2005). Productivity also has another definition, including performance factors production rate, and unit person hour rate. Generally in construction, productivity is stated as an in-place value divided by inputs, such as work hours. Although most project owners and contractors adhere to the definition of productivity as dollars of output per dollars of input or an increase in sales, this definition is not widely accepted (Adrian, 2004). Therefore, thereby substituting dollars for person-hours of input, labor productivity is the ratio of physical output per unit of work hour requirements as shown in the equation below.

$$\text{Productivity} = \frac{\text{PhysicalOutput(Units)}}{\text{LaborHours}}$$

Research on Productivity Competitiveness

Productivity is a way of measuring how much a sector in construction industry to produce by a given amount of resources or how much resource is needed when producing a given number/volume of a product. The reason for measuring productivity is to understand the production processes and learn about capacity of machinery and workers (Ingvaldsen et al., 2004). Measuring productivity is to quantify how efficient resources are used and to provide the performance ability of companies/project owners/contractors in a competitive market.

In response to the industry needs, the primary goal of this research is to conduct an accurate measurement of on-site construction productivity in China for comparison of labor productivity in the U.S. at task level. To realize this goal, the following objectives need to be accomplished: (1) to conduct on-site data collection in China; (2) to analyze and compare the effectiveness of building construction productivity from collected data and reference; and (3) to provide a summarization of research and guidelines for future development of on-site construction productivity measurement. It is widely accepted that productivity measurement plays an important role in the construction management process. Productivity measurement provides the necessary data to analyze factors for project owners, constructors, and management professionals to control construction progress, estimate the cost of future construction projects, and determine its competiveness in the global market. In achieving these objectives, the researcher hopes that it could help the U.S. construction firms stay competitive and profitable in the Chinese and global markets.

Labor Productivity Measurement in China

Measurements of productivity are the prerequisite for improving the labor productivity in the construction industry by qualifying current performance. To achieve this goal, this research effort is being proceed to measure and document the record of and will help to understand the construction labor productivity at task level in Chongqing, China. This research is based on a collaborative arrangement between the University of Kansas and the Chongqing University in China. Assistance is being provided from faculty members, Prof. Guiwen Liu and Ms. Wenhua Hou, in the Chongqing University Faculty of Construction Management and Real Estate for an in-depth examination of construction productivity measurement arrangement, advisement about Chinese ethical issues involved in conducting research, providing research assistants from the Chongqing University to assist one of the researchers in conducting on-site measurements, and selecting multiple building construction sites in Chongqing area to collect labor productivity data. There are three frequently used techniques – time studies (stopwatch), work sampling, and foreman delay survey methods – that are being used in this research. These methods have the desirable features of providing information rapidly. The similarity in these methods is to obtain data of time spent on direct work activities, contributory activities, and nonproductive activities.

The researchers started the data collection on a jobsite in Chongqing for a period of five weeks since mid-October of 2009 (see Figures 2 and 3). Data collection from on-site observation has made possible evaluations of project performance in relation to appropriate indicators at a latter study. There are three general principles which guide the researchers during data collection: (1) be consistent in methods used; (2) document methods thoroughly; and (3) integrate monitoring and evaluation activities with implementation activities.

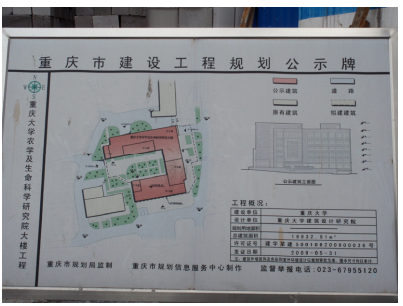


Fig. 2. Jobsite at Chongqing University


Fig. 3. North entrance of building jobsite

Data Collection Procedure

In this research, the work sampling method has been used to measure and assess the construction work process, and provide useful, nearly real-time information about the process. The work sampling is based on non-probability sampling theory. The difference between non-probability and probability sampling is that non-probability sampling does not involve random selection and probability sampling does. Therefore, the work sampling method is purposive with a specific plan in mind. The actual, qualitative data obtained by work sampling ensures objective assessment of the work process.

The researcher and research assistants strived to be as unobtrusive as possible so that no bias to the on-site observations for productivity measurement. In fact, observations need to be free of bias to avoid having systematic observation errors. In addition, observation often suggests a more detached perspective. The researcher and research assistants were observing for data collection rather than taking part in the construction site. Consequently, stopwatch method was used as a portable means of measuring execution time in seconds and it was a useful part of the on-site observation for productivity measurement. The researcher and research assistants also observed certain groups rather than trying to become immersed in the entire masonry workforce on-site. Last but not least, the foreman delay survey was carried out on a regular basis for identifying the sources of problems and monitoring the performance of workers.

Data Collection and Analyses Results

A total of 318 measurements were collected for masonry works in Chongqing, China. Table 2 presents the measurements observed.

Table 2. On-site Observations Measurements for Concert Block Installation in Chongqing, China

Time Range in seconds	Number of Measurements	Overall Percentage
< 20	2	0.6
20-40	42	13.2
41-60	143	45.0
61-80	93	29.3
81-100	30	9.4
> 100	8	2.5
Total:	318	100%
Minimum Time:	18 seconds	
Maximum Time:	118 seconds	
Average Time:	58.6 seconds	

Based on the collected data from Chongqing, the researchers have determined that the average labor productivity rate on a bricklayer with one bricklayer helper for installing a solid 40 cm X 30 cm X 20 cm concrete block is 58.6 seconds per block. Figures 4 and 5 show the site conditions. As for physical output per hour of labor productivity from a bricklayers and a bricklayer helper, they can install a total of 7.61 m^2 of partition walls per hour. In comparison between the collected data and information obtained from *2009 RS Means*, it would take 26.28 labor-hours for a Chinese crew and 119.48 labor-hours for a U.S. D-9 crew (labor productivity rate – 1.195 labor-hours/m^2 from *RS Means*) to complete a total of 100 m^2 partition walls. The Chinese crew and a D-9 crew both include three bricklayers and three bricklayer helpers. All data excludes labor-hours for scaffolding.



Fig. 4. Bricklayer and bricklayer helper



Fig. 5. Bricklayer and bricklayer helper

The collected data from Chongqing has indicated that the bricklayers lead the critical path of the task with their direct work activities in a normal 12-hour day with an hour

of lunch-and-break. In the meantime, the bricklayer helpers are responsible for all material supplies to the bricklayers. Furthermore, the bricklayers had minimum time spent on contributory activities – mainly time spent on scaffolding. In addition, there were no nonproductive activities on the jobsite being recorded for the bricklayers. The only factor which is being aware of and has affected the work process is directly related to materials supply. It might describe the performance variation between the Chinese crew and a D-9 crew listed in *RS Means*.

Conclusion

China is a socialist country with differences in the social political system and culture, as compared to other developed countries, and these differences are enshrined in its construction industry as well. The high labor productivity of masonry measured at one jobsite in China is a surprise. It provided an evidence of the fundamental changes in the Chinese construction industry since the economic reform. Dramatic progress has been made by the industry. Although the Chinese construction industry attracts international construction firms and is evolving towards a more mature industry based on developed nation models, the industry is unlikely to be the same as that of the U.S. in its industrial mechanism within the next 10 to 20 years. In this study, the researchers recognized many issues on the jobsite in relation to safety and quality. It indicates that the challenges ahead for the Chinese construction industry are serious and deeper reforms are required.

This paper provides an opportunity for U.S. construction firms to distinguish their own strengths and weaknesses and improve their competitiveness and performance thereafter. As for the Chinese construction industry, it is important to improve and sustain its competitiveness from research and study, to resolve its own weaknesses, to learn the advanced construction techniques and management skills, and to gradually integrate with the global construction market.

The overall weaknesses of Chinese construction industry can be attributed to the following – due to most Chinese construction enterprises not having sufficient exposure to and is behind in the adoption of advanced construction technologies, the technology index is below other sectors in China and other developed countries with excessive average number of construction enterprises' employees being unskilled workers who previously were farmers and have no proper training for construction (Xu et al., 2005). In this study, the background of all bricklayers and bricklayer helpers is described. Figure 6 shows the distribution of education level of Chinese construction employees. In addition, there are too many tasks on construction sites are being done manually instead of using machinery with skilled workers. In most situations, advanced equipment is used only for large or major projects (Hinton and Tao, 2006). Finally, a lack of appropriate knowledge in engineering design, project management, information system, application of computer software, construction laws, codes, standards, and drawings from management personnel and workers also results in problems in construction productivity, scheduling, quality, and safety on site.

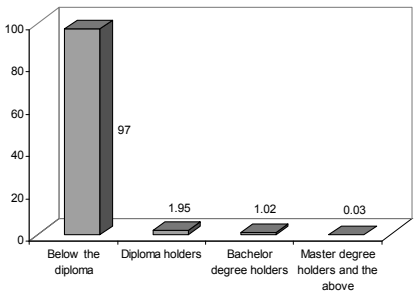


Fig 6. Distribution of Education Level of Construction Employees (He, 2000)

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Development of Performance Measurement Framework for Value Management Studies in Construction

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Abstract

Value management (VM) has been reported to be useful in reducing costs while maintaining or even improving the performance of a project. However, many potential users in the construction industry are reluctant to use VM because of a lack of tools to assess VM studies. This paper is to develop a proper measurement framework for VM studies in construction. The strengths and weaknesses of the existing measurement frameworks are reviewed in the context of VM. Thirteen factors which have major impacts on the performance of VM studies in construction are identified and a theoretical foundation is established based on these factors. A preliminary framework is developed to explain how the desired features could be achieved. The identification of the key performance indicators (KPIs) by a questionnaire survey is then presented. A detailed framework which consists of the measurement processes, data providers, weightings of KPIs and definitions of the scoring is then developed. Case studies, focus group meeting have been conducted to refine the framework.

Introduction

Value management (VM) is widely regarded as a useful method in addressing challenges such as budget constraints and project complexity in the construction industry. It has been reported to be useful in reducing costs while maintaining or even improving the performance of a project at the same time. However, many potential users in the construction industry are reluctant to use VM because of a lack of tools to assess the effectiveness of VM studies. It appears that performance measurement of VM studies is rarely conducted due to the lack of rigorous models. Therefore, organizations have no clear way of knowing whether adequate returns have been achieved on their investment in VM studies. Without a reasonable assessment of the effectiveness of VM studies in achieving clients' target, it is also difficult to know what changes can be made to obtain more benefits.

The objectives of this paper are (1) to investigate the strengths and weaknesses of the existing performance measurement models used in measuring the performance of VM studies in construction; (2) to develop, validate, and refine a performance measurement framework that is capable of measuring the processes and outcomes

of VM studies in construction on a timely basis. Research methods including a critical review, interviews, questionnaire surveys, theoretical analysis, case studies and focus group meeting are used in this research to achieve the objectives.

Strengths and weaknesses of the existing performance measurement models

The Balanced Scorecard (BSC) has been one of the most popular frameworks used for measuring organizational performance since its birth in the 1990s. It was developed by Kaplan and Norton (1992) and has been considered an excellent contribution to performance measurement. However, the financial, process, development and customer perspectives of the BSC have been considered insufficient by many researchers (Neely et al., 2002; Kagioglou et al., 2001). The BSC provides a valuable perspective to measure performance according to a multi-criteria principle that should be adapted to measure the performance of VM studies. However, months are required before the outcomes of implementing the BSC can be seen and the BSC focuses on strategy perspectives, so it is not suitable for VM studies, which last only a few days.

The EFQM (EFQM, 2003) and Baldrige models (Public Law 100-107, 1987) have gained much popularity in the field of performance measurement. The EFQM model provides a perspective to integrate result areas (lagging indicators) and organization areas (leading indicators) in one model, which can be adopted when measuring the performance of a VM study. However, studies have to be conducted to identify the proper criteria that meet the unique requirements of VM studies. The criteria of the EFQM model are fixed because of their similarity to organizational performance. This feature limits flexibility when measuring VM studies that are different from each other.

The KPI framework has also been considered problematic by some researchers. Kagioglou et al. (2001) pointed out that a) the indicators offer little indication from a business point of view, b) the framework lacks a holistic viewpoint on the relationship between the different indicators, c) none of the indicators are designed to measure the performance of suppliers, and d) none of the indicators deals with the "innovation and learning perspective." Neely et al. (2002) figured out that benchmarking activities are for short-term improvement initiatives. Moreover, the KPI framework gives no explanation of the cause and effect between best practices and project processes. According to these problems and the uniqueness of VM studies, the benchmarking method is not suitable for measuring the performance of VM studies. However, the benchmarking method could be implemented to collect and compare the values of indicators to identify the best practices.

Specifically, Table 1 shows a comparison of these popular frameworks.

Table 1 A Critical Comparison of Several Popular Frameworks

Frameworks or models	Multiple perspectives	Flexibility	Continuous measurement	Real-time feedback	Accessibility of data
Balanced Scorecard	√	√	√		
The European Foundation for Quality Management Excellence Model	√			√	√
The Malcolm Baldrige National Quality Award	√			√	√
Key Performance Indicator Framework	√		√	√	√

Development of a theoretical foundation

An in depth investigation of the factors which have an influence on the performance of VM studies is necessary to establish the theoretical foundation of the research. Based on these factors identified from the nature of VM studies, the overall processes of projects, and the principle of performance measurement, the research foundation can be established. Thirteen major factors which have an impact on the performance of VM studies are identified as follows:

1. Projects
2. Clients
3. Facilitators
4. Participants
5. Team and team dynamics
6. Techniques used in VM studies
7. Time and venue of VM studies
8. Process of VM studies
9. Types of VM studies
10. Critical Success Factors (CSFs)
11. Key Performance Indicators (KPIs)
12. Post Occupancy Evaluation (POE)
13. Post Project Evaluation (PPE)

Figure 1 portrays a theoretical framework for performance measurement of VM studies and shows how the factors relate to one another. The facilitator, client and participants constitute the human resources of VM studies. These human resources, as well as the duration, venue, and the techniques used in VM studies are seen as the inputs of VM studies. A VM study is a systematic approach which consists of a pre-workshop, a six-phase workshop and a post-workshop. Each phase requires the input of previous phases and yields output for the subsequent phases. The whole process of a VM study is integrated into the project management process to add value to the project. Measuring the performance of a VM study will stem from the objectives of the study. Each objective should be linked to one or more CSFs which are identified according to the inputs and processes of the VM study. Each CSF should have a few KPIs that can be measured and quantified. The outcomes of the VM study will include issues will also be linked with relevant KPIs. The KPIs with their relevant weightings make up the core of the measurement framework. The feedback of the measurement could be used to improve the performance of the VM study and guide the following VM activities.

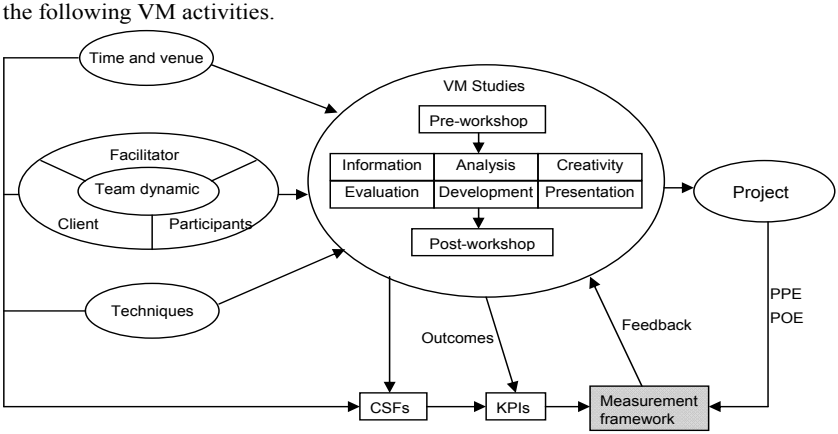


Figure 1 Theoretical framework for performance measurement of VM studies [Source: Shen et al. (2005)]

Development of a preliminary measurement framework

The desired features of the framework should be clarified based on the investigation of existing approaches and the theoretical foundation before developing the performance measurement framework for VM studies. VM studies are unique because of the uniqueness of each project (Lin et al., 2004). This means that the objectives of individual VM studies will vary from each other. Therefore a coherent but flexible measurement framework should be established to meet the requirements of different VM studies. The measurement framework should be multi-criteria so as to provide a comprehensive measurement. Both objective and subjective indicators, tangible and intangible factors, as far as they can indicate the performance of VM studies, should be taken into consideration. In order to achieve a real-time measurement and control, methods for collecting and processing the data of the indicators should be prompt and succinct.

Based on the desired features of the performance measurement framework, a preliminary framework has been developed. As shown in Figure 2, leading indicators are used to measure the process performance of VM studies while lagging indicators are used to measure the outcome performance. It is possible to measure and improve promptly when acquiring and comparing leading indicators to historical results. Choosing proper indicators to measure a specific VM study makes this framework flexible. A comprehensive measurement of a VM study can be achieved by integrating the measurement results of previous VM both in terms of process performance and outcome performance. Meanwhile, the measurement results of overall performance will be added to the database as historical results, which can benefit subsequent VM studies and enable this framework to grow continuously.

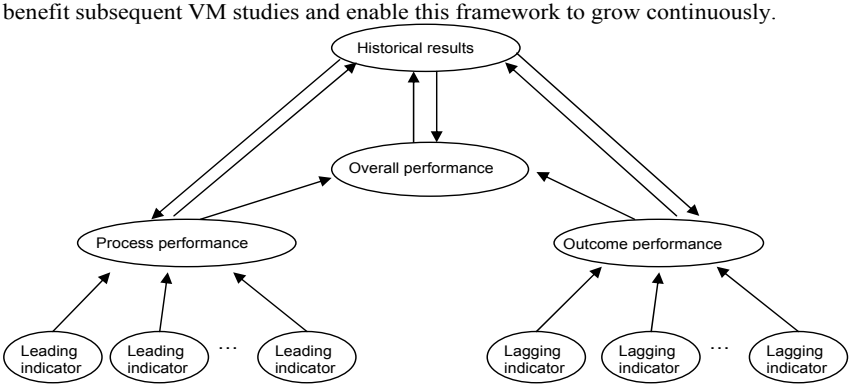


Figure 2 A preliminary measurement framework

Identification of the key performance indicators

Questionnaire design

The respondent was required to tick the weighting of each potential indicator on a scale ranging from: (0) useless; (1) least important; (2) slightly important; (3) somewhat important; (4) important; and (5) very important. Open questions are given in the questionnaire to collect the indicators which are considered to be important by the respondents but not included in the potential indicators. The questionnaire was

sent to 285 VM practitioners. Qualified VM facilitators, architects, engineers, surveyors, consultants and government officers were carefully selected from the list of delegates attending the international conferences on VM hosted by SAVE International and The Hong Kong Institute of Value Management from 2005 to 2007, and were found by searching the lists of delegates. These experts are either VM clients or practitioners who are active in the construction industry, which ensures that the indicators identified focus on VM studies in construction.

Results of the survey

According to the survey, the mean values of the indicators range from 4.58 for *Clients' support*, to 2.44 for *Average number of ideas generated by each participants*. The mean value for all indicators listed in the questionnaire is 3.70 indicating that the respondents weighted the indicators on average as important. There are 18 indicators that have means higher than the four which means they are considered to be extremely important according to the responses.

According to their characteristics, the 18 KPIs were then divided into three groups. This is shown in Table 2. The KPIs in Group 1 are those leading indicators which can predict the performance of VM studies. However, the scores of these KPIs do not indicate the performance of VM studies. For example, a score of five for i3 means that the VM team consists of all stakeholders of the project, which ensures a holistic view of the tasks of the VM study. The score is an indicator of factors conducive to a successful workshop but a high score itself can not guarantee workshop success. The KPIs of Group 2 are also leading indicators. The difference between Group 2 and Group 1 is that the KPIs of Group 2 can indicate the processes performance of VM studies. The KPIs of Group 3 are the lagging indicators which indicate the outcome performance of the VM studies, including both tangible and intangible issues.

Table 2 Groups of the KPIs

Group 1 (Predicting indicators)	**Group 2 (Process performance indicators)**	**Group 3 (Outcome performance indicators)**
• *Disciplines of participants*	• *Background information collected*	• *Quality of the report*
• *Qualification of facilitator*	• *Interaction between participants in each phase*	• *Percentage of action plan carried out*
• *Client's support*	• *Client's objectives clarified*	• *Improving the project quality*
• *Client's participation*	• *Project givens/ assumptions clarified*	• *Identifying and clarifying the client's requirements*
• *Clear objectives of workshop*	• *Primary function identified*	• *Accelerating the decision-making*
• *Relevant departments' support*		• *Improving communication and understanding among stakeholders*
		• *Client's satisfaction*

Development of a detailed measurement framework

A detailed performance measurement framework is developed from the preliminary framework and the selected KPIs.

Measurement processes

As shown in Figure 3, the identified KPIs are put in a systematical order along with the processes of the VM studies. The measurement starts from the objectives and the other inputs of the VM study. Each stage of the VM study has several indicators linked to its performance. The indicators cover most aspects of a VM study to map the performance in a holistic way. Both subjective indicators and objective indicators are considered in the framework. The indicators before the end of VM workshop are leading indicators which indicate the process performance. Corrective measures could be conducted during the process of the VM study whenever the values of these leading indicators turn out to be problematical. Data about the project collected after the application of VM and to the completion of the project could be added to give an overall indication of the performance of VM studies.

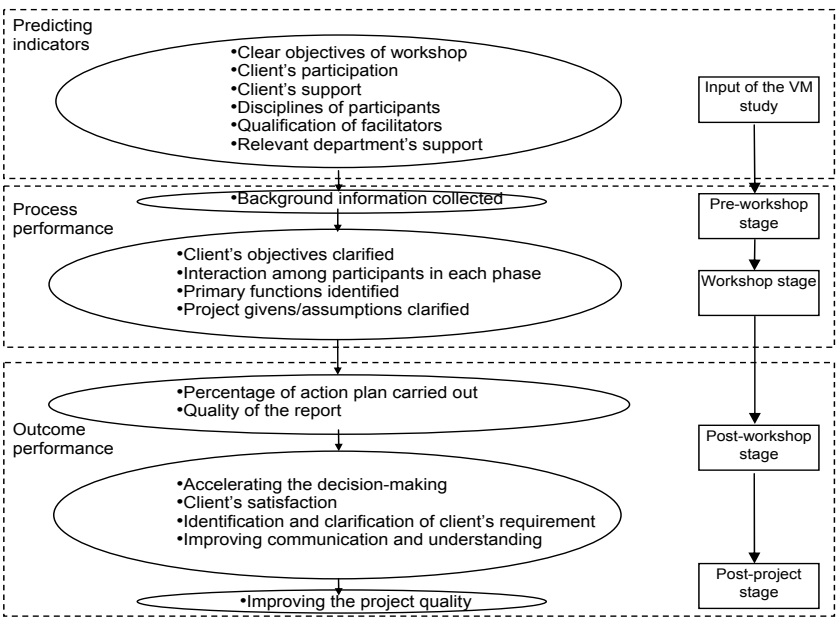


Figure 3 KPIs for measuring the performance of VM studies

Data providers

All the stakeholders, including the clients, facilitators and participants of the VM studies, should take part in the measurement process. However, not all the stakeholders provide data for each KPI. The data of each KPI should be provided by the appropriate parties. Taking *Client's support* as an example, the data of this KPI should be provided by facilitators and participants but not clients. This can avoid risk

of bias if the clients provide the data, and ensure the validity of the data. Table 3 lists the proposed data providers for the three groups of KPIs.

Table 3 Data providers for the KPIs

KPIs	Numbers of answers		
	Facilitator	Client	Participant
Predicting indicators (Group 1)			
Clear objectives of workshop			√
Client's participation	√		
Client's support	√		√
Disciplines of participants	√		
Qualification of facilitator		√	
Relevant stakeholders' support	√	√	
Process-related performance indicators (Group 2)			
Background information collected			√
Client's objectives clarified			√
Interaction among participants in each phase	√		
Primary functions/processes identified			√
Project givens/assumptions clarified			√
Outcome-related performance indicators (Group 3)			
Percentage of action plan without uncertainty carried out		√	
Quality of the report		√	
Accelerating the decision-making		√	
Client's satisfaction		√	
Identifying and clarifying the client's requirements		√	√
Improving communication and understanding among stakeholders		√	√
Improving the project quality		√	

Weightings of the KPIs

In order to simplify the calculation and distinguish the difference among the performances, the weightings of the KPIs are standardized based on the questionnaire results. The formula for standardization is as follows:

$$W_i = \frac{(M_i - 2.44)}{(4.58 - 2.44)} \times 10$$

Where W_i = calculated weightings of the indicators. M_i = original means of the weightings according to the questionnaire. The calculated weighting of each KPI is rounded to an integral number to form the standard weighting.

Definition of the scorings of each KPI

Given that a data collection method should be succinct and prompt without impairing accuracy to meet the desired features of the measurement framework, a five-point scale method has been adopted to score the KPIs. To mitigate the subjectivity of scoring, the meaning of each point to each KPI is clearly defined. The example of definitions of scorings are presented as follows:

Qualification of facilitator

5 — World-famous qualified VM facilitator;

4 — Qualified VM facilitator with more than 10 years experience and who has facilitated more than 10 VM studies in the past two years;
3 — Qualified VM facilitator with more than five years experience and who has facilitated more than five VM studies in the past two years;
2 — Qualified VM facilitator who has facilitated at least two VM studies;
1 — Qualified VM facilitator who has facilitated less than two VM studies or not qualified VM facilitator.

Validation of the framework

Case study

The objective of the case study is to test two hypotheses: VM studies which have clearer objectives will lead to better outcome performance; and VM studies which have better scores in leading indicators will have better scores in lagging indicators. Two experimental studies were carried out to implement the performance measurement framework. Each VM study had 17 participants and was prepared independently. A task based on the information of a real public project was used in these two studies. The participants acted as the key stakeholders of the real project in the VM study. The two groups choose different methods to conduct the workshops. One chose the traditional face-to-face approach and the other chose the computer-aided approach. Two colleagues attend the workshops as observers. The relevant data were collected by the observers without interrupting the process of the workshops.

The results show that the computer-aided workshop received higher scores than the traditional face-to-face workshop. The face-to-face workshop only performed better in "The client participated in the VM workshop process" and "Adequate background information has been collected". However, there are only two indicators of the computer-aided workshop which are statistically larger than those of face-to-face workshop, namely "This VM workshop has clear objectives" and "Client's requirements have been identified and clarified". Considering the scores in a holistic way, the computer-aided workshop still leads in both leading indicators and lagging indicators. The scores of lagging indicators of computer-aided workshop are statistically larger than face-to-face workshop. Therefore, hypothesis 1 has been proved valid in this study. However, the scores of the leading indicators of the computer-aided workshop are not statistically larger. Hypothesis 2 is not fully supported in this study.

Action research

The objective of action research is to investigate the application of the preliminary performance measurement framework in a VM workshop to find the advantages and disadvantages which will be borne in mind to develop the detailed framework. Based on a given scenario adapted from real project, the experiment was carried out with the cooperation of a group of construction practitioners who were taking the subject 'Value Management in Construction and Property' at the Hong Kong Polytechnic University. These 19 participants were instructed to act as a team of professionals including VM facilitators, client's representatives and other key stakeholders in order to conduct this VM study, which included preparing and attending a one day workshop and production of the VM report for the project. The researcher attended the whole process of the VM study as an observer and scored the potential indicators.

The results of the measurement showed that a full picture of the performance of a VM study can be drawn by applying the performance measurement framework. The participants all indicated that the measurement result represented the performance of the VM study fairly. However, some of the performance indicators were overlapping, such as "experience of the facilitator" and "qualification of facilitator". This indicated that there is a need to identify the KPIs to make the measurement process more succinct. The scores of the indicators were given by the observer in this study, which ensured objectivity and consistency. In real life VM studies, it is not possible to assign performance observers during the studies. Therefore, how to ensure objectivity and consistency when scoring the indicators should be carefully considered in the detailed framework. Another disadvantage of the preliminary framework is that no weightings were assigned to the indicators. The importance of these indicators should be different according to the performance which they measure.

Focus group meeting

The objective of the focus group meeting is to ensure the reliability and validity of the developed performance measurement framework for VM studies in construction. Eight participants attended the focus group meeting, including one facilitator, four government representatives, two VM researchers and the author. The facilitator is a world famous VM facilitator who has more than 20-years' experience in VM. The four government representatives each have more than 10-years' working experience in construction-related departments and have attended VM studies in their departments. Two of them are VM experts in the governmental sector. The private developers and quasi-governmental organisations were also invited to attend the focus group meeting. No representative from these two parts accepted the invitation. The reasons maybe that the private developers in Hong Kong seldom use VM in their projects in recent years so there is limited motivation for them to spend time in this area.

The developed performance measurement framework for VM studies in construction has been considered as a systematical framework to help the clients ensure their returns on the investment of VM according to the focus group meeting. The attendants from government also admitted that they do not have system like this framework to prepare their workshops. They suggested that this framework could be used to measure the performance of future VM studies in their departments. Two indicators, "knowledge of VM of the participants" and "knowledge of the project of the participants" have been raised as important but are missed in the group of predicting indicators. After discussions, the indicator "knowledge of the project of the participants" was linked to the existing KPI "clear objectives of workshop". "Knowledge of VM of the participants" remained for investigation in further discussions during the interviews. "Relevant departments' support" was revised to be "relevant stakeholders' support" to better represent the meaning of this indicator. It is pointed out that relevant departments may refer to the departments in the client's organization which may lead to misunderstanding. The term "relevant stakeholders" provides a better explanation of this indicator. The group of process-related performance indicators has been considered to be adequate. "Timely submission of the report" and "add value to the project" were raised as two important outcome performance indicators. After discussions, the indicator "add value to the project" was linked to the existing KPI "client's satisfaction". "Percentage of action plan carried

out" was modified to be "percentage of action plan without uncertainty carried out" to make this indicator more accurate.

Conclusions

The review of popular measurement frameworks summarizes the strengths and weaknesses of their implementation in the context of VM studies in construction. It is not suitable to adopt these frameworks to measure VM studies due to their limitations in the context of VM. However, perspectives like multi-attitude measurement could be adapted to a developed performance measurement framework for VM studies. The interrelationships of the 13 factors are introduced as the theoretical framework which explains how the factors interact with each other and where the performance measurement framework will be in this theoretical foundation. Eighteen KPIs are identified by a questionnaire survey and divided into three groups according to their characteristics, namely predicting indicators, process performance indicators and outcome performance indicators. A detailed measurement framework which follows the processes of VM studies was developed according to the preliminary framework and the identified KPIs. The measurement starts from the objectives of the VM study and is in line with the processes of the study. The data providers for the KPIs are identified to avoid bias in measuring. A simplified calculation of the weightings of KPIs is introduced. In order to mitigate the subjectivity of scoring, the definition of each scoring is described precisely. The findings of the case study show that VM studies which have clearer objectives lead to better outcome performance. The action research presents the use of the preliminary framework to the entire process of a VM study. The results show that a full picture of the performance of the VM study can be drawn by applying the performance measurement framework. A focus group meeting was conducted with the VM practitioners and government representatives to test the validity of the framework. The results show that the clients and VM facilitators are positively disposed toward the framework.

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Emergent Themes of Instruments used to Measure Safety Climate in Construction

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Abstract
Each year, occupational injuries in the construction industry disable many workers and accounts for the lives of others. The commonly used indicators to measure construction safety are reactive, or lagging. On the other hand, predictive indicators such as measures of safety climate reduce the need to wait for incident to occur. Safety climate, referred to as the people's perception of the value of safety in the work environment, has been measured in various industries including construction. This paper has reviewed 15 such surveys to find the emergent themes of the instruments used in construction industry. Using content analysis and constant comparison analysis to analyze the data, the authors examined the survey instruments to identify key terms that reflect the main safety climate themes. While this study is no way exhaustive, analysis on the thematic basis of the survey questionnaires suggest that common themes relate to implication of safety rules and attitude of the management.

Introduction

The construction industry has historically been one of the most demanding and dangerous industries in the United States due to its complex and dynamic nature. This fact is reflected in the data published by United States Bureau of Labor Statistics which shows that private construction industry sector recorded 969 fatal work injuries in 2008, the most of any industry sector . Each year, occupational injuries and fatalities in the construction industry temporarily or permanently disable many workers and accounts for the lives of others throughout the world. In Great Britain, construction and agriculture have the highest rates of fatal injury, accounting for 46% of fatal injuries to workers (Haro and Kleiner 2008). These alarming statistics continue to highlight the importance of health and safety in the industry.

The poor safety records of the construction industry have forced researchers to analyze the occupational health and safety. Typically the analysis has been confined to retrospective data such as man hours lost, direct cost of accidents and number of accidents; all of which can be categorized as 'lagging indicators'. The lagging indicators do not take into consideration the precursors of accidents. This is in conflict with the underlying belief that the majority of accidents are not caused by careless workers or technical failure but by failure in control, which ultimately is the responsibility of management (Baxendale and Jones 2000). From the later part of last

decade, there has been a movement away from safety measures purely based on retrospective data, toward so-called 'leading indicators,' such as measurements of safety climate (Flin et al. 2000). This change in paradigm is brought by findings that organizational, managerial, and human factors rather than purely technical failures are prime causes of accidents. Margolis (1973) found that engineering solutions to accidents were insufficient and thus recognized the importance of worker behavior in accident prevention. Findings of Margolis (1973) Beck and Feldman (1983) , reiterate the fact that implementation of safe work practices is dependent on the expectations of the employees. Following this notion, initiatives have been taken to systematically measure expectations towards occupational health and safety at various levels of organizations. On a similar note, Cohen (1977) observed that the "best" safety programs are dependent on "people" variables and improvement of these variables will result in improvement of overall safety. In a broad sense, Simonds and Shafai-Sahrai (1977) demonstrated that organizational climate and the way employees perceive it affects the individuals function within its structure. Organizational climate in this context refers to the social and organizational circumstances in which the employees work. Further research such as the study by Neal et al. (2000) has been undertaken to determineT the influence of organizational climate on industrial accidents. Safety climate is considered as a subset of this organizational climate as it is a snapshot of the safety attitudes and perception of employees (Findley et al. 2007; Flin et al. 2000).

Safety Climate

Safety climate is a "summary concept describing the safety ethic in an organization or workplace which is reflected in employees' beliefs about safety and is thought to predict the way employees behave with respect to safety in that workplace" (Williamson et al. 1997).

An attempt to assess this descriptive measure reflecting the employees' perception of, and attitudes toward safety within the organizational climate was first made by Zohar (1980). The study by Zohar (1980) investigated the effect of safety climate in industrial organizations in Israel. He used factor analysis to identify eight principle components of safety climate. These are: (1) perceived importance of safety training programs, (2) perceived management attitudes on safety, (3) perceived effect of safe work practice on promotion, (4) perceived level of risk at workplace, (5) perceived effects of work pace on safety, (6) perceived status of safety officer, (7) perceived effects of safe conduct on social status and (8) perceived status of safety committee. However the study conducted by Dedobbeleer and Beland (1991) on construction workers, suggested that the management commitment to safety and workers' involvement in safety were the two most important factors impacting the safety climate. This work has been followed by further attempts at investigating the descriptive measures of safety climate which revealed several facets of safety climate (Cox and Cox 1991). A separate study on road workers found two separate set of principles for workers and for supervisors both of which included attitudes to safety in the organization, changes in work demands and safety as part of productive work (Niskanen 1994). Thus it is clear that though all the previous studies are in little agreement among each other on the dimensions which should be incorporated into a

safety climate model, the commonality among them are views about management attitudes to safety and about employees' involvement or attitudes to safety.

Instruments to measure Safety Climate

In order to determine and effectively translate these descriptive measures into an operational measure for safety management, several instruments have been developed. The majority of these instruments are in the form of self-reported questionnaires administered as large scale surveys in an attempt to determine the key factors affecting safety climate. Increasing interest in the measurement of safety climate has resulted in a large number of assessment instruments. Flin et al. (2000)and Guldenmund (2000) between themselves have identified twenty seven such studies and summarized the instruments used. The instruments are designed to measure a set of themes derived from the review of safety literature. Interviews and focus groups present at the work site are used to point out particular issues concerning the workforce and to customize the instrument accordingly (Flin et al. 2000).

As the number of instruments used to measure safety climate has increased over the years, the lack of a unified theoretical model has become more visible. It can be argued that the lack of a unified theoretical model (Guldenmund 2000; Williamson et al. 1997) in this area indicates a state of development. In spite of the ongoing development in these instruments, a scrutiny of their component themes suggests the emergence of a basic set of principles (Flin et al. 2000). But it is still a long way away from a position where a basic set of features start emerging from the component themes of the instruments. Never the less, examining the instruments in reference to the composition of the questionnaires gives an idea about the common factors among them. The similar factors aimed at measuring a particular employee perception can then be grouped into broader categories which become the themes of the questionnaires. These themes in turn provide a summary of the factors on which a particular report has focused. This study tries to identify these themes emerging from the questionnaires and rank order the themes according to their frequency of occurrences in different reports. Unlike earlier studies trying to achieve similar goals (Flin et al. 2000; Guldenmund 2000) which have focused on various industries, this study only focuses specifically on the construction industry. In the construction industry, as in any other, the management needs safety indicators to aid decision-making on safety related issues. Since safety relies on human and organizational factors along with technical factors, indicators for all these different factors become imperative (Glendon and Litherland 2001).

Content Analysis

Following a literature review, fifteen published reports of safety climate surveys in the construction industry were identified. The reports were selected based on two main criteria; the sample size of all the selected surveys are greater than fifty and the reports are published in English. When the sample size exceeds 30, most of the sampling distribution of various statistics approaches the normal distribution. Thus in this case a number greater than 50 has been made the criteria for selection as this will assure the validity of the surveys. The reason for selecting the reports which are only produced in English is for the ease of understanding on the part of the authors. As the

purpose of the study was to compare instruments, the reports were scrutinized for original scale items which are summarized in Table 1.

The primary types of data analysis for this study were content analysis and constant comparison analysis. Content analysis which is a common approach to documentary analysis is a research technique for making replicable and valid inferences from data to their context. Instead of directly observing, or interviewing for the purpose of enquiry, in this approach the researchers are dealing with previously produced documents. The reports were studied to see what scales in the survey instruments were identified in the original reports. These have been referred as Category-I (C-I) in Table 1. Data analysis began with the coding of each individual instrument. Authors reviewed the reports to identify key terms or phrases that summarized participant responses related to their perception of safety climate. Following coding, the authors identified patterns within the open codes. These patterns were developed into categories (second iteration) having commonality and were further narrowed into themes. These are referred as Category –II (C-II) in Table 1.

Emergent Themes

A wide range of categories were identified in the instruments which reflect the perception of the employees about the state of safety in the respective organization such as management commitment, safety rules and procedures, competency of safety supervisors. In some instruments, categories such as harmony, work environment, peer influences which reflect self reported work behavior were identified. After each instrument had been coded the second time to narrow the open codes, the top five recurring categories were identified. From these categories, the interrelated themes of safety rules and procedures, management role, work environment, worker involvement, and communication emerged as predominant themes and are depicted in Figure 1.

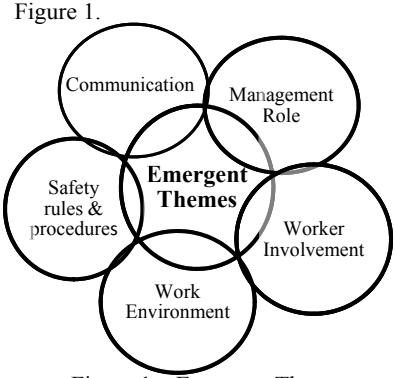


Figure 1 – Emergent Themes

Safety Rules & Procedures	Management Roles	Work Environment
Safety attitude	Encouragement	Job demands
Risk taking behavior	Systems & procedures	Supportive environment
Safety Training	Work pressure	Peer influence
Competency of supervisor	Management Commitment	

Worker Involvement	Communication
Harmony	Relationship
Personal role & safety	Free flowing exchange
Competence	Communication
Worker involvement	Safety information/ meeting

Results

From Table 1 it can be seen that the theme related to safety rules and procedures appeared the maximum number of times (more than 39%). The other major theme that emerged was involving the role of management (more than 21%). The remaining themes had a comparable share of occurrence – impact of work environment (19%), workers' involvement (17%) and communication (10%).

The review of the instruments reveals that most of the questionnaires emphasized on prevalent safety rules and procedures in any organization. The uniqueness and complexity of the construction industry requires a more specific approach for preventive programs. The major implication of safety rules and procedures in the construction industry is that workers should be trained so that they can identify their own contribution to risks and can maintain a professional standard on safety (Zhou et al. 2008). In construction, a strong prevalence of subcontracted activities which take place on site away from the office, suggests that workers may be loosely connected with the main company. This physical and psychological distance from the parent organization makes the implementation of a strong preventive program very crucial and it is up to the organization to offset these distances. Thus it is evident that perception of the state of safety procedures in any organization is an important component of the safety climate, but there are also other sources to gather data regarding employee perception (Flin et al. 2000).

The second very broad theme that was identified in this study was the labeled role of management. This theme encompassed many different managerial aspects of an organization such as commitment of the management to the safety and well being of the employees, their encouragement and incentive programs, and the work pressure. According to Rasmussen (1994) the management pressure towards efficiency is a major factor for workers to migrate towards the boundary beyond which work is no longer safe. While senior managers set the rules and regulations for organizational climate, by establishing priorities and allocating resources, there is little evidence how this takes place in actuality (Flin et al. 2000). Although positive managerial behavior can contribute (Larsson et al. 2008), given the scenario of construction settings where subcontracting activities is the rule and not the exception the main company may be far away and the worker may never interact with the managers or supervisors. In these situations, it may be hard to perceive the safety influences of the organization (Meliá et al. 2008).

Conclusion

While the reports included in this study are no way exhaustive, it can be concluded that there are two core themes (safety rules and procedures, role of management) which have been repeatedly used in safety climate measures, along with a number of other dimensions (impact of work environment, workers' involvement, communication) emerging less frequently. It is evident that the perception of the workers about the state of safety of their work environment is difficult to gauge through the use of survey mechanisms, still there are common perception about safety which are shared by most workers. This study tried to identify the apparently consistent safety attitudes within the construction industry by examining the instruments used for measuring safety climate.

Table 1 – Summary of Instruments

Research Team	Participants	Questionnaire	C - I	C-II
Dedobbeleer and Beland 1991	384	Version used by Brown and Homes (9 items)	Management	M
			Commitment/ Worker Involvement	WI
Mattila et al. 1994	217	Workers questionnaires consisted of 48 questions and 29 questions for foremen	Housekeeping/ Work Environment	WE
			Safety Behavior/ Foremen promoting safe behavior	SB
			Safety Rules/ PPE	SR&P
			Information about hazard	C/S
			Safety Attitude	SA
Niskanen 1994	1890 workers + 562 supervisors	Literature, 12 items for workers, 11 items for supervisors	Change job demands	WE
			Attitudes to Safety	SA
			Work Value	WI
			Safety/Production	S
Gillen et al. 1997	255	Modified version of Safety Climate Measure for Construction Site (Dedobeleer and Beland, 1991)containing a final instrument with 10 questions	Management Concern	M
			Management Safety Activities	M/SAct
			Employee Risk	R
Marsh et al. 1998	Around 500 (mentioned as %)	Interviews with checklist	Knowledge of performance goal	PG
			Current Levels	WP
			Intervention Methodology	S
Glendon and Litherland 2001	192 (includes construction crews and maintenance crews)	Adapted version of Safety Climate Questionnaire developed by Glendon et al. (1994) - 40 questions	Safety Rules/ PPE	SR&P
			Commitment and Support	WI/C
			Adequacy of Procedures	M
			Work Pressure	WE
			Relationship	WE/C
Gillen et al. 2002	255	Adapted from Dedobbeleer & Beland (10 questions - divided 11 question into 2 parts after pilot study)	Management Concerns	M
			Employee Risk Perception	SAct/R
Mohamed 2002	68	The questionnaire contained, in its final form, a total of 82 statements about safety issues at the organizational, group, and individual level	Commitment/ Competence	WI
			Communication	C
			Safety Rules and Procedures	SR&P
			Supportive Environment	WE/M
			Supervisory environment/ Work pressure	M
			Workers' involvement	WE
			Personal appreciation of risk	R/WI

			Appraisal of work hazards	R/M
Siu et al. 2003	374	The 12 subscales of the Safety Attitudes Questionnaire (SAQ) by Donald and Canter (1993) were used to measure safety attitudes - 45 questions	Shop floor satisfaction with safety system/ Housekeeping and safety equipment	W E / S
			Shop-floor encouragement and support	WE
			Training, level of safe working behavior	ST
			Safety meetings	SR&P
			Safety information	S/C
			Management encouragement & support	M
			Pressure from management	WP
			Team leader practice	TL
			Team leader satisfaction w/ safety system	SC/TL
			Team leader knowledge w/ safety system	SC/TL
Siu et al. 2004	374	Safety attitude (45 questions) and communication (7 questions)	Yourself and safety	SA/WI
			Your colleagues	WE
			Management/ Your supervisors	M
			Safety Officers	S/M
			Open Communication	C
			Free flowing exchange with management	C
Fung et al. 2005	423	Questionnaire based on the software developed by Health & Safety Executive in United Kingdom HSE - 36 questions	Org. commitment & communication	M/C
			Reporting of accidents & near misses	SR&P/R
			Line Management commitment	M/WI
			Supervisor's role	M
			Personal Role	WI
			Workmate's influence	WE/WI
			Risk taking behavior/ Obstacles to safe behavior	R
Fang et al. 2006	4127	Questionnaire contains 110 questions, out of which 87 is pertaining to safety climate and rest related to demographic. It was developed based on the safety climate survey questionnaire of Health and Safety Climate Survey Tool of HSE, United Kingdom and the safety management system in Hong Kong. The questionnaire of HSE contained 71 items and covered the five safety management elements in the	Safety Attitude & Mgt Commitment	M/SA
			Safety Consultation & Safety Training	ST
			Supervisor's role & workmate's role	M/P/WI
			Risk Taking behavior/ Improper safety procedure	R
			Safety Resources	SR&P
			Appraisal for safety procedure & risk	SR&P/M

		Safety Management Model of HSE	Workers' involvement	WI
			Work mate's influence	P
			Competence	T
Shoji and Egawa 2006	600	120 items (safety attitudes of workers - 36, perception of the cause & responsibility of labor accidents - 20, perception of safety climate - 27)	Harmony	CO/WI
			Intransigence of overseers at work sites	M
			Cooperation	CO/C
			Tacit Rules	SR&P
			Active Discussion	C
			Skill & ability	WI
			Cheerful Atmosphere	WE
Meliá et al. 2008	473	Taking these agents into account, safety climate can be split up into five main safety climate variables: Organizational Safety Response (OSR), Supervisors' Safety Response (SSR), Co-workers' Safety Response (CSR), Worker Safety Response (WSR), and Perceived Risk of Accidents (PRA). OSR - 10 item quest., SSR - 8 item quest., CSR - 8 item quest., WSR - 7 item quest., PRA - 8 item scale	Presence of safety structure/ Fulfilment of safety rules/ Safety inspections	SR&P
			Safety training & info/ Safety meetings	C/S
			Promotional campaigns/ Safety incentives/ Encouragement of worker safety	M
			Supervisor's safe or unsafe behavior/ Reaction to safe and unsafe work behavior	SC
Zhou et al. 2008	4719	The questionnaire was composed of two parts. The first part included 87 questions related to safety climate, and the second part included 21 demographic questionnaires. The safety climate questionnaire was developed based on the safety climate survey questionnaire of Health and Safety Climate Survey Tool of HSE, United Kingdom, as well as the safety management system in Hong Kong	Safety Attitudes	SA
			Safety consultation & training	ST
			Management commitment	M
			Risk taking behaviors/ Appraisal of work risk	R
			Safety resources	SR&P
			Safety management systems & procedures	SR&P/M
			Employees involvement	WI
			Workmate's influence	WE/C

C - Communication
CO - Cooperation
M – Management
P - Peer
PG – Performance Goal
R - Risk
S – Safety
SA – Safety Attitude
SAct – Safety Activity
SB – Safety Behavior
SC – Safety Consciousness
SR&P – Safety Rules & Procedures
ST – Safety Training
TL – Team Leader
WE – Work Environment
WI – Workers' Involvement
WP – Work Pressure

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From Construction Project Success to Integrated Construction Project Selection

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Abstract

It is noted that project success and project selection and their corresponding criteria and factors have been treated as two separate project management topics. Project success and project selection have not been related to each other yet, but according to our research, they share at least fourteen common traits. This paper seeks to identify the common overlapping themes, which can be used to form a new common model known as the "Integrated Construction Project Selection Process". The model, which is based on the level of success of a construction company's previous projects, uses this information in the company's multi criteria project selection process. As a result, the model enhances the level of project success when a company selects a project. This integrated construction project selection model will be of considerable value to both senior managers and general practitioners within the construction operational environment as it will enable the industry to draw benefits from an integrated approach rather than from two disparate systems.

Keywords: Project Success, Project selection, Integrated Project Selection

1. Introduction

Project selection and project success are perceived differently and have always been addressed separately with no clear linkage between them. Success means different things to different people and there is a significant difference in the perception of the meaning of "success" in the minds of people who evaluate project performance (Webster & Rielly 2003). Project managers, system analysts,

sponsors and users all have a discipline specific definition of "project success". It is also common for organizations to struggle with hundreds of new projects and, according to Chung & Huda (2004, p. 57), all organizations must select the projects they decide to pursue from amongst numerous opportunities. Meredith & Mantel (2006, p. 41) believe that this project selection process is a way to ensure that the objectives of the parent organization are achieved. There is little literature that discusses the relationship between the terms "Project Success" and "Selection Process". There have been some attempts (i.e. Hatush & Skitmore 1997) to relate project success and selection in the construction projects context but these have only been dealt with in a superficial way. This paper investigates the current literature in an effort to discover common themes between these two concepts. The findings will offer construction companies a project selection process based on previous project success rate.

2. Research Methodology

The exploratory approach is used in this ongoing research. As asserted by Chileshe (2004), the exploratory stage is an extensive literature review on the management writing. For the purpose of this research, this aimed at indentifying the common overlapping themes of project success criteria/factors and project selection criteria, establishing the implementation issues and key concepts of the individual systems, exploring the benefits. Another objective is to review the existing modes of implementation and identification of their inadequacies in terms of integration and implementation. The research process can be identified as having three distinct phases, namely literature review, pilot study and phase three as the main study. The findings reported here are drawn mainly from an extensive literature review in phase one. In achieving the aims and objectives of this research, a robust methodology is being developed as part of an ongoing process.

3. Literature Review

The search for critical success criteria and factors has been occurring for some four decades as evidenced by Ansoff's 1965 work. It has generally focused on diverse alternatives such as products, project or business unit levels. "Project success criteria are used to measure success whilst success factors facilitate the achievement of success (Shokri-Ghasabeh et al. 2009)". Similarly, project selection is a very complex decision-making process and is affected by many critical factors. Selecting projects might be different from country to country and depends on various factors such as mission, objectives, threats and so on. Shokri-Ghasabeh et al.'s (2009) research produced a list of project success criteria and factors and project selection criteria. These criteria and factors which are currently considered by managers are indicated in Table 1 and Table 2 below.

Table 1. "Project Success" Criteria and Factors (Shokri-Ghasabeh et al. 2009)

No	Project Success Criteria/Factors	No	Project Success Criteria/Factors
1	Stakeholders Satisfaction	9	Project Manager
2	Cost	10	Quality
3	Technical Related Factors	11	Project Team
4	Project Risk Management	12	Project Size
5	Project Contracts	13	Time
6	Scope	14	Business Opportunity and Market Impact
7	Safety	15	Management & Organization
8	Environmental Impact	16	Resource Availability

As part of their ongoing research the authors reviewed the current literature in an effort to compare construction project success and selection criteria and subsequently discovered fourteen overlapping themes between these two concepts.

Table 2. "Project Selection" Criteria (Shokri-Ghasabeh et al. 2009)

No	Project Selection Criteria	No	Project Selection Criteria
1	Client Organization Policy and Strategy	11	Project budget
2	Terms of contract	12	Market Opportunities and Competition
3	Technical Related Factors	13	Human Resources
4	Time and Schedule	14	Availability of Resources
5	Regulations and Standards	15	Profitability
6	General Public	16	Management
7	Product related factors	17	Environmental Related Factors
8	Political Environment	18	Socio-economic Environment
9	Project Risk Management	19	Health and safety
10	Project Size	20	Project Geographical Location

3.1 Project Stakeholders

Undoubtedly, stakeholders whether or not they are directly or indirectly involved in projects, play crucial roles in all kinds of projects. Satisfying stakeholders' (including clients, contractors, managers, etc) needs is considered a project success factor and given importance by a great number of researchers (e.g. Wang & Huang 2006). In project selection, there are several factors that are related to different stakeholders in a project. For example project impacts on local people and society and the general public benefit has been identified as a project selection criterion by some researchers (e.g. Cheng & Li 2005). Moreover, many projects, due to their political significance, are quite dependent on political decisions, which can impact the project selection process (e.g. Okpala 1991). As a result, all stakeholders might affect a company's project selection process and consequently the success of the project might be influenced by stakeholders.

3.2 Client Organization Policy and Strategy

No matter how effective a project is, it should abide by the client's political and organizational objectives and complying with organization policy is considered as a project success factor (Berman 2007). Similarly, in a project selection process, the client is very important and his/her past experiences in managing projects (Mohanty 1992), learning capabilities (Cooke-Davies 2002) and ability to successfully undertake a project (Thamhain 2005) are considered.

3.3 Project Product

Alongside time and cost of a project, quality is one of the main project success criteria (Ahadzie, Proverbs & Olomolaiye 2007). Quality might cover both project management quality and product quality. In project selection, a number of factors are related to the quality of a project's product and these are generally connected with the different product characteristics (Brenner 1994).

3.4 Project Human Resources

It is common knowledge that projects are delivered by people, who are directly involved in a project and facilitate achieving project goals and consequently project Success (Cooke-Davies 2002). Some researchers such as Belout & Gauvreau (2004) introduced some project success factors associated with human resources (HR) including project managers and project team members. A project manager and his attitudes (i.e. competency, commitment and capabilities) are some of the key project success factors (Nguyen, Ogunlana & Lan 2004). Some success factors such as nationality, culture, competency, commitment, motivation, leadership and experience are related to the project team (Muller & Turner 2007). Top management support is also a very crucial project success factor (Slevin & Pinto 1986). Accordingly HR in project selection is now becoming increasingly important whereas previously behaviour of people in organizational settings and the different cultural backgrounds of the project managers were ignored in a company's project selection process. Some of the project selection criteria pertinent to HR are top management support (Jiang & Klein 1999), management attitudes (Mohanty 1992), staffing and managerial competence (Cheng & Li 2005).

3.5 Market

Business opportunities and possible impact on the business market is perceived by some researchers (Freeman & Beale 1992) as measures of project success and consequently considered as a project success criterion. This issue shows an organization's place in the business market and its reputation, which subsequently brings more advantages to the organization. This fact is also mentioned by some researchers (Chung & Huda 2004) as a project selection criterion which potentially impacts the organization's market position when, for example, a project introduces a new line in the business market.

3.6 Project Technical Issues

Technically related issues include both technological risk (uncertainty) and project design consideration. Some researchers (Shenhar & Dvir 1996) placed technological uncertainty as a project success criterion while some other researchers (Freeman & Beale 1992) insisted on having design consideration as

one of project success factors. Some project selection criteria concerning technical issues are important to project stakeholders and enhance the chance of selection (i.e. introducing a new or untested technology to a project). Other criteria such as technical plan and competitiveness of the technology are also addressed in a project selection process (e.g. Cleland & Ireland 2007).

3.7 Resource Availability

Resource availability (including people and material) is undoubtedly a very crucial factor in selecting a project and moreover, it can facilitate the achievement of a project's success. It can also be considered as a constraint and its absence might result in failure for an organization. Some researchers (Slevin & Pinto 1986) believe that having sufficient resources is one of the most important factors in project success while other researchers (Puthamont & Charoenngam 2007) considered it an important and crucial selection criterion.

3.8 Project Time

Time or schedule is one of the most important construction project success criteria and helps a project manager/team monitor and control the project and steer it towards a successful outcome. Time is considered as a very crucial project success criterion by the majority of researchers in this field (Collins & Baccarini 2004). Time, is also one of the main criteria of the project selection process and is considered by decision makers in order to evaluate whether or not an organization is able to undertake a potential project within the predicted time. Many researchers (Cheng & Li 2005) verified the importance of time in a project selection process.

3.9 Project Monetary Issues

Project cost/budget is usually manageable within an intellectual budget plan and undoubtedly is one of the most important project success criteria (Chua et al. 1999). From the project selection perspective, financially related criteria are inevitably important. One of the major criteria for any type of project is project budget and the availability of that budget (Oberlender & Trost 2001). The knowledge of how much of the budget is allocated to a project will assist a decision maker to select a more feasible project. Profitability, which is sometimes referred to as financial return is also important in the project selection process since senior managers will know when a project can repay the original investment and how much a project will benefit during its life cycle (Thamhain 2005). Similarly, the economic standing of the organization might influence its project selection decision (Okpala 1991). All of these issues provide evidence that financially related issues are critically important in both project selection and project success processes.

3.10 Project Risks

Risk management is also a topic, which is considered by researchers, who work separately on project selection and project success topics. In his empirical research, Cooke-Davies (2002) mentioned that an adequate an up-to-date risk management plan is needed for a project in order to lead the project towards achieving success. Berman (2007, p. 41) suggests that performing a risk

assessment based on facts is the only way to adequately determine the risk of a project, which in turn increases the overall probability of success. Other researchers had slightly different points of view and suggest that including risk management as a project selection criterion provides an opportunity to account for external risks and encourages senior executives to take some ownership of project risks before the project commences (World Bank 2003).

3.11 Project Environmental Impacts

A project's environmental impact is always important for project stakeholders especially when it affects the general public welfare. Although projects' environmental impacts (i.e. construction waste, environmental degradation and pollution) are not profoundly scrutinized in the literature, Ahadzie, Proverbs & Olomolaiye (2007) included all of these issues in one project success criterion. Other researchers on the other hand believe that choosing an environmentally friendly project is a crucial aspect of the project selection criterion (Pinto 2007).

3.12 Project Safety

Safety has always been an important topic in every project since the lack of safety might result in disasters that no one can recompense. Project safety is observed as a project success criterion by some researchers (Hughes, Tippett & Thomas 2004; Phua 2004). On the other hand, occupational health and safety was considered as a project selection criterion by Cheng & Li (2005) and Pinto (2007) who defined it as measure to protect workers' and other project related personnel's health on-site. This ensures that the selected project considers all of the health and safety related issues of the project. Consequently using a better plan for health and safety at the time of project selection enhances the likelihood of achieving a successful project.

3.13 Project Contracts

Sanvido et al. (1992) demonstrated that a series of contracts, which encourage the various specialists to behave as a team without conflicts and also to allocate risk and reward correctly is considered as a project success factor. Likewise, other researchers (Westerveld 2003) define contractual arrangements as a project success factor. Moreover, according to Cheng & Li (2005) and Mohanty (1992), terms of contract, as constraints, are concerned with procurement management and are an effective criterion in the project selection process. The comparison indicates that there is a relationship between how an organization chooses a project based on the applicable contract and the success of the selected project if the chosen contract is administered correctly.

3.14 Project size

Project size, which can be measured against monetary value, duration or the required resources, is directly linked to many characteristics of a project and is regarded as a project success factor by some researchers (Phua 2004), for example, Yang, O'Connor & Wang (2006) declared that larger projects are more complex to scope thereby making them harder to control. Similarly, as suggested by Cleland & Ireland (2007, p.212), it is very important at the time of selecting a project to pursue whether or not the size of the project is appropriate for the

organization. This indicates that by being aware of what project size is suitable for a company increases the chance of undertaking a project successfully.

4. The outcome of the literature review

In this paper many construction project success criteria were categorized and compared with relevant construction project selection criteria. The result, which presents the similarities between these two sets based on the literature, is outlined in Table 3. The categories presented in Table 3 cover the related project success and selection criteria. It should be noted that all of these criteria and factors were collected from a variety of literature sources composed by different researchers. According to Table 3, the roots of many project success criteria and factors are very similar to project selection criteria and supports. The fact is that to some degree there is a direct relationship between all of the project selection criteria and one or more project success criteria and factors. Accordingly, an integrated construction project selection process (Figure 1), which is based on the success rate of a company, could be applied to cover a systematic way of selecting a project based on the ability of a company to satisfy the preliminary selection criteria. As a result, this selection process is more realistic and a company's deliverable from this process is the undertaking of a realistically feasible project. The more realistic the selected project is the more feasible and successful it will be. This concept requires further research and practical verification by construction companies to ensure that the theoretical benefits of such a project selection method can be realised.

Table 3. Fourteen common categories between project success and project selection

Categories	Covered Project Selection Criteria		Covered Project Success Criteria and Factors
Project Stakeholders	• General Public • Political Environment	+	Stakeholders Satisfaction
Client organizational strategy	Client Organization Policy and Strategy	+	Organization and Management
Project Product	Product related factors	+	Quality
Project HR	Human Resources	+	Project Team and Project Manager
Market	Market Opportunities and Competition	+	Business Opportunity and Market Impact
Project Technical Issues	Technical Related Factors	+	Technical Related Factors
Resources Availability	Availability of Resources	+	Resource Availability
Project Time	Time and Schedule	+	Time
Project Monetary Issues	• Project budget • Profitability • Financial situation	+	Cost
Project Risk	Project Risk Management	+	Project Risk Management
Project Environmental Impacts	Environmental Related Factors	+	Environmental Impact
Project Safety	Health and safety	+	Safety
Project Contracts	Terms of contract	+	Project Contracts
Project Size	Project Size	+	Project Size

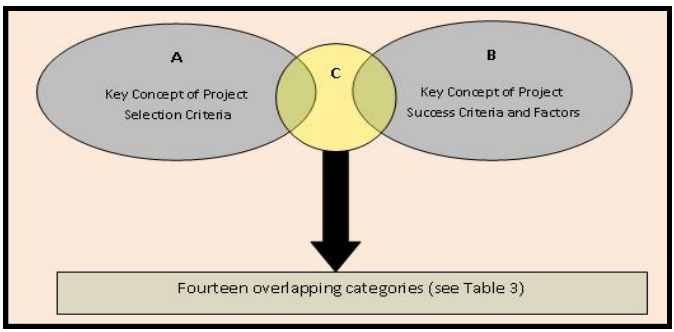


Figure 1. Literature review outcome: A conceptual framework for an Integrated Construction Project Selection Process

4. SUMMARY

Organizations must select the projects they decide to pursue from many different opportunities. To facilitate the evaluation of the potential projects a process called project selection is conducted so that the organization's senior managers can justify which projects are the most feasible ones to undertake. Currently, among a variety of project selection techniques, one of the most effective project selection techniques is multi-criteria project selection in which the organization's senior managers set a list of criteria which are important and evaluate the potential projects against these criteria. This paper reviews the criteria that are applied in the multi-criteria project selection technique and compares them with construction project success criteria and factors. The results indicate that there is a close relationship between a project selection criterion and a project success criterion/factor so that they can be grouped together under the same topic to cover both project success and project selection. Fourteen categories of similarity have been identified by the researchers. The ultimate result of this comparison is a creative project selection process called "Integrated project selection" (also called success-feedback project selection process by Shokri-Ghasabeh et al. 2009) which covers some of the project selection criteria, whose satisfaction subsequently leads to project success.

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Top 10 Areas for Construction Productivity Improvement on Alberta Oil and Gas Construction Projects

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Abstract

The current global economic situation and its negative impact on major oil and gas capital projects in Alberta have made construction productivity improvement more and more important. This paper describes the findings of an ongoing research project, presents the most critical aspects that can improve productivity in the delivery of oil and gas construction projects of Alberta. In this study, we have surveyed professionals from owner organizations, EPC firms and construction contractors to identify factors for improving productivity on future construction projects. Industry recommendations for improving construction productivity are categorized and tabulated into 10 major areas. These areas are labour management, project front-end planning (loading) and workface planning, management of construction and support, constructability in engineering design, engineering management, communication, contractual strategy and contractor selection, government influence and modularization, prefabrication, pre-build in shops.

Introduction

The statistics for major Alberta construction projects illustrates that in 2006, $32.9 billion was spent on construction projects. In five years (2002-2007), construction projects in the oil and gas sector alone were worth $146.7 billion (Alberta Economic Development, 2007). This represents a substantial portion of Alberta's as well as Canada's economy.

This Significant growth in the oil and gas sector in Alberta, Canada over the past decade has resulted in a trend of constructing "mega" projects that are both capital and labour intensive. While this trend has created tremendous economic opportunities, it has also posed a number of challenges, including significant cost and schedule overruns.

Fiori and Kovaca (2006) defined mega projects as, “a construction project, or aggregate of such projects, characterized by: magnified cost, extreme complexity, increased risk, lofty ideals, and high visibility, in a combination that represents a significant challenge to the stakeholders, a significant impact to the community, and pushes the limits of construction experience. Jergeas (2008) defined mega projects as being huge in magnitude and over $1 billion (CAD) in total installed cost, excluding development costs expended prior to the project being formally approved. These projects are characterized by a significant number of interfaces, interdependencies, complexity, and risks, some of which are strategic and must be managed at a level above the project team.

Jergeas (2008) and Ruwanpura et al. (2006) indicated that a historical review of the major oil and gas in Alberta, Canada, revealed that cost overruns in most cases exceed the total project values. In almost all the projects, evidence of 50 to 100 percent overruns are evident as identified by the Association of Professional Engineers, Geologists and Geophysicists of Alberta (APEGGA, 2004).

A study conducted for the government of Alberta, Canada (McTague & Jergeas, 2002) found that cost overruns and labour productivity losses on large oil and gas construction projects were the result of many factors such as the apparent "management" deficiency in managing scope, time, quality, cost, productivity, tools, scaffold, equipment, materials, and lack of leadership, among other things. Jergeas (2008) indicated that while these projects are normally successful from an engineering, operational, and safety standpoint, the cost and schedule overruns are a cause for concern and needs attention in many areas including construction productivity.

Jergeas (2008) and Elliot (2005) listed several reasons for the poor project results and cost and schedule overruns for oil sands construction projects.

The Opportunity and Need

Having reviewed the published work presented by the most important research centers, around the world, the author feels that productivity research is mostly focused on civil or building type of projects and out of date and therefore not suitable for Alberta construction industry. Existing research does not reflect the complexity associated with the delivery of construction projects in the oil and gas sector in Alberta as productivity conditions in Alberta are different due to geographic location, weather conditions, size of projects and contractual arrangements.

The lack of relevant productivity research work in Alberta’s oil and gas construction industry provides an opportunity and a need for a specific Alberta related research and hence this pilot work.

Pilot Study

The main goal of this pilot work is to identify and prioritize factors and practices that have the potential for improving construction productivity in the delivery of Alberta oil and gas projects.
The author surveyed of 77 project management professionals and engineers from the oil and gas industry in Alberta who represent owner organizations, EPC contractors and construction contractors. Thirty five respondents represented the Owner organizations, twenty four represented the EPC firms and eighteen represented the construction contractors. The average experience of this sample is 23 years.

To achieve our stated goal, industry professionals were asked the following simple question:

What do you suggest to improve the construction productivity in delivery of the oil and gas capital projects?

Industry responses provided strategies and ideas for improving construction productivity on oil and gas capital projects of Alberta.

Research Findings

Industry opinion and ideas were collected, tabulated, analyzed, grouped and prioritized in accordance to the number of times quoted by respondents. Industry professionals made 309 specific recommendations for construction productivity improvement. Table 1 following lists the top 10 areas for construction productivity improvement and shows the number of recommendations received by each area and % of the overall observations.

Rank	Target Areas	Number of Recommendations	%
1	Labour Management, Conditions and Relations	86	27%
2	Project front-end Planning (Loading) and Work Face planning	40	13%
3	Management of Construction and Support	31	10%
4	Engineering Management	30	10%
5	Effective Supervision and Leadership	29	9%
6	Communication	25	8%
7	Contractual Strategy and Contractor Selection	24	8%
8	Constructability in Engineering Design	23	8%
9	Government Influence	11	3.5%
10	Modularization, Prefabrication, Pre-build in Shops	10	3.5%
		309	100%

Table 1: Top 10 areas for Construction Productivity Improvement in the Oil and Gas Industry

The following provides a summary of the proposed actions and strategies for improving construction productivity on oil and gas construction projects:

1. Labour Management, Conditions and Relations

This area brought 27% of comments and feedback and is divided into six categories, incentive
programs, remote locations, access to jobsites, labour management and relations, resource scheduling (shifts and overtime) and training and certification of workforce both local and foreign labour.

1.1 Incentive programs

Industry recommends the consideration of an incentive system at the trade, foreman and management levels. This means incentive system must filter right down to the worker. Industry practitioners also encouraged the promotion of a healthy competition between crews in terms of safety and results by posting performance by crew in selected locations across the site.

1.2 Remote Locations

Because a large number of projects are constructed in the remote region of Fort McMurray, industry professionals provided specific suggestions focussing on transportation to site and accommodation and camp facilities.

1.3 Access to job-site

Industry recommends a careful monitoring of the time taken to get thousands of workers into and out of the site every day. They note that workers are usually in the parking lot at 6:30am but they do not start productive work until 8:30am at earliest. Then work stops at 4:00pm, transportation leaves parking lot at 5:30pm.

1.4 Labour management and relations

Better labour relations simply mean if you treat workers better, they perform better. Many ideas are provided including incentives for attraction, education, retention, loyalty, drug testing, working with unions.

1.5 Resource scheduling (shifts and overtime)

This issue has a significant impact on labour productivity. Industry professionals are encouraging the development of good work schedules that respect workers home needs both local to area and external to area. This means management to provide a balance between safe site and happy home life. More work is accomplished using 5 x 10 hr shift than 4 x 12 hr shifts because a tired worker is not productive and is not safe. Expensive overtime does not always lead to better productivity due to declining rate of return. Shorter work hours or limited work-hours with a cap on overtime are strongly recommended.

1.6 Training and certification of workforce

Training programs for both local and foreign labour help companies achieve greater success. More organizational training for lower level supervisors who are directly responsible for people on the tools and providing training, mentoring for front line supervision were suggested.

2. Project Front-end Planning (Loading) and Work Face Planning

Front end planning is the process of developing sufficient strategic information with which the project team can address project scope and requirements that allows the project to be executed successfully. On the other hand, Work Face Planning enables craft persons to perform detailed planning and scheduling to achieve quality work in a safe, effective and efficient manner.

With regard to front-end planning industry is recommending that we do more complete job of defining long-term plan, scope and objectives, rather than jumping into design and construction quickly. If long term planning and goals are more concretely defined, re-work can be limited.

Implementing Work Face planning and buy-in to it by providing a realistic and properly detailed schedule for on site co-ordinators to follow was strongly recommended.

3. Management of Construction and Support

In this category, industry professionals have identified many areas for improvement and suggested the proper management of construction tools, equipment, access to site and site layout, camp facilities, travel, health programs, scaffolding, safety, management of change and rework minimization, material management and supply chain management, quality management, contract administration, and progress measurement.

4. Engineering Management

Feedback relating to engineering management stressed spending more time (not rushing) on front-end engineering to reduce the rework during detailed engineering thus avoiding

hold-ups during the construction. Many projects begin with a small amount of engineering done (less than 50%). It is suggested to complete engineering deliverables including clarity in scope of work (work packages) definition prior to construction and adherence to and strict enforcement of the 80-100 rule. This means among other things:

- 80% of engineering complete before mobilizing to site.
- 100% of "Issued for Construction" (IFC) drawings and specifications issued on time and must be completed before construction.

5. Effective Supervision and Leadership

Industry professionals suggest a labour to supervision ratio of 1 – 8 to 1 – 20 and should not exceed 20. Industry also suggests that team members should be empowered to make timely decisions at all levels.

6. Communication

Industry professionals indicate that improving on site communications between construction manager, foremen, and the labour force can increase worker confidence and overall buy in to each task. They propose the focus should be on providing:

- Clear vision
- Clear and complete design
- Clear scopes
- Clear contracts:
    - Site standard formats/clauses
    - Minimum superfluous clauses and attachments
    - Executed prior to start
    - Understood & adhered to by all

7. Contractual Strategy and Contractor Selection

Contractual strategies adopted for the project and the selection of contractors have been cited as key factors for determining the successful execution of projects. Industry professionals recommend the selection of the appropriate contracting strategy for the project in line with the project drivers. This may include the contractual relationships and alliances with large contractors and equipment suppliers to streamline construction input and place more responsibilities on the contractor to improve efficiency and control costs. Using the Construction Management approach, cost reimbursement with maximum upset and bonus scale and use lump sum contracting were cited.

8. Constructability in Engineering Design

The constructability of engineering work is a common long standing issue within the construction industry; its effects are obvious and evident. Industry proposes a more involvement of operation and construction in detailed engineering to ensure that engineering deliverables are correct and complete (not issued because the time was up and we needed to get them out) to minimize field changes later. Simply put, industry is saying that if engineering does their work well construction will not have to fix it later for more expenditure.

9. Government Influence

The factors that influence productivity in Alberta's Oil and gas projects do not end at the responsibilities of the owner company managers, labour and EPC firms. It extends to include the Government. Industry suggested that Alberta Provincial Government should have a role in pacing the start up of mega projects and apply higher level of approval measurement to reduce the number of players in the huge oil sands projects. The drastic competition over workers between many mega projects created higher cost and lower productivity. Government and industry needs to plan work together to ensure projects flow together and there are no peaks and valleys in the work force. An overall project schedule of the projects would go a long way to help. This is counter-intuitive to some extent because all producers want their production on sooner.

10. Modularization, Prefabrication, Pre-build in Shops

Prefabrication, preassembly, and modularization can affect the schedule and productivity in a positive manner. Industry is strongly recommending the use of standardization where possible in plant design and construction without reinventing the wheel each time. Doing as much work in vendor's shops to avoid field work (pre-wiring, modularized skids) and standardize drawings on repetitive installations are some recommendations among many.

Conclusions

The findings of this pilot study conducted within the Alberta construction industry in the oil and gas sector is another example of the great need for the development of efficient and effective best practices to improve construction productivity. The prioritization of the 10 areas for improvement as assessed by industry professionals provides a framework and a guideline for productivity improvement on future projects. Future improvements as suggested by industry professionals can be summarized to include:

- Incentive and recognition program
- Transportation systems for people and large modules to remote sites
- Job-site access to workers
- Labour management and relations including working with unions
- Overtime and work schedule
- Training for supervisors and field personnel
- Front-end planning
- Workface planning
- Proper management of tools, equipment, health, scaffolding, safety, management of change, and rework, minimization, material management, quality management, contract administration, progress measurement
- 80% engineering completion, 100% IFC drawings before construction
- Supervision and leadership
- Communication
- Contractual strategy
- Constructability in engineering
- Pacing of projects
- Modularization, prefabrication, pre-build in shops

Our analysis of the industry survey findings shows that each of the players be they, the Owner, the EPC firm or Labour, has a role to play to achieve better productivity and to do a good job in performing their duties. Owner's role may include doing a good job in leadership, scope, specifications, project requirements, staffing, managing change, contract and contractual arrangements, and communication. EPC firm role includes doing a good job in leadership, organization, communication, cost management, time management, safety management, material management, tools management, equipment management, access management, scaffold management, design management and setting priorities. EPC role also includes doing a good job in supervision and labour relations, subcontract work vs. direct hire, work week, large job experience, work density, summer work vs. winter construction, skill of engineering, training, morale, bussing, camp, overtime, shift-work, turnover, rework, progress measurement, contingency plans and work face planning.

For labour on the other hand, their role is basically doing a good job in dealing with availability, absenteeism, continuity, skills and competence, supervision skill, supervision training, and supervision availability, jurisdiction, size of crew, waiting time, walking time, rework, weather, start, quit and break and communication.

How good are we as players in fulfilling our roles and doing our jobs? This question must be answered by industry, because to improve construction productivity we must improve stakeholder performance in achieving their respective responsibilities. Improving construction productivity is not impossible and can be done. It takes commitment of players to overcome barriers to implementing the suggested ideas and lessons learned.

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Principles for Utilization of Construction Equipment Operator Training Simulators

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Abstract
Due to the costs and hazards of field training on heavy construction equipment, a market has emerged for computer-based simulators that eliminate such risks involved in construction-equipment operator training. Systems endorsed and utilized by equipment manufacturers are also being adopted by independent equipment operator

training schools. Although the potential for facilitating skill development is evident, proof of the principles that make for efficient utilization of these systems is still not found in the published literature. Careful experimentation on how these systems are used is needed to demonstrate both the successful acquisition of skills and transfer of those skills to the operation of real equipment. After reviewing the market and summarizing principles of learning applicable to the skill development required for operation of heavy construction equipment, this paper highlights how those principles should be embodied in the implementation of training simulators and summarizes an experimental investigation focused on excavator training.

Introduction

Concurrent with the popularity of gaming systems that utilize high-resolution graphics, simulator systems for training operators of specialized equipment are becoming more prevalent in the marketplace. Training for the operation of construction equipment is one of the leading applications because of the obvious benefits of reduced costs and hazards associated with training on heavy construction equipment in real field conditions. Initial training in the simulated or virtual environment (VE) can save some of the early training phases and associated resources while reducing exposure to hazards in the real world practice under operational conditions. In addition, the game-like objectives inherent in such tasks as earthmoving and driving make the simulator technology appealing to the high-technology-oriented younger generation of would-be construction equipment operators.

The impressive, high-resolution graphics displayed by these training simulators lead many to quickly assume the value of the systems for operator training. Apparently, because this long-awaited ability to present a visually convincing, interactive virtual scene has arrived, the foregone conclusion is that the necessary elements for effective training are finally here. Although such an assumption is probably not completely unfounded, the lack of critical experimental testing may result in unrecognized opportunities for maximizing the efficacy of these virtual training systems. This paper presents an assessment of the state-of-adoption of this technology, the motivations for research questions, and a summary of a research program that is underway to establish scientific support for effective implementation of virtual training technologies.

Market Acceptance of Training Simulators

In an earlier study by two of the present authors (Wang and Dunston 2005), a review of technology revealed that a wide array of options were available for developing equipment operator training through artificially constructed scenarios that they collectively referred to as Virtual Training Systems (VTSs). Since that time, the Virtual Reality-based simulators with high-resolution graphics have emerged more firmly as a popular and cost-effective option, most costing from $4,000-$25,000 for a basic station (Weiler 2009). Figure 1 shows an example of training and feedback displays that are presented to a trainee of a VTS.

A cursory investigation regarding the use of training simulators has revealed that the benefits of such systems are touted by several construction equipment manufacturers (e.g., Caterpillar, John Deere, Volvo and Komatsu). According to company websites and equipment training brochures, the equipment types most consistently modeled are the hydraulic excavator, wheel loader, and motor grader, followed by off-highway trucks. In each instance, the manufacturers have partnered with simulator technology companies to develop training systems modeled after their equipment.

Non-manufacturer-based commercial operator training organizations in the United States and Canada (e.g., Associated Training Services (ATS), www.equipment-school.com; National Association of Heavy Equipment Training Schools (NAHETS), www.nahets.org; VISTA Training, Inc., www.vista-training.com) are also now using simulators although they sometimes do not market their utilization as openly as the equipment manufacturers. Their training programs incorporate simulator-based training into either traditional classroom-plus-hands-on, field-based training or a more customizable media-based training approach that adds both video and computer-based experiences to the field components. In addition to the training schools, there is indication that heavy construction contractors are seeing value in having these training simulators for their own in-house workforce development (Sanchez 2007). This trend of adopting simulator-based training, following the lead of equipment manufacturers, indicates a solid step within the industry toward widespread utilization of the technology.

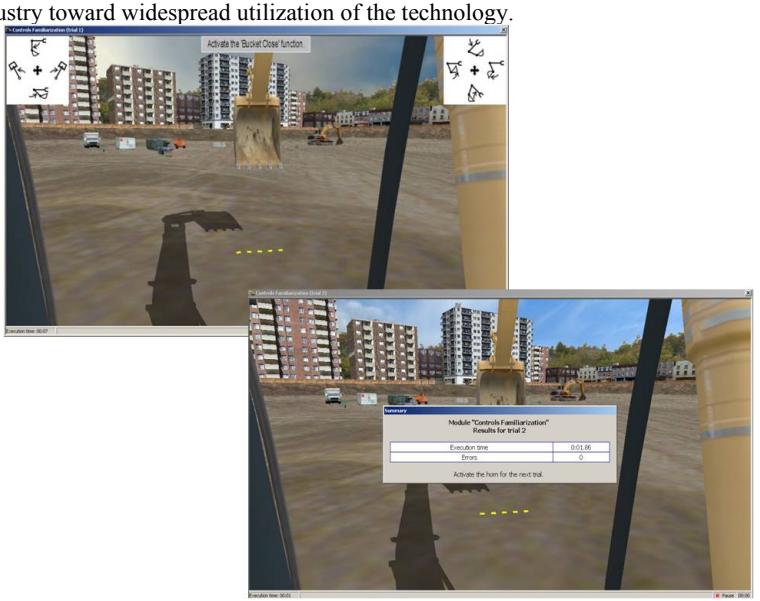


Figure 1. Example screen shots from simulator training scenario, with bottom window displaying feedback on the training trial

Skill Acquisition and Transfer

It is notable that the published literature contains little in the way of experimentally established evidence of the effectiveness of VTSs for construction equipment training. However, there is more general evidence that (1) virtual environments can evoke the necessary responses to stimulate desired application of reasoning and planning abilities (Schumie et al. 2001); (2) spatial skills developed in a virtual environment can transfer from the virtual to real-world settings when the virtual environment adequately provides critical landmarks and cues (Witmer et al. 1995; Brooks et al. 1999), and (3) procedural learning that occurs in a virtual environment can transfer to the real world (Regian 1997). Even though these positive indications occur, the history of studies of virtual environments for training is still relatively new compared to that of the general learning and training discipline, and therefore, assessments have been described as casual, subjective, unsystematic and inconsistent (Kyllonen 2000). More rigor is needed to establish knowledge in this field of inquiry.

The general literature on skill acquisition divides skill types into sub-domains that overlap considerably and are often distinguished in name only for "heuristic convenience" (Newell 1991). However, the general use of the comprehensive term *perceptual-motor skill* is commonly used to capture the relation between cognitive and perceptual elements that are related to the performance of motor tasks. Wang and Dunston (2005) also use the term *sensorimotor skill* instead of pure motor skill to underscore the element of a feedback loop that is present even when executing a simple motion control. The operation of construction equipment falls into this category due to its nature of manipulative activities of the hands in the context of interacting with the work environment to fulfill a designated task.

When it comes to specifically defining skill in the operation of construction equipment, the parameters of skill are not a completely settled matter, although some consistency of thought is emerging. It is understood that sensorimotor skills cannot be measured directly, but are inferred by observing behavior or performance (Wang and Dunston 2005). Objective methods refer to the quantitative measurements such as performance time and accuracy, whereas subjective methods refer to such qualitative assessments as quality of output, consistency of operation, proactive thinking, adaptability to changing environments, and capability for skill improvement, and incorporating of oral interview with experts. The actual measurements of skill in any experimental program will vary depending on the selection of the test task and the essence of the skill. Noting that even skilled operators have difficulty describing their own skillfulness, Bernold (2007) proposed six characteristics of a skilled excavator:

- High quality output (speed and accuracy)
- Consistency of operation
- Smoothness of bucket motion
- Proactive thinking
- Adaptability
- Capacity to improve

It is evident that these characteristics address both cognitive and motor performance. Utilizing a sensor-equipped excavator simulator, Bernold went on to compare the

quantitatively monitored performance of operators of varying experience levels. The "simulator" he used was a laboratory-based excavator platform set up to dig into prepared selected soil and operated from a mock-up of an operator's cabin seat. Data on smoothness of bucket motion patterns and cutting force consistency revealed that an increasing efficiency of motion was associated with the more experienced, i.e., skillful, operators. It is important to note that none of the PC-based simulators surveyed above explicitly monitored smoothness of motion and cutting forces. While the latter could only be hypothetical for such VR simulators, the former might actually be monitored for evaluating performance.

The final element to consider in the development of skill is the evaluation system which consists of the performance evaluation and the coaching provided. While the performance evaluation assesses how well the trainee is learning to execute the training task(s), coaching is the real-time feedback intentionally provided to enhance learning. Bernold (2007) also spoke to this matter, suggesting that the coaching system (1) be adaptive, (2) provide rewards and/or help in the form of tips or suggestions, and (3) reinforce what is learned.

Effective integration of a simulator into a training program requires that skill transfer be established. *Skill transfer* may be defined as application of a skill acquired in one situation to a different but similar situation (Healy et al. 2005), which is a critical concept that defines the effectiveness of any virtual training technology for equipment operator training. Although studies (Regian 1997; Brooks et al. 1999) indicate that transfer is possible, as noted above, identifying the transferrable skill and measuring how well the associated learning is preserved is something that must be studied explicitly in correspondence to specific training.

An Integrated Training Program

In light of the issues covered in the literature review, incorporating a simulator into an overall training program that still involves traditional elements should be done in a structured fashion that acknowledges distinctions between the virtual and real training environments. As implied from the preceding discussion, two primary components are required: (1) identification of specific skills and evaluation of the development of those skills by carefully selected and monitored indicators and (2) measurements that can be compared to evaluate how well the critical skills learned in the virtual training phase are demonstrated in trainees' performance in the real world training phase. Tichon (2007) put forth these same general considerations for incorporating a virtual training environment into formal efforts to develop skill for real world applications. Her considerations were applicable to the broad range of operational environments for which she noted VR to be increasingly used to accomplish training. Drawing upon her recommendations and upon explicit consideration of construction equipment operator training, the flow diagram in Figure 2 is now offered as a framework for the implementation of any VTS as a component of an overall training program (Bhalerao 2009).

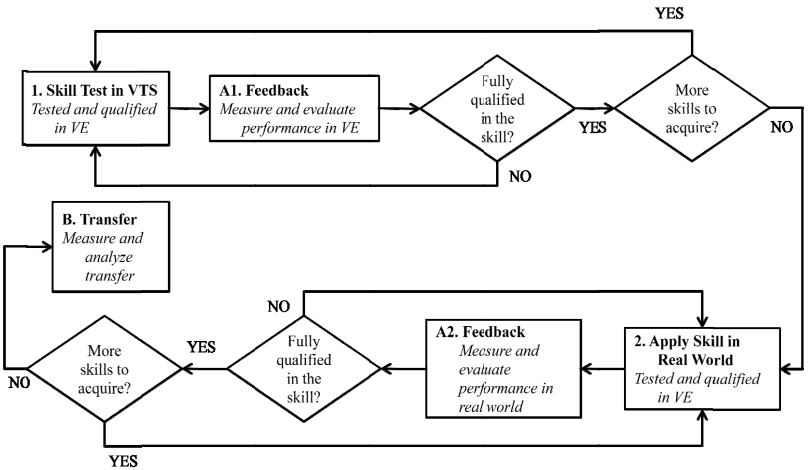


Figure 2 Conceptual model for integrating a Virtual Training System into conventional hands-on, field-based training, incorporating feedback and evaluation for both skill development and skill transfer

Figure 2 illustrates the process of a trainee developing a set of individual skills through some number of training trials in the virtual environment (VE). During this time, feedback (i.e., coaching) is provided for each skill being practiced. Once the skill set that the simulator is designed to develop is demonstrated to some benchmarked level of proficiency, the trainee moves on to the real world training phase where those critical skills, as well as others that the simulator was not designed to develop, are practiced for proficiency. As the transferred skills are practiced, however, the real world performance is compared against the virtual world performance to measure the degree of transfer. The benefit of such a programmed approach is that it automatically provides the trainer with a measure of the effectiveness of the virtual training phase with respect to each skill. In the course of training new operators, the trainer can also make critical evaluations of the appropriate amount of time to spend in each phase and use historical data to assess how any new VTS compares against another.

Experimental Program

More research must be conducted to better understand (1) the methods that best promote the development of the perceptual-motor skills that construction equipment operators need and (2) the measurements that correlate between the virtual and real-world phases of training. Toward that end, the authors have initiated a research program that formulates and experimentally tests questions that are based upon the literature in learning and skill acquisition. Developers of the aforementioned PC-base simulators promote their systems as being developed with consideration of that body of literature. However, their claims of effectiveness should be tested because the complexity of construction equipment operation is at least an order of magnitude

greater than that of those tasks or skills typically studied and described in the literature to which they allude.

The authors are presently utilizing one of the lower cost commercial VR simulators. In consideration of the game-like nature of the VR simulators, the first stage of experimentation compared the influence of a lecture-style orientation to the operator controls versus unguided hands-on exploration. Learning curves obtained from this study described the subject trainee's mastery of the basic controls and reinforce the practice of retaining a classroom orientation. This result has implications for how structured the use of such training simulators should be. Experiments in the near future are set to examine the impacts of mixed training between varied operator control configurations and the impacts of blocked and mixed training for various tasks. Subsequent experimentation will investigate transfer of skills from operating in the simulated environment to the operation of a real excavator under field conditions.

The research efforts thus far have been restricted somewhat by critical limitations in using an off-the-shelf system. Namely, control of certain variables is limited, and some parameters cannot be measured from the system due to the proprietary concerns of the system developer. These restrictions hinder open-ended experimentation, so plans are being pursued for developing a more flexible prototype virtual environment for some of the future experimentation.

Conclusion

This paper has provided a brief overview of the state-of-adoption of Virtual Reality simulators for training of construction equipment operators. It has further described the need for rigorous experimental verification of how principles of learning and skill acquisition apply to training in virtual environments and to transfer of such skills to real world performance. A structure has been described for integrating monitored training on these virtual systems with training on real field equipment. The structure highlights questions concerning the training program and methods of performance evaluation. A research program has been launched to investigate these issues and others that experimentation will reveal.

Acknowledgement

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The Relationship between the Maturity of Safety Management Practices and Performance

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Abstract

The construction industry requires an ability to assess the organizational performance with respect to occupational health and safety and to identify areas in need of improvement. For this purpose, a model has been developed to evaluate a safety management program with an emphasis on organizational processes. The result is an organizational safety management maturity model based on the hypothesis that continuous improvement of the safety program denotes higher organizational maturity and greater safety performance. This paper presents the researchers' development of the model; its application in collaboration with practitioners; and a sample of results to date. The model was developed through a literature review of safety performance, safety culture, safety climate, and maturity modelling research. Validation of the model includes elicitation from occupational health and safety experts, and application of the model to a representative set (in size and expected maturity) of construction organizations. The validation and data collection processes are completed in collaboration with the New Brunswick Construction Safety Association and WorkSafeNB (regional government's occupational health and safety organization). Only sample results to date are provided, to demonstrate how the model can be used to focus on the larger opportunities for improvement with respect to the factor groupings of 1) management commitment, 2) policy and standards, 3) worker involvement and commitment, 4) hazard management, 5) equipment, materials, and resources, and 6) working environment, and within each factor grouping the management cycle steps of 1) plan, 2) do, 3) check, and 4) act.

1 Introduction

Research has established that the safety performance of construction organizations is indicative of many other related aspects of the company, such as employee morale, project costs, and productivity (Mohamed 1999). The underlying hypothesis of the research described in this paper is that there is a direct relationship between the maturity of safety management practices and safety performance. Therefore, the thinking is that an assessment of safety management practices provides a leading indication of safety performance and indicates, with more insight, areas which should be addressed to positively impact both safety and overall performance. The research is being undertaken in cooperation with the New Brunswick Construction Safety Association (NBCSA) and WorkSafeNB (a regional government occupational health and safety commission). The ultimate goal of the research is to develop a proactive solution to monitor the safety practices of a given construction company at the organizational level and identify areas that are in need of improvement. This paper reviews the research points of departure, presents the framework for assessing the maturity of safety management practices and demonstrates how it is being implemented. The framework has been developed for consistency within a national construction industry performance benchmarking effort. It builds on recent safety management research that focuses on the assessment of safety climate and safety culture, and employs the concepts of management maturity modeling. The paper is intended for both industry researchers and practitioners.

2 Points of Departure

Figure 1 depicts a high level process view of construction (Fayek et al. 2008). The performance of the process is measured at some level of granularity (e.g., activity, project, organizational, sector, industry) to assess the ratio of outputs to inputs (A to A) and the extent to which objectives are achieved (C), under a given set of conditions (B), while employing a set of practices (D).

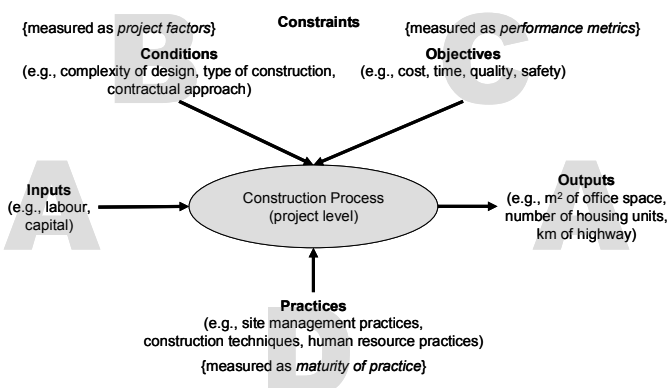


Figure 1: A conceptual model for assessment of the industry (from Fayek et al. 2008).

The research described in this paper explores the relationship between safety performance (C) and safety practices (D) at the organizational level. By adopting well established performance metrics for safety, such as the number of reportable incidents, number of accidents, time lost due to accidents, property loss, etc., emphasis is placed on the practices and a supporting framework for assessing them. The framework builds on more recent construction safety management literature, as well as the concept of management maturity.

2.1 Safety management practices

A review of more recent construction safety management research was used to established a set of factors for use in assessing safety management practices (Goggin and Rankin 2009). The six safety factor groupings identified are: 1) management commitment, 2) policy and standards, 3) worker involvement and commitment, 4) hazard management, 5) equipment, materials, and resources, and 6) working environment. A selection of key references are listed in Table 1, along with the general factor groupings that each addresses.

Table 1: Key references and factor groupings.

Reference; (key topic)	Factor Groupings					
	1	**2**	**3**	**4**	**5**	**6**
1. Williamson et al. 1997; (safety climate)	✓		✓	✓	✓	
2. Shannon et al. 1997; (injury rates)	✓	✓			✓	✓
3. Flin et al. 2000; (safety climate)			✓		✓	✓
4. Mohamed 2002; (safety climate)	✓	✓	✓	✓		✓
5. O'Toole 2002; (safety climate and culture)	✓	✓	✓			
6. Trethewy 2002; (workplace safety)	✓		✓	✓		
7. Mohamed 2003; (safety culture)	✓		✓			✓
8. Tam et al. 2004; (site specific safety)	✓		✓		✓	✓
9. Guldenmund 2007; (safety climate and culture)	✓	✓	✓	✓	✓	
10. Choudry et al 2008; (site specific safety)	✓	✓	✓	✓	✓	

2.2 Management maturity

Willis and Rankin (2009) have defined a maturity model to assess management practices within the construction industry at an industry level. The model uses a three level construct for maturity where a practice is: 1) immature in that it is ad hoc in its application, 2) transitional mature in that it is defined and repeatable, and 3) mature in that it is measured and improved. The model is based on process maturity modeling and the earlier concepts of process improvement, such as the Shewhart plan-do-check-act cycle, as well as Philip Crosby's quality management maturity grid which "describes five evolutionary stages in adopting quality practices" (Crosby 1979), and more recent Capability Maturity Model (CMM) (Paulk et al. 1995). CMM highlights the five thresholds of maturity which a process must transition through in order to be sustainably improved. The assessment of the maturity of a process at the organizational level entails determining the extent to which the process is defined, managed, measured and controlled and is commonly achieved by observing the practices. Related to the construction industry and management of projects are more

recent maturity models that include the Project Management Process Maturity (PM)2 Model (Kwak and Ibbs 2002), the Standardised Process Improvement for Construction Enterprises (SPICE) Model (Sarshar et al. 1998), and research in the area of learning organizations in construction (Chinowsky et al. 2007).

2.3 Safety Management Practices Framework

An assessment framework for safety management practices at the organizational level was developed by combining the safety factor groupings with the concepts of process. Figure 2 depicts the framework and the implementation approach. The six factor groupings are each assessed with respect to the steps of plan-do-check-act (PDCA). The assessment is completed through a questionnaire that determines the level of maturity for each factor–step couplet. The resulting values of maturity (typically displayed using descriptive statistics) are used for identifying opportunities for improvement through comparison against other organizations, industry benchmarks, or to measure progress internally.

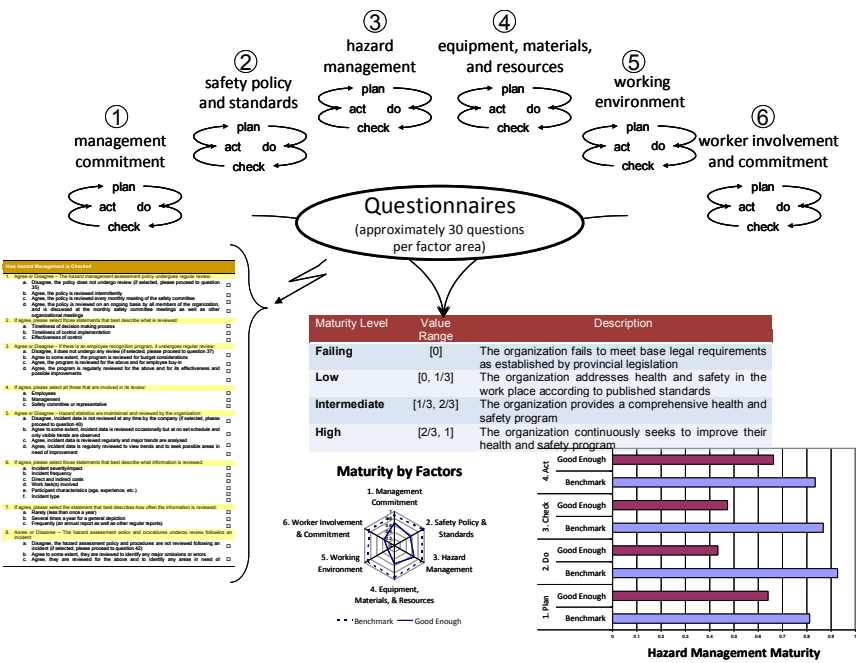


Figure 2: Conceptualized practice assessment framework.

In addition to a score of 0, in cases where a factor is tied to compliance with legislation, there are three levels of maturity in the framework, minimizing the complexity of the model and aiding in the data collection and analysis process:

- Level 1 (low maturity; score of 0 to 1) – the organization fails to meet basic regulatory requirements. Safety is assigned a low priority within the organization and there are few or no formal policies to dictate safety management procedures.
- Level 2 (intermediate maturity; score of 1 to 2) – the organization adheres to base regulatory requirements as established by a governing authority. There are written formal policies to dictate safety management procedures and safety is regarded as a significant factor in project and company performance.
- Level 3 (high maturity; score of 2 to 3) – the organization adheres to and exceeds regulatory requirements. Management actively seeks continuous improvement in their safety management procedures and all members of the organization are involved. The written formal procedures undergo regular review.

3 Data Collection

Data collection consisted of two phases: 1) the development of weighting for the factor groupings and management cycle steps for safety management, and 2) the assessment of practices for a representative group of construction companies. The weighting process was completed through an elicitation process with the in-house expertise of the NBCSA, including its senior management and safety auditors. The representative group of companies was selected to develop initial benchmarking information and explore the relationship between practice maturity and performance. The two factors taken into account for the representative group are the relative size of the organization and its perceived safety management maturity. The size of each organization is classified by the value of construction undertaken on an annual basis and the perceived maturity is determined in consultation with NBCSA in consideration of their knowledge of members and previously completed safety audits.

3.1 Weighting Process

The weighting of factor groupings and management cycle steps was accomplished using the analytical hierarchy process (AHP) (Saaty 1980). The group of NBSCA experts were guided through the AHP by a researcher and considered pair-wise comparisons on a nine point scale of a six by six matrix of safety factors and a four by four matrix of management cycle steps. The final weights were then established using the aggregation of individual judgments approach (AIJ) since it was desired that the group act as a single unit (Forman & Peniwati 1998). This was achieved by using the geometric mean to aggregate the pair-wise judgments provided by the experts.

3.2 Assessment of Practices

The assessment of a company's safety management practices consists of face-to-face interviews with several individuals from each company that include general management, safety management, and workers. The questionnaire is structured according to the factor groupings, with between 18 (equipment, materials, resources) to 44 (hazard management) questions. Each interviewee is guided through the questionnaire by a researcher. The questions are structured as a progression of maturity from ad hoc to continuously improving.

4 Preliminary Results

To date, the weighting of practices has been complete through consultation with four experts from the NBCSA. In parallel, the assessment of practices has been partially complete for the representative set of companies. Performance information is available in the form of external audits conducted by the NBCSA and reporting required by law (e.g., accidents and incidents).

4.1 Weighting of Practices

Table 2 summarizes the weighting of factor groupings and management cycle steps as a result of the AHP.

Table 2: AHP results for management cycle steps and factor groupings.

	Weighting
Management Cycle Step	
Plan	0.48
Do	0.13
Check	0.26
Act	0.13
Factor Groupings	
Policy and Standards	0.08
Management Commitment	0.29
Worker Involvement	0.20
Equipment, Materials, Resources	0.09
Working Environment	0.05
Hazard Management	0.29

Consistency in the order of factor groupings and management cycles steps was observed across the experts. However, the consistency indices achieved for the aggregate weightings warrant an expansion of the expert group.

4.2 Organizational Maturity Assessment

The results for the assessment of safety management maturity are provided only for Company A. The results are for demonstration purposes, as the assessment for all members of the representative group is not yet complete.

Figure 3 depicts the relative maturity attained in each factor grouping for Company A, where a perfect score corresponding to full maturity is three (3). For example, Company A scores 2.16 out of three for *Hazard Management*. In Figure 3, the *Industry* scores are representative of what can be determined as an industry average, or as best in class, and in this case it is set at 2.5 for demonstration purposes.

Combining the weighting of practices with the assessment of maturity provides more insight in determining potential opportunities for improvement. Figure 4 is a depiction of Company A's maturity of factor groupings adjusted by weightings. If fully mature, the sum of all factor groupings would be one (1). The first portion of each bar represents the maturity achieved, whereas the second portion is the

remaining opportunity to reach a fully mature score. The results for Company A suggest that the factor grouping of *Hazard Management* presents the greatest opportunity to affect safety management maturity while *Worker Environment* presents the least opportunity

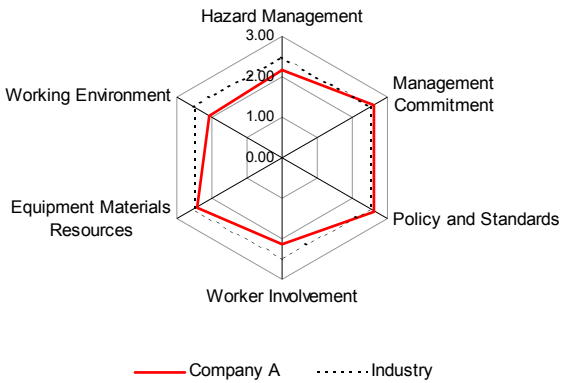


Figure 3: Radar chart of Company A maturity by factor grouping.

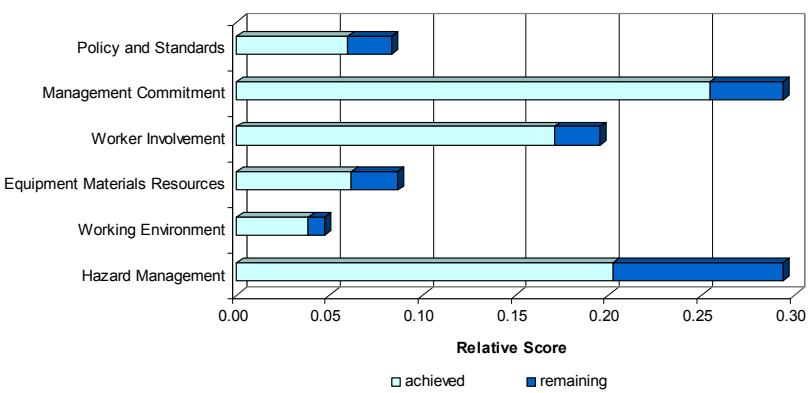


Figure 4: Company A safety management opportunities by factor groupings.

With a focus on *Hazard Management* opportunities, Figure 5 represents the results for Company A of the assessment scoring per management cycle step and with the corresponding weighting (where the aggregate of all scores equals one). Again, the

Check step is emphasized as an area of greater opportunity (more so after the application of weighting).

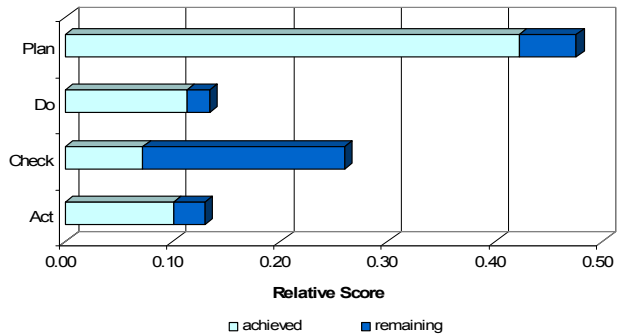


Figure 5: Company A *Hazard Management* opportunities by management cycle.

A second example for Company A is provided in Figure 6, depicting the opportunities for improvement in the factor grouping of *Worker Involvement*. In this case the *Plan* step is emphasized as the greatest area for improvement.

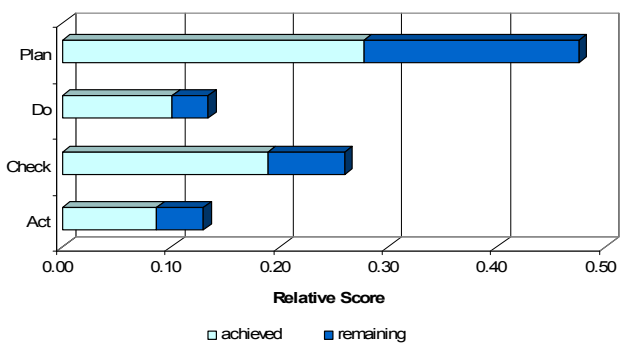


Figure 6: Company A *Worker Involvement* opportunities by management cycle.

4.3 Performance results

A review of recently completed external safety audits for Company A highlight deficiencies in the areas of: communication of corrective actions, systems to measure

knowledge and competency of workers, and performance evaluations of health and safety management. However, the audits do not provide additional information on what specifically to address in these areas and are silent on safety management practices that are determined to be compliant with the defined program (i.e., no opportunity to improve on the current process). An analysis of the performance of Company A with respect to legislative requirements is not yet complete.

5 Conclusions

The framework presented describes an approach for assessing safety management practices at an organizational level. The approach employs the measurement of the maturity for different factor groupings and the four steps in a continuous improvement process to provide insight as to which areas provide the best opportunities. By combining these results with performance data, a relationship can be established. The research described is nearing the completion of the data collection phase for a representative group of companies. The immediate steps to follow will be an analysis of the relationship between assessed practices and performance data. Extending the approach to a broader data collection exercise will also facilitate the use of the information collected for industry performance benchmarking and allow normalized comparisons across regions (e.g., provinces or countries). The preliminary results highlight the need for the involvement of more experts in the weighting process to ensure the consistency of the final weights. The parameters set out by Aull-Hyde et al (2006) on the relationship between group size, matrix size and consistency will be followed.

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VALIDITY OF INDUSTRY BENCHMARKS AND METRICS FOR ENGINEERING PRODUCTIVITY

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Abstract

In order to evaluate the productivity of a project or a group of projects, the estimate or the schedule of the project in hand should be compared to those of other projects of similar nature. In the absence of proper data and points of comparison within the organization, industry standards and metrics are usually used. The standard industry metrics commonly used for assessing the productivity of the engineering phase of construction projects are the ratio of engineering hours per quantity of designed elements and the ratio of engineering cost to total installed cost (TIC) of the projects. The research into the validity of these industry standards for projects with different sizes is very limited. The scope of this paper is to assess the validity of the existing industry metrics for engineering productivity by illustrating the effect of projects size on the expected values of these metrics.

Introduction

Setting benchmarks to evaluate the productivity of a construction project or a construction contractor has long been of interest of construction industry researchers and practitioners. Statistics Canada figures for construction industry shows a lower ratio of hours worked to Gross Domestic Product (GDP) dollars generated for construction industry compared to other industries in Canada. While other researchers (Rankin et al. 2008) have interpreted this as a lower labour productivity for construction industry, these figures can simply mean that construction operations and processes are more labour intensive.

The primary objective of benchmarking in construction industry is to provide the means to measure the competency and efficiency of a construction process, project or company compared to similar processes, other projects or other construction companies. The first step in this process is to define the context within which the comparison should be carried out and therefore determine the quantity that has to be measured. In early 1990s, three major criteria identified in the literature of

construction industry for measuring the success of a construction project were project duration, project cost and quality of project's deliverables (Navarre et al. 1990). Later on, customer satisfaction and safety were added to the series of criteria based on which a construction project's success and competency can be determined (Pinto et al. 1991, Kometa et al. 1995).

Many studies in construction industry have been carried out for establishing metrics and competitive benchmarking of the performance of construction of a construction project. These studies include the efforts to measure multi-factor productivity of a construction project (Park et al. 2005), to quantify labour productivity in the construction phase of a project (Zhi et al. 2003), to establish a pilot program for measuring the performance of construction industry in Canada (Rankin et al. 2008) and to improve project management performance of construction contractors through benchmarking (Luu et al. 2007).

Unlike the multitude of efforts in developing benchmarks and productivity metrics for the construction phase of construction projects, the research into establishing productivity metrics and benchmarks for the engineering phase of the construction projects has been very limited. Three main metrics proposed for assessing engineering productivity are engineering hours per drawing (Thomas 1999), engineering hours per designed element (Song et al. 2003) and engineering hours per quantity of designed elements (Kim 2007). In addition to these academic contributions, three major organizations have started initiatives in benchmarking and developing metrics for the construction industry. Construction Industry Institute (CII), Independent Project Analysis (IPA) and Movement for Innovation (M4I) have collected data on the engineering and construction phases of many construction projects throughout the years for benchmarking purposes. These organizations measure the engineering productivity as the ratio of engineering hours or cost to the quantity of engineered elements or material. They use the expected values of these metrics to establish the productivity of a group of project executed by an engineering firm.

The objective of this paper is to review the efforts by these three organizations and illustrate the analytical flaw in the existing approaches in comparing different groups of projects based on the existing engineering productivity metrics. The next section of the paper reviews the existing engineering productivity metrics used in construction industry. This section is followed by two other sections which include a discussion on statistical inference of the introduced metrics and a quantitative example. The statistical inference discussion and the numerical example show that the reviewed metrics have to be normalized before being used to compare productivities of different groups of engineering projects.

Engineering Productivity Metrics

Productivity is defined as the ratio of output to input. Based on this basic definition, Thomas (1999) proposed the first metric to measure productivity of the engineering phase of a construction project by measuring the quantity of engineering hours spent to produce an engineering drawing. This metric has been criticized by other researchers. The main problem pointed out by others with respect to this metric is that the drawings are not standardized in the constructions industry. Different engineering houses may issue different numbers of drawings for the same scope of work. On the

other hand, engineering drawings have a wide range in terms of type and the effort required to produce them. For example it usually takes much less engineering hours to produce a demolition drawing than it takes to produce a new installation drawing. The same is true about modifying an existing drawing versus creating a new drawing.

The second metric for engineering productivity proposed by Song et al. (2003) was based on measuring engineering hours per designed element like a beam or a column. The main problem with this metric is the intrinsic subjectivity of the term "designed element". Considering a beam versus considering an entire spool as a design element would definitely affect the outcomes of the metric. Another problem with this metric is again the wide range of designed element in construction industry. Without further categorization of the construction projects, the results of this metric may be inconclusive.

Another metric for engineering productivity used by CII (Kim 2007, Liao 2008) was the ratio of engineering hours to the quantity of designed elements. Using this metric, CII suggests measuring the engineering hours consumed to complete the design for a ton of steel, a linear meter of pipe or a piece of equipment. The results of applying this metric on projects with different sizes from different sectors in construction industry showed a linear relationship between the engineering hours and the designed quantity. However, the statistical analysis of the metric presented by Kim (2007) was not very conclusive as the metric proved to have large variances for many designed quantities.

Another metric that is very often used by the construction industry practitioners due to lack of data and information is the ratio of engineering cost to the total installed cost of the project. The general perception in the industry is that there is a linear correlation between the engineering cost of a construction project and the size of that project.

Equations 1 and 2 illustrates the relationship between engineering hours or cost and the quantity of designed materials and total installed cost (TIC) of construction projects as established by CII and IPA while Equation 3 shows the relationship of engineering cost to TIC as used by the practitioners when no data is available on the quantity of designed elements:

$$EH = a + b * Q \quad \text{(CII)} \qquad \textbf{Equation 1}$$

$$EH = c + d * Q^{m} * TIC^{n} \quad \text{(IPA)} \qquad \textbf{Equation 2}$$

$$EC = e + f * TIC \qquad \textbf{Equation 3}$$

Where EH represents engineering hours, EC represents engineering cost, Q is the quantity of designed elements, TIC is the total installed cost of a project and a, b, c, d, e, f, m and n are coefficients whose values are different for different types of projects. The main difference between Equations 1 and 2 used by CII and IPA and the other equation is that CII and IPA consider the effect of quantity of designed elements. The fact that projects with the same TIC may require different level of engineering effort and cost is well recognized. Using Equations 1 and 2 as the basis of relationship between engineering hours and quantity of designed elements and total installed cost, CII and IPA have tried to address this issue.

Statistical Inference of Engineering Productivity

CII and IPA correctly use the expected values of these metrics to compare groups of projects. Although the metrics can be calculated for individual projects, because of

the specific properties of each project like scope complexity and scale of scope change, the metrics are not a good indicator of the productivity of a single project. On the other hand, those project specific properties can be assumed to be normally distributed for large enough groups of projects. CII and IPA use the statistical moments of the metrics to compare the engineering productivities of two groups of projects.

Statistical analysis of the engineering productivity data as defined by CII and IPA are usually presented in box and whisker diagrams (Kim 2007). These diagrams show a great variance for the ratio of detail engineering cost to the TIC or total quantity of engineered elements. Assuming validity of Equations 1, 2 and 3, it can be shown that statistical moments of the ratio of detail engineering cost to the TIC (EC/TIC) or the ratio of detail engineering hours to total quantity of designed elements (EH/Q) depend on the statistical moments of 1/TIC and 1/Q. Equations 4 to 6 calculate EC/TIC and EH/Q based on relationships illustrated Equations 1,2 and 3 respectively.

$$EH/Q = a/Q + b \quad \textbf{Equation 4}$$

$$EH/Q = c/Q + d * Q^{m-1} * TIC^{n} \quad \textbf{Equation 5}$$

$$EC/TIC = e/TIC + f \quad \textbf{Equation 6}$$

Based on these equations, the expected values of EC/TIC and EH/Q can be calculated as:

$$E(EH/Q) = a * E(1/Q) + b \quad \textbf{Equation 7}$$

$$E(EH/Q) = c * E(1/Q) + d * E(Q^{m-1} * TIC^{n}) \quad \textbf{Equation 8}$$

$$E(EC/TIC) = e * E(1/TIC) + f \quad \textbf{Equation 9}$$

As shown in Equations 7 to 9, the expected values or means of EC/TIC and EH/Q directly depend on the size of the projects executed by an engineering firm and the quantity of designed elements. Assuming TIC is measured in million dollars, an engineering house with no projects less than one million dollars would have a lower mean for EC/TIC or EH/TIC and consequently a higher productivity compared to another engineering company with many projects in the TIC range of less than one million dollars. These Equations clearly show that expected values of the metrics used in construction industry for measuring engineering productivity should be normalized for the size of the jobs and range of the designed elements quantity of the groups of projects.

Quantitative Example

A sample numerical example is necessary to illustrates how the expected value of the ratios of engineering hours to quantity of designed elements for a group of projects executed by an engineering firm depends on the expected values of Q and TIC. For the sake of simplicity, assume that the relationship between EH and Q follows Equation 1 (CII's model) and that the objective is to compare engineering productivities of companies X and Y. Tables 1 and 2 illustrate the lists of hypothetical piping projects performed by companies X and Y, the quantities of installed pipes in kilometers for each project and the projects' total engineering hours as calculated by

Equation 1 using a=10 (hrs) and b=0.1 (hrs per kilometers of pipe). Tables 1 and 2 also shows the ratio of EH to Q for each project assuming that the engineering hours calculated by Equation 1 equal the total spent engineering hours on the projects. In other words we assume the cost performance index (CPI) of one for each piping project performed by either company. The average ratio for EH/Q for company X is 0.15 while this ratio for company Y is 0.58.

Table 1 Piping Projects by Company X

Projects	Q (kilometer)	Required EH (hr)	EH/Q
X1	100	20	0.20
X2	150	25	0.17
X3	200	30	0.15
X4	300	40	0.13
X5	250	35	0.14
X6	380	48	0.13
X7	220	32	0.15
X8	120	22	0.18
X9	500	60	0.12
X10	520	62	0.12

Table 2 Piping Projects by Company Y

Projects	Q (kilometer)	Required EH (hr)	EH/Q
Y1	10	11	1.10
Y2	15	11.5	0.77
Y3	20	12	0.60
Y4	30	13	0.43
Y5	25	12.5	0.50
Y6	38	13.8	0.36
Y7	22	12.2	0.55
Y8	12	11.2	0.93
Y9	50	15	0.30
Y10	52	15.2	0.29

Based on the calculations for this example, company X has a much lower ratio of engineering hours per quantity of designed elements and so company X has a higher engineering productivity compared to company Y by CII definition. However, it was established that the required engineering hours to perform a project can be calculated using Equation 1 and that both companies have CPIs of one. This example clearly shows the effect of size of Q on the expected value of EH/Q. While companies X and Y are equally productive, company X has a lower average EH/Q only because it performs bigger projects. Using Equations 2 or 3 as the basis for relationship between EH or EC, Q and TIC will produce similar results.

Conclusions and Recommendations

This paper reviewed the existing metrics used for benchmarking engineering productivity of engineering projects. Through analytical formulas, it was illustrated that the expected values for the metrics used in the industry to measure the productivity of a set of engineering projects are in fact dependent on the size of the projects in that group and so have to be normalized. Not normalizing the expected value of the metrics for the size of the projects results in always calculating a higher engineering productivity for the engineering firms executing only larger engineering projects. This was also shown by a numerical example where the engineering productivities of two companies for a group of piping projects were calculated and compared. Although the example was set up so that both companies have the same engineering productivity, it was shown that using CII's metric the company with larger projects shows a better engineering productivity.

In order to have a better metric for engineer productivity, either the existing metrics used by the industry should be normalized for projects' TIC and Q or a new metric should be introduced. A recommendation for a revised and normalized engineering metric based on the findings of this paper is to use Equations 1, 2 and 3 or other similar model to calculate the total required engineering hours for a construction project and then define the productivity metric as the ratio of total required engineering hours to total engineering hours spent for each project. This definition of engineering productivity will also be consistent with earned value management method.

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WORKER SATISFACTION AND WORK-LIFE RELATED CHARACTERISTICS IN THE U.S. CONSTRUCTION INDUSTRY

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ABSTRACT: While the U.S Construction industry is currently experiencing minimal shortage in craft workers, the shortages that existed prior to the current economic downturn are likely to return. Previous research argues that worker satisfaction plays an important role in retaining and attracting more workers into the construction industry. The authors previously presented a longitudinal study at the 2003 ASCE Construction Research Congress that examined construction worker characteristics related with satisfaction, including race, union status, education attainment, age, and worker preference from 1970s to 1990s. This paper extends those analyses along with investigation of work-life related characteristics (e.g. respondents' annual income and spousal employment) among U.S. construction workers from 1970s to 2000s, utilizing the General Social Survey (GSS) data. A comparison of these demographic characteristics between construction and other industries is made as well.

INTRODUCTION

The current U.S. economy has had a significant impact on the employment levels in the construction industry. According to the U.S. Bureau of Labor Statistics (BLS), by September 2009, the unemployment rate in the construction industry reached17.1%. This economic downturn, to some extent, may have eased the craft shortages in many sectors of the U.S. construction industry, but there is little reason to believe that the industry has developed an immunity to craft shortages once the economy rebounds. A variety of reasons have been offered for why craft worker shortages occur in construction, including declining real wages and an unattractive public image of construction career (Slater 1997). Compounded with an aging construction workforce as millions of baby boomers approach retirement age (Choi 2009), the need to improve the recruitment and retention of craft workers remains.

Construction has also experienced relatively higher turnover and absenteeism rates compared to other industries. A recently completed research effort (CII 2007) identified the average unexpected turnover rate among member companies of the Construction Industry Institute at 15.5% with an average absenteeism of 7.2% of a project's daily force. This exasperates the issue of craft availability facing the

construction industry. To address this issue, a number of solutions have been suggested. For example, the application of multiskilled labor utilization strategies (Burleson et al., 1998) examined how to better utilize a smaller construction workforce. Improving public image and increasing recruiting efforts is another solution. Some researchers (Borcherding and Oglesby 1974, Maloney and McFillen1984, Rowing et al. 1996) have examined the motivation and job satisfaction on craft workers in order to improve the worker productivity, performance, and retention.

In the sociological research realm, a significant number of research efforts have studied how job satisfaction is associated with work-life characteristics. Clark (1996) sampled 5000 British employees and found older workers have higher job satisfaction. Borjas (1978) studied the effect on union membership status on job satisfaction. Judge and Watanabe (1993) examined the relationship between job and life satisfaction, and positive relationships were found. Schneer and Reitman (1993) did find that increases in spousal employment were related to increased career satisfaction among M.B.A. degree holders; the researchers attributed the increased satisfaction as a result of fulfilling multiple roles of spouse and worker.

Having recognized that worker satisfaction plays an important role in retaining and attracting more workers into construction industry, investigating the worker satisfaction is of essence to the research effort described herein. The authors previously presented a longitudinal study(from 1970s to 1990s) at the 2003 ASCE Construction Research Congress that examined construction worker characteristics related with satisfaction, including race, union status, education attainment, age, and job preference. This paper extends those analyses along with the investigation of work-life related characteristics (including age, union status, respondents' income, and spousal employment) among U.S. construction workers from 1970s to 2000s.

SCOPE OF ANALYSES

This paper studies the trend of construction craft worker satisfaction between the 1970s to 2000s decades and makes a comparison in construction's worker satisfaction with other industries. This paper also examines job satisfaction of construction craft workers with respect to work-life related characteristics, such as age, union status, respondents' income, and spousal employment. The main purpose of this paper is to study how these characteristics vary from 1970s to 2000s in both construction and other industries, and how these characteristics relate to craft worker satisfaction.

RESEARCH METHODOLOGY

The analyses of this paper utilize the General Social Survey (GSS) data containing the sample from 1972 to 2008. The GSS has been conducted by the Nation Opinion Research Center (NORC) since 1972, and it is the biggest project funded by the National Science Foundation (NSF) to monitor the social change and growing complexity of society in the U.S. The GSS is publicly accessible, and it records respondents' information with respect to demographic, behavioral, attitudinal,

and other special interests. The 1972-2008 GSS contains responses from 53,043 respondents on 5,364 questions. Many of the questions in GSS have remained unchanged since 1972; therefore it is an excellent source of data to examine the changes in a population's characteristics over time.

The GSS asks respondents to self identify themselves as blue or white-collar workers. For the analyses described herein, only blue-collar workers were included. For construction respondents to the GSS survey, blue-collar workers include craftsman and kindred workers, equipment operators (including truck drivers), and laborers. For all other industries, blue-worker excludes supervisory, administrative and engineering occupations. Based on the respondents' answers on the industry they are working in, the sample was grouped into construction and non-construction industries. In total, there are 2,032 (10.9%) blue-collars from construction industry and 16,642 (89.1%) blue-collars from all other industries included in the analyses.

With respect to how respondents were satisfied with their job, the GSS used four measures: very satisfied, moderately satisfied, a little dissatisfied, and very dissatisfied. To simplify the analyses, the responses indicating very satisfied and moderately satisfied were classified as satisfied, and other responses indicating a little dissatisfied and very dissatisfied were classified as dissatisfied.

The GSS data used for analyses involves categorical and numerical data. For categorical data, Chi-square was used for the test of overall difference, and the test of difference between two proportional was used throughout the analyses as well. As to the numerical data, ANOVA was employed to test the mean difference among the groups.

RESULTS OF ANALYSES

Work-life Characteristics

Age Sociological studies tend to group a population into baby boomers (born before 1965), X generation (born between 1965-1980), and Y generation (born after 1980). Along this logic, the respondents were categorized into 3 age groups: younger than 29, between 29 and 44, and older than 44. As shown in Table 1, over the last four decades, the sampled workers between age 29 and 44 performing construction works have nearly increased by 7%. Overall, there has been a decline in the over 44 years of age group although it still remains the largest segment, at least among the GSS sample of construction workers.

Table 1: Worker Age in Construction: 1970s, 1980s, 1990s, and 2000s.

	Decade			
Age	*1970s (N=421)*	*1980s (N=540)*	*1990s (N=471)*	*2000s (N=599)*
<29	24.7%	28.7%	18.7%	21.9%
29-44	29.7%	35.0%	42.2%	36.6%
>44	45.6%	36.3%	40.1%	41.5%
TOTAL	100.0%	100.0%	100.0%	100.0%

Note: Data Source: GSS 1972-2008; Sample size does not total to the study's total size of 2032 due to non-responses in the GSS.

Table 2 examines the observed trend of blue-collar workers' age in all other industries over the past four decades. A comparison was made with the construction industry as well. Overall, all other industries have a higher percentage in the over 44 years old age group, which constantly shows a statistically significant difference at the 95% confidence level when compared to the construction industry from the 1970s to 2000s. Although there are a multitude of reasons that could perhaps explain the difference, the physically demanding nature of construction is one obvious reason.

Table 2: Worker Age in all other industry: 1970s, 1980s, 1990s, and 2000s.

	Decade			
Age	*1970s (N=3257)*	*1980s (N=4202)*	*1990s (N=4451)*	*2000s (N=4701)*
<29	20.4%	20.7%	18.3%	18.0%
29-44	27.0%	30.0%	36.5%	30.9%
>44	52.6%	49.3%	45.2%	51.1%
TOTAL	100.0%	100.0%	100.0%	100.0%
Difference to Construction				
<29 (Sig. of Difference[a])	-4.3%(.04)	-8.0%(.00)	-0.4%(.83)	-3.9%(.02)
29-44(Sig. of Difference[a])	-2.7%(.24)	-5.0%(.02)	-4.7%(.05)	-5.7%(.00)
>44 (Sig. of Difference[a])	7.0%(.01)	13.0%(.00)	5.1%(.03)	9.6%(.00)

[a] These values are the result of the application of the test of significance of the difference between two proportions.

Union Status Table 3 examines the change in union status among the sampled construction workers. The percentage of union workers among the sampled workers decreased from 38.5% during 1970s to 19.0% during 2000s, reflecting the decline in union construction workers as a whole.

Table 3: Union Status in Construction: 1970s, 1980s, 1990s, and 2000s.

	Decade			
Union Status	*1970s (N=252)*	*1980s (N=346)*	*1990s (N=127)*	*2000s (N=63)*
Union	38.5%	24.6%	18.9%	19.0%
Non-union	61.5%	75.4%	81.1%	81.0%
TOTAL	100.0%	100.0%	100.0%	100.0%

Note: Data Source: GSS 1972-2008; Chi-square for the overall difference between columns, with d.f.=3, is 23.64 (sig. = 0.00); Sample size does not total to the study's total size of 2032 due to non-responses in the GSS.

Respondent's Annual Income Tables 4 compares the respondents' average annual income between construction and non-construction industries. To make the respondents' annual income longitudinally comparable, all income values were converted to 2000 U.S. dollar values using BLS Consumer Price Index. There was no statistically significant difference identified in the 1970s and 1980s decades in the respondents' annual income in construction and non-construction. However, in decades of 1990s and 2000s, statistically significant differences were observed in the respondents' annual income between construction and non-construction blue-collar workers. The sampled construction workers tended to earn more than their counterparts in annual terms from non-construction industry. Although the difference in income as well as the upward trend in construction appear surprising considering wide spread reports of declines in construction real wages, the annual incomes do not reflect the number of hours worked. The GSS data tracks the respondents' work hours per week, which shows an increase in the number of weekly hours worked from

1970s to 2000s (Table 5). This upward trend could be partially explained by the increase in number of hours that construction workers worked across the four decades. This trend increase in annual income could also be explained by other factors, not measured by the GSS, such as benefits, bonuses, and trade distributions.

Table 4: Respondents' Annual Income (in 2000 US $ Value) in Both Construction and All Other Industries: 1970s-2000s

	Decade			
Industry	*1970s*	*1980s*	*1990s*	*2000s*
Non-construction	27,182.3	25,907.8	23,130.6	23,188.7
	(N=1489)	(N=2605)	(N=2887)	(N=2455)
Construction	28,253.9	25,306.9	28,690.3	30,760.4
	(N=224)	(N=407)	(N=332)	(N=359)
Difference(sig.[a])	-1,071.6(.49)	600.9(.58)	-5,559.7 (.00)	-7,571.7(.00)

Note: Data Source: GSS 1972-2008; Sample size does not total to the study's total size of 2032 for construction due to non-responses in the GSS;

[a] These values are the result of the application of ANOVA to test the significance of the difference between two groups.

Table 5: Respondents' Number of Hours Worked Last Week in Construction Industry: 1970s-2000s

	Decade			
	1970s (N=195)	*1980s (N=287)*	*1990s (N=238)*	*2000s (N=305)*
Work hours	39.0	39.0	40.7	43.0

Note: Data Source: GSS 1972-2008; Sample size does not total to the study's total size of 2032 for construction due to non-responses in the GSS;

Spousal Employment Table 6 and 7 examine the respondents' spousal employment status and compare the difference between construction and non-construction industry across the four decades. As to respondents' spousal employment, the change in spousal employment status in both construction and non-construction industries was statistically significant across the four decades. There has been a dramatic increase in the number of spouses working full-time over the past four decades. The percentage of part time working spouses also slightly increased though the increase was not as remarkable as that of full time working spouse. Table 7 also provides a comparison of respondents' spousal employment status between construction and non-construction industry. Across the four decades, non-construction workers' spouses were more likely to pursue full time employment than construction workers' spouses. The difference in part-time and unemployment between construction and non-construction respondents' spouses was not statistically significant. However, it is noted that, in percentage, more construction workers' spouses tend to work part-time or not work at all.

Table 6: Respondent's Spouse Employment Status in Construction: 1970s-2000s

	Decade			
Employment Status	*1970s (N=317)*	*1980s (N=316)*	*1990s (N=255)*	*2000s (N=268)*
Full Time	22.1%	39.9%	47.9%	45.5%
Part Time	9.5%	12.0%	12.9%	13.1%
Unemployed	68.4%	48.1%	39.2%	41.4%
TOTAL	100.0%	100.0%	100.0%	100.0%

Note: Data Source: GSS 1972-2008; Chi-square for the overall difference between columns, with d.f.=6, is 65.58 (sig. = 0.00); Sample size does not total to the study's total size of 2032 due to non-responses in the GSS;

Table 7: Respondent's Spouse Employment Status in All other Industries: 1970s-2000s

	Decade			
Employment Status	*1970s (N=2254)*	*1980s (N=2380)*	*1990s (N=2133)*	*2000s (N=2050)*
Full Time	39.8%	44.3%	54.1%	55.8%
Part Time	8.7%	9.8%	10.1%	10.0%
Unemployed	51.5%	45.9%	35.8%	34.2%
TOTAL	100.0%	100.0%	100.0%	100.0%
Difference to Construction				
Full Time (Sig. of Difference[a])	17.7%(.00)	4.4%(.14)	6.2%(.06)	10.3%(.00)
Part Time (Sig. of Difference[a])	-0.8%(.64)	-2.2%(.22)	-2.8%(.17)	-3.1%(.12)
Unemployed (Sig. of Difference[a])	-16.9%(.00)	-2.2%(.46)	-3.4%(.27)	-7.2%(.02)

Note: Data Source: GSS 1972-2008; Chi-square for the overall difference between columns, with d.f.=6, is189.9 (sig. = 0.00);
[a] These values are the result of the application of the test of significance of the difference between two proportions.

WORKER SATISFACTION

In regards to its examination of worker satisfaction, this paper examines the change of workers' satisfaction in both construction and non-construction industries from 1970s to 2000s. A comparison between the industries was made as well. As shown in Table 8 over the four decades, the construction blue-collar worker satisfaction did not change very much, since there was no statistically significant difference identified. The vast majority of the surveyed construction workers were satisfied with their work.

Table 8: Worker Satisfaction in Construction: 1970s, 1980s, 1990s, and 2000s.

	Decade			
Satisfaction	*1970s (N=303)*	*1980s (N=445)*	*1990s (N=370)*	*2000s (N=342)*
Dissatisfied	12.5%	13.5%	12.7%	9.9%
Satisfied	87.5%	86.5%	87.3%	90.1%
TOTAL	100.0%	100.0%	100.0%	100.0%

Note: Data Source: GSS 1972-2008; Chi-square for the overall difference between columns, with d.f. =3, is 2.42 (sig. = 0.49). Sample size does not total to the study's total size of 2032 due to non-responses in the GSS;

For non-construction industries, the change in blue-collar worker satisfaction across the 4 decades was statistically significant different, but the magnitude of change was not very substantial. According to Table 9, more construction workers reported that they were satisfied with their work compared to non-construction workers. The difference over the last three decades was statistically significant at the 95% confidence level.

Table 9: Worker Satisfaction in Non-construction and Comparison with Construction: 1970s, 1980s, 1990s, and 2000s.

	Decade			
Satisfaction	*1970s (N=2346)*	*1980s (N=3212)*	*1990s (N=3435)*	*2000s (N=2613)*
Dissatisfied	15.7%	18.9%	17.5%	15.4%
Satisfied	84.3%	81.9%	82.5%	84.6%
TOTAL	100.0%	100.0%	100.0%	100.0%
Difference to Construction				
Dissatisfied (Sig. of Difference[a])	3.2%(.14)	5.4%(.01)	4.8%(.02)	5.5%(.01)
Satisfied (Sig. of Difference[a])	-3.2%(.14)	-5.4%(.01)	-4.8%(.02)	-5.5%(.01)

Note: Data Source: GSS 1972-2008; Chi-square for the overall difference between columns, with d.f. =3, is 16.57% (sig. = 0.00).;
[a] These values are the result of the application of the test of significance of the difference between two proportions.

Next, this paper exclusively studies the construction worker satisfaction difference by decade in terms of age, union status, respondents' income, and spousal employment status.

Worker Satisfaction vs. Age

Table 10 examines differences in construction worker satisfaction with respect to respondent's age from 1972 to 2008. For the three age groups, no statistically significant change in satisfaction across the four decades was observed within the same age groups. As shown, statistically significant differences in satisfaction were identified between less than 29 years old and 29-44 years old age groups and between less than 29 years old and over 44 years old groups during the decade of 1980s. Among all four decades, respondents older than 44 years of age were more likely to indicate that they were satisfied with their work, which coincides with Clark's (1996) finding that older workers tend to be more satisfied with their jobs.

Table 10: Worker Satisfaction Difference in Construction Industry by Age: 1970s, 1980s, 1990s, and 2000s.

	Decade			
Satisfaction	*1970s*	*1980s*	*1990s*	*2000s*
Dissatisfied				
<29 years old	14.9% (N=13)	20.0%(N=29)	12.8% (N=11)	11.3% (N=11)
29-44 years old	15.0% (N=17)	11.0%(N=20)	14.7% (N=27)	9.4% (N=13)
>44 years old	7.8% (N=8)	9.2%(N=11)	9.0% (N=9)	9.4% (N=10)
Satisfied				
<29 years old (χ^2=4.04, df=3, sig.=.26)	85.1% (N=74)	80.0% (N=116)	87.2% (N=75)	88.7% (N=86)
29-44 years old (χ^2=3.00, df=3, sig.=.39)	85.5% (N=96)	89.0% (N=161)	85.3% (N=157)	90.6% (N=125)
>44 years old (χ^2=.22, df=3, sig.=.97)	92.2% (N=95)	90.8% (N=108)	91.0% (N=91)	90.6% (N=96)
Diff. in satisfaction between				
<29 and 29-44 years old (sig[a])	.1% (.98)	-9.0% (.02)	1.9% (.68)	-1.9% (.64)
29-44 and >44 years old(sig[a])	-7.2% (.10)	-1.8% (.62)	-5.7% (.17)	.0% (1.00)
<29 and > 44 years old(sig[a])	-7.1% (.12)	-10.8%(.01)	-3.8% (.41)	-1.9% (.66)

Note: Data Source: GSS 1972-2008; Sample size does not total to the study's total size of 2032 due to non-responses in the GSS; Chi-square analyses were performed to see the difference in satisfaction among the decades.

[a] These values are the result of the application of the test of significance of the difference between two proportions.

Worker Satisfaction vs. Union Status

Table 11 presents the worker satisfaction difference according to their union membership status. Presumably, one may consider that union workers may receive more work satisfaction from their work, since they are under the shelter of trade union organization and typically receive greater benefits and pay. However, analyses did not show any statistically significant difference in work satisfaction between union and non-union construction workers.

Table 11: Worker Satisfaction Difference Among Union and Non-union Workers: 1970s, 1980s, 1990s, and 2000s.

	Decade			
Satisfaction	*1970s*	*1980s*	*1990s*	*2000s*
Dissatisfied				
Union	6.8%(N=5)	14.1%(N=10)	13.3%(N=2)	0%(N=0)
Non-Union	13.1%(N=14)	12.5%(N=27)	11.3%(N=9)	0%(N=0)
Difference(sig.[a])	-6.3%(.17)	1.6%(.73)	2.0%(.82)	--
Satisfied				
Union	93.2%(N=69)	85.9%(N=61)	86.3%(N=13)	100%(N=4)
Non-Union	86.9%(N=93)	87.5%(N=189)	88.7%(N=71)	100%(N=9)
Difference(sig.[a])	6.3%(.17)	-1.6%(.73)	-2.0%(.82)	--

Note: Data Source: GSS 1972-2008; Sample size does not total to the study's total size of 2032 due to non-responses in the GSS;
[a] These values are the result of the application of the test of significance of the difference between two proportions.

Worker Satisfaction vs. Respondents Annual Income

Table 12 describes the construction workers income difference between the satisfied and dissatisfied respondents. During the 1970s and 1980s, statistically significant difference was found in the respondents' annual income at the 95% confidence level. A respondent who reported a higher income tended to indicate greater satisfaction from his/her work. The same trend was observed during the decades of 1990 and 2000s, but the difference was not statistically significant. This result also somewhat concurs with the findings presented on 2003 Construction Research Congress (Goodrum 2003) that "high income" was the second most important factor among construction craft workers ranking after "sense of accomplishment."

Table 12: Worker Satisfaction in Construction Industry vs. Respondents' Annual Income: 1970s, 1980s, 1990s, and 2000s.

	Decade			
Satisfaction	*1970s*	*1980s*	*1990s*	*2000s*
Dissatisfied	$20,770	$20,091	$24,488	$23,832
	(N=21)	(N=50)	(N=42)	(N=17)
Satisfied	$31,120	$26,610	$29,761	$29,983
	(N=173)	(N=342)	(N=282)	(N=208)
Difference(sig.[a])	-10,350(.02)	-6,519(.02)	-5,273(.14)	-6,151(.30)

Note: Data Source: GSS 1972-2008; Sample size does not total to the study's total size of 2032 due to non-responses in the GSS;
[a] These values are the result of the application of ANOVA to test the significance of the difference between two groups.

Worker Satisfaction vs. Respondent's Spousal Employment Status

Table 13 examines the relationship between construction worker satisfaction and spousal employment status. In this analysis, the writers collapsed full time and part time into employed group for the sake of sample size. The analyses did not reveal any statistically significant difference beyond the 95% confidence level in spousal employment status between dissatisfied and satisfied respondents, however it is noted that there was a difference at the 90% confidence level in the 2000s with greater job satisfaction among construction workers with employed spouses (either part or full time). While these analyses suggest that the relationship between job satisfaction and spousal employment status is limited, further research is needed to examine how significant increases in spousal employment among construction workers is effecting other workforce characteristics, particularly worker mobility

Table 13: Worker Satisfaction in Construction Industry vs. Spousal Employment Status: 1970s, 1980s, 1990s, and 2000s.

		Decade			
Satisfaction		*1970s*	*1980s*	*1990s*	*2000s*
Dissatisfied					
	Employed	9.1% (N=8)	11.9% (N=18)	15.0% (N=21)	4.3% (N=4)
	Unemployed	12.7% (N=19)	8.3% (N=9)	8.6% (N=5)	11.5% (N=6)
	Difference (Sig.[a])	-3.6% (.40)	3.6% (.35)	6.4% (.23)	-7.2%(.10)
Satisfied					
	Employed	90.9% (N=80)	88.1% (N=133)	85.0% (N=119)	95.7% (N=89)
	Unemployed	87.3% (N=131)	91.7% (N=99)	91.4% (N=53)	88.5% (N=46)
	Difference (Sig.[a])	3.6% (.40)	-3.6% (.35)	-6.4% (.23)	7.2%(.10)

Note: Data Source: GSS 1972-2008; Sample size does not total to the study's total size of 2032 due to non-responses in the GSS;
[a] These values are the result of the application of the test of significance of the difference between two proportions.

CONCLUSION

This paper primarily examines the blue-collar workers' job satisfaction in terms of work-life characteristics using GSS data. The authors studied work-life characteristic change in both construction and non-construction industry from 1972 to 2008 and compared the difference between the construction industry and all other industries. Particularly, the construction blue-collar worker satisfaction difference with respect to different work-life characteristics was investigated. The following findings were identified:

- Over the last four decades among the sampled population of construction workers, at least 7.0% more 44-year older workers were working in non-construction industries when compared to the construction industry (Table 2). The construction industry had more workers younger than 44-year-old as opposed to other industries.
- Union workers diminished approximately 19% in construction industry over the last four decades among those sampled in the GSS (Table 3).
- Among the sampled blue-collar workers, construction workers tended to have higher annual income than the workers from all other industries (Table 4).
- The sampled construction respondents' spouses were less likely to work full time than other industry respondents' spouses (Table 7). Over the last four decades, among the respondents engaged in construction industry, the number of full time working spouse significantly increased (Table 6).
- According to the responses from the sampled respondents, there was no statistical significant change found on overall worker satisfaction in construction industry between the 1990s to 2000s decades (Table 8). However, among the sampled population, at least 3.2% more construction blue-collar workers reported they were satisfied with their job compared to other industry workers (Table 9).
- Among the sampled construction blue-collar workers, a larger percentage of construction respondents that were 44 years or older indicated receiving satisfaction from their job compared to other age groups (Table 10).
- Among the GSS sampled construction workers, there was no obvious satisfaction difference observed in terms of union status and spousal employment (Table 11& 13).

- The GSS sampled construction workers who indicated that they were satisfied with their job had higher annual income than workers who indicated otherwise (Table 12).

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A Framework for Evaluating the Effect of Fast-Tracking Techniques on Project Performance

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Abstract

Reducing project duration is rewarding for both owners and contractors in any competitive industry. Fast-tracking strategies are the most practical way to achieve shorter project duration, although these strategies invariably impose additional risks and may negatively impact project performance. Despite all negative impacts, if the effect of applying fast tracking techniques on project performance can be theoretically and practically identified, monitored and controlled throughout the project, the fast tracking can result in better outcomes. The objective of this paper is to demonstrate a theoretical framework for evaluating and quantifying the impact of fast-tracking techniques on project duration and cost. The ultimate outcome of the research presented in the paper is to provide project managers with benchmarked fast-tracking techniques which assist them in effective and efficient utilization of fast-tracking techniques from the preplanning phase of the projects.

1- Introduction

Reducing project duration has significant strategic implications on the market share and revenue stream for both owners and contractors in any competitive industry. The business benefits of early completion challenges project managers to employ fast-tracking strategies to achieve shorter project duration; however, these strategies may negatively impact project performance by imposing additional risks and driving up the costs. Therefore, fast-tracking is a stressful and troublesome approach when executing projects. Despite the major shift from conventional project management to fast-track project management in recent years, companies still face serious shortcomings and challenges in fast-tracking their projects and consequently for many of them the term "Fast Track" creates a negative impression. While industry practitioners have consensus on the importance of schedule reduction and are trying to achieve it, a few of them are following a systematic and scientific approach for fast-tracking projects. They rely heavily on their own judgment, experience and input from peers in other similar projects. This lack of scientific basis leads, in many cases, to extra costs and even significant schedule overruns and lowers the project profit. However, if the effect of applying fast-tracking techniques on project performance can be identified, monitored and controlled throughout the project, fast-tracking can result in better outcomes (Park 1999). Using a scientific and analytical approach for fast-tracking would improve managers' decision making abilities and leads to millions of dollars profit and cost saving.

The purpose of this paper is to demonstrate a theoretical framework for evaluating the most common fast-tracking techniques and quantifying their impact on project duration and cost. The outcome of this research assists project managers in effective and efficient utilization of fast-tracking techniques in the preplanning phase of the projects. This research is unique in its own way because it provides a scientific framework for quantifying the impact of different fast-tracking techniques on project objectives. The enhanced capability in planning and management through the results of this research effort may help ensure that the fast-tracking approach achieves sizeable delivery time reductions without driving up costs.

2- Fast-tracking Techniques

"The term fast-track is in general use to describe something that takes place more quickly than normal and that is indeed the essence of a fast-track project "(Eastham 2002). In some texts, fast-track has been defined as the overlapping between different project phases which creates significant additional risks. "There are, however, a variety of ways in which this reduced project duration can be achieved and it has been normal in the construction/building industry to limit the definition to exceptional ways of executing the activities involved in the creation of a new asset" (Eastham 2002). In this paper, the term fast-track refers to exceptional project

management practices deployed to achieve shorter project duration. These exceptional strategies impose severe and newer risks and may increase the amount of change, rework and cost of the project. Some of the most common fast-tracking techniques employed by project managers to achieve shorter project duration are as follows: Scope reduction or de-scoping (size reduction, eliminating "nice to have features", etc.), design simplification (standardization, off the shelf components, over-design, concurrent interactive engineering, etc.), modularization and prefabrication. Each of the above mentioned techniques can be applied to fast-track a specific area within the project. Identification of these areas is another important step in the study of fast-tracking techniques. Table 1 provides three examples of different fast-tracking techniques and their areas of application.

Table 1: Example of Different Fast-Tracking Techniques and Their areas of Application

Fast-Tracking Technique	Areas of Application
Pre-fabrication	Steel structure
Overdesign	compressor
Standard design	Pumps

3- Impact of Fast-tracking on Project Objectives

The major targets of construction projects include time, cost, quality and safety. These targets are interrelated and interdependent. As discussed earlier, fast-tracking techniques may help to shorten the project duration; however, it may negatively impact other project objectives. The art is to maintain a proper balance between the objectives of the project so that safety, quality and cost are not sacrificed for time (Ruwanpura 1992). In fast-tracking, projects should be completed in less time but without compromising safety and quality. However, the cost has always been troublesome. The general belief is that adopting fast tracking strategies may impose extra costs on the project. However, in practice, there are many cost saving opportunities as well. Furthermore, some of these extra costs can be compensated with the business benefits of early completion and/or performance bonuses. This research examines the relationship between time and cost in fast-tracked projects.

4- Theoretical Framework for Quantifying the Impact of Different Fast-tracking Techniques on Project Time and Cost

In this section, theoretical foundation for quantifying the impact of fast-tracking on project time and cost is discussed in two stages as follows.

4-1 Framework for Quantifying the Impact of Fast-Tracking on Overall Project

In order to identify the impact of fast-tracking on project duration and cost, the first step is to determine the areas of application of different fast-tracking techniques

within the project. It means the overall project is broken down into smaller components so that the fast-tracked areas can be recognized. This breakdown continues up to the level that information about the time and cost impacts resulting from fast-tracking a specific area can be easily obtained either from industry experts or by investigating project documents (Figure 1). In Figure 1, the dark grey/shaded rectangles represent the areas of application for different fast-tracking techniques within the project.

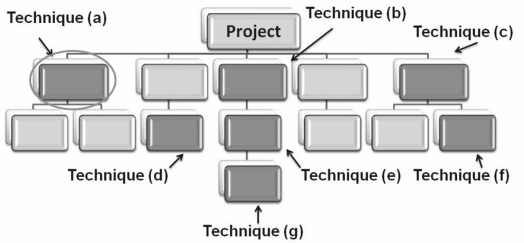


Figure 1: Schematic View of Recognized Fast-tracked Areas within the Project

If the time and cost impact resulting from fast-tracking each specific area can be determined, then the overall time and cost impact on the main project can be easily obtained from Equation (1) and Equation (2).

Cost Impact (on overall project) = ∑ Cost Impact (on each fast-tracked area) Eq. (1)

Time Impact (on overall project) = ∑ Time Impact (on each fast-tracked area which is on the critical path) Eq. (2)

It is important to note the symbol (∑) in Equation (2) represents the summation according to the scheduling relationships.

4-2 Framework for Quantifying the Impact of a Specific Fast-Tracking Technique Applied to a Specific Area within the Project

After outlining the overall framework, the next step would be developing the procedure to determine the effect of a typical fast-tracking technique on its area of application (e.g. circled area in Figure 1) from the time and cost point of view. The overall methodology for this part of the research is a case study analysis. The purpose is to establish a benchmark for different fast-tracking techniques. To achieve this purpose, an extensive industry survey will be performed to identify similar fast-tracked areas, called cases hereinafter, in different projects. In order to draw more valid conclusions, it is better to limit the study to a specific industry. Furthermore, by interviewing industry experts or investigating project documents, additional information regarding the fast-tracked cases will be obtained which allows for the drawing of more reliable conclusions from the case study analysis. The additional information includes but is not limited to the following.

- Normal duration and cost of delivering the specific cases which creates the baseline models. Baseline models can be developed by referring to previous similar projects, benchmarked industry averages and initial estimates. These references provide the inputs to the initial models; however, further interviews are needed to validate the baseline models with several key contacts, including the project managers. In addition to the above information, it might be useful to have the cost and duration breakdowns.
- Case characteristics (e.g. weight, number, type, etc.)
- Reason for fast-tracking (e.g. technical, commercial, schedule reduction, quality, political, etc.)
- Extent of application of fast-tracking technique(s) or application limitation
- Applicability of more than one fast-tracking technique at the same time
- Applicability of fast-tracking technique(s) to other cases

After finding similar fast-tracked cases in different projects, the effect of the fast-tracking technique on time and cost of a specific case can be determined using Equation (3) and Equation (4).

Cost Impact (on a specific fast-tracked case) = Cost after fast-tracking - cost before fast-tracking (Normal Cost) Eq. (3)

Time Impact (on a specific fast-tracked case) = Duration after fast-tracking - Duration before fast-tracking (Normal Duration) Eq. (4)

Then, the results will be processed to provide information regarding the percentage of time and cost impact, and also the relationship between time and cost impact. These processes will be performed using Equation (5), Equation (6) and Equation (7) respectively.

Percentage of Cost Impact = Cost Impact/Normal cost Eq. (5)

Percentage of Time Impact = Time Impact/Normal duration Eq. (6)

Relationship between Time and Cost = Percentage of Cost Impact/ Percentage of Time Impact Eq. (7)

In Equations 3 to 6, normal duration and cost are obtained from the baseline models described in previous steps. However, the cost and duration after fast-tracking should be determined in this step. There are several methods which help to obtain the data which will be explored in detail in section 5 of this paper; however, for the purpose of this section, which is developing the theoretical framework, it is assumed that the data regarding the time and cost after applying the fast-tracking techniques are available. With this assumption, the results obtained from the calculations presented in Equations 3 to 7, will be stored in Table 2.

Table 2: Information Regarding the Effect of Specific Fast-tracking Technique Applied to Similar Cases in Different Projects

	Percentage of Time Impact	Percentage of Cost Impact	Relationship Between Time and Cost
Project # 1			
Project # 2			
…			
Project # n			

After analysis, the expectation is that different numbers for the relationship between time and cost in different projects will be obtained, thus these numbers should be consolidated to provide a benchmark for each fast tracking technique aimed at establishing a reliable relationship between time and cost which can be converted to paradigms. To achieve this, the relationship between time and cost obtained from each project (last column of Table 1) will be converted to the coordinates of points in a *Cartesian coordinate system* and plotted in a graph (Table 3 and Figure 2).

Table 3: Converting the data of Table 1 to the coordinates of points in a Cartesian coordinate system

	Coordinate of Points
Project # 1	P1 =(a,b) a=% Time Impact AND b= % Cost Impact
Project # 2	P2 =(c,d) c=% Time Impact AND d= % Cost Impact
…	…
Project # n	Pn =(x,y) x=% Time Impact AND y= % Cost Impact

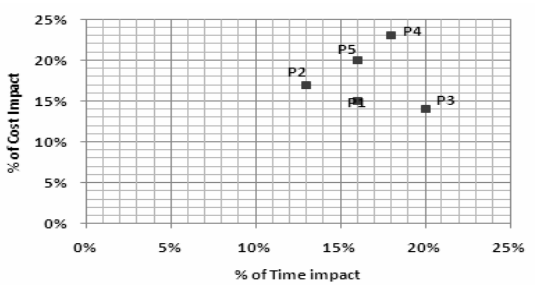


Figure 2: Typical Graph Representing the Relationship between Cost and Time for a Specific Technique Applied to Similar Cases in Different Projects (Based on the data extracted from Table 2)

The graph presented in Figure 2 will be statistically analyzed. The area shown in Figure 3, which covers all of the points, presents the maximum and minimum of time and cost impacts resulting from the application of a specific technique to similar cases in previous projects. It is evident that the denser this area, the more reliable the results. However, if the area is not dense enough to allow drawing valid conclusions, it is possible to either determine a range for the index or to divide the graph into several graphs depending on the characteristics of the cases.

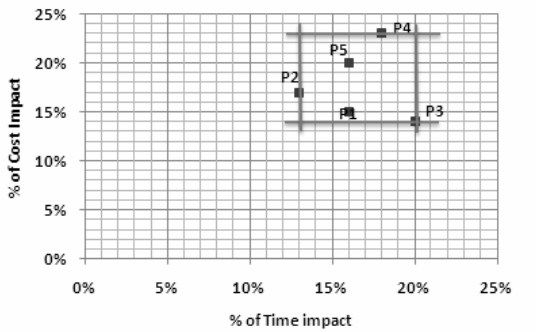


Figure 3: The Boundaries of Cost and Time Impact

Within the area presented in Figure 3, there should be one point which has a minimum distance from the other points. This point can be an index or benchmark of the relationship between time and cost for a specific technique (schematically shown in Figure 4).

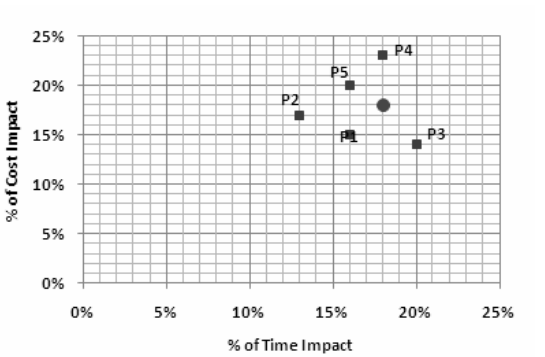


Figure 4: Schematic view of Time and Cost Impacts Indices for a Specific Fast-tracking Technique

The above process should be repeated for all of the fast-tracking techniques applied in the project to obtain the "time and cost impact indices" for each set of (fast-tracking technique and its area of application). These indices are further used to

quantify the effect of a typical fast-tracking technique on time and cost using Equation (8) and (9).

Time Impact of Technique (n) applied to Case (n) = Suggested percentage of utilization × Time Impact Index Eq. (8)

Cost Impact of Technique (n) applied to Case (n) = Suggested percentage of utilization × Cost Impact Index Eq. (9)

In Equation 8 and 9, the percentage of utilization of a specific technique will be suggested by the project manager who considers the feasibility (e.g. technical, political, etc.) of implementing the technique on all units of the work. The results obtained from Equation 8 and 9 will be used to quantify the overall impact of fast-tracking on project time and cost using Equation 1 and 2 (Section 4-1). Furthermore, quantitative and qualitative analysis of time and cost impact indices, and cost-time trade-offs leads to useful information including but not limited to:

- The effectiveness and/or efficiency of a specific fast-tracking technique which might be applicable to different areas
- The most effective and/or efficient technique applicable to a specific area
- The most effective technique from the time point of view
- The most cost sensitive technique
- The most efficient technique

5- Inputs for the Framework

As discussed earlier, there are several methods which help to provide the required inputs for Equations 3 to 7. These inputs include the cost and duration after implementing the fast-tracking technique. The suggested methods for provision of these inputs include: 1) Factual Data gathering, 2) Virtual Experiment. The type and nature of the fast tracking technique dictates which way is more appropriate; however, the aforementioned methods are applicable in general. In the following, each method is described in detail.

1) **Factual Data gathering:** This method is one of the most reliable methods for the purpose of this research. In this method, data regarding the actual duration and cost of the fast-tracked areas will be gathered through either questioning the corresponding industry experts or investigating the project documents. Therefore, reviewing the projects' historical records and holding interview sessions with industry experts are the main methodologies for this part of the research. Since a small fast-tracked area within the body of the main project is investigated individually, it is expected that the actual data can be easily collected. The most important advantage of this method is that the data are not opinion-based; therefore, they allow for the drawing of more valid conclusions.

However, in order to maintain the reliability of the method, an in-depth analysis should be performed on the collected data to distinguish among the time and cost impacts resulting from fast-tracking or resulting from or other causes. Therefore, any decrease/increase in cost/schedule which is not directly resulting from fast-tracking will be excluded from further studies and only direct impacts will be used for calculations. Also, as discussed earlier in section 4-2, it is possible for an area to be fast-tracked by more than one technique. In these situations, when analyzing the time and cost impacts resulting from fast-tracking, the cumulative effect of the techniques should be taken into account and the effect of each single technique should be specifically determined.

2) **Virtual Experiment**: When it is not possible to collect actual data from the selected case studies, virtual experiment can be used for evaluation and quantification of different fast-tracking techniques. There are two different approaches in virtual experiment described in the following.

In the first approach, modeling and simulation techniques will be employed to virtually investigate the effect of applying different fast-tracking strategies on project duration and cost. In this method, different cases in the projects will be modeled using a scheduling software program which considers range estimates for time and cost (most probably PertMaster® or Simphony® (Hajjar and AbouRizk 2000)). Then an industry survey will be performed to extract the industry expert ideas on time and cost impacts resulting from application of specific fast-tracking techniques. This is a subjective analysis; however, it can be converted to a numerical analysis using Fuzzy Logic Theory, developed for the first time by Dr. Lotfi Zadeh of U.C. Berkeley in the 1960's. In this research, Fuzzy Logic Theory will help to convert the subjective estimates of the industry experts to numerical ranges. The results will be applied to the model of the selected cases and the overall time and cost impacts will be evaluated accordingly and will be used for further calculations presented in sections 4-1 and 4-2.

In the second approach, virtual experiments can also be performed by modeling the project using simulation software progarms such as SimVision®. “SimVision is an agent based computational model, and models both project tasks and management structure; it is an agent based information processing model of the project organization with which we can run systematic ‘virtual experiments’ to examine the effects of managerial choices on performance” (Carroll et al. 2004). Since each fast-track tactic affects information processing directly, and thus performance indirectly, it can be assumed that SimVision and similar products can be helpful for the purpose of this research as well. Carroll et al. (2004) used this software to simulate the effect of decentralization, interdependency and additional resources on project duration and cost. Another example would be Virtual Design Team® (VDT) which is a project organization design simulator developed at Stanford. VDT can predict the schedule, cost and quality performance for a user-specified organization and work process (Khosraviani et

al., 2004). However, as stated earlier, the type and nature of the fast-tracking technique will dictate which software platforms are more appropriate.

6- Conclusion

Strategic implications of shorter project duration such as competitive positioning, rate of return and investment payback period pressures project managers to shorten the project duration; however, reducing the project duration might adversely impact project cost. In order to maintain a proper balance between time and cost in fast-track projects, different fast-tracking techniques should be evaluated and compared to each other so that the most efficient techniques are applied to the project. Efficient utilization of fast-tracking techniques leads to the most reduction in project duration with the least amount of extra cost; therefore, results in increased amount of business benefits and/or performance bonuses for both owners and contractors.

Hence it is of vital importance for project managers to be able to evaluate the impact of different fast-tracking techniques on project time and cost. The purpose of the research presented in this paper is to provide a theoretical foundation for evaluating different fast-tracking techniques and for quantifying their impact on project time and cost, which is a great contribution for the field of fast-tracking. The outcome will be benchmarked fast-tracking techniques which can be used by project managers in the preplanning phase of the projects to help ensure that the fast-tracking approach achieves sizeable delivery time reductions without driving up costs.

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A New Approach for Resource-Constrained Multi-project Scheduling

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Abstract
Construction and facilities maintenance projects involve a large number of people and tasks with resource constraints and precedence constraints. This paper presents a new approach to model this problem as a resource-constrained multi-project scheduling problem (RCMPSP) with cost minimization. The scheduling problem is first decomposed into two sub-problems: schedule generation and sequencing. For the schedule generation problem, an effective forward and reverse schedule generation (FRSG) method is developed to generate a feasible solution for a given valid sequence. For the sequencing problem, a novel complete local search with memory approach embedded with FRSG is proposed to find the solution which has the best objective value. The proposed approach has been tested on the benchmark instances. Computational results show that it performs very well in terms of both effectiveness and efficiency.

1. Introduction

Construction and facilities maintenance projects usually involve a large number of people and tasks with resource constraints and precedence constraints. This problem can be modeled as a resource-constrained multi-project scheduling problem (RCMPSP). The objective of multi-project scheduling is to allocate available resources to multiple projects and tasks with the highest efficiency and cost effectiveness. The problem belongs to the class of NP-hard (Blazewicz et al. 1983) problems and it is very difficult to solve. Considerable efforts have been devoted to deal with the classical resource-constrained project scheduling problem (RCPSP) throughout the past decades (Herroelen et al. 1998; Weglarz 1999). Similar to machine scheduling, a representation was introduced for project scheduling. Classical project scheduling models were classified, along with their algorithms being surveyed. New models were also investigated for various applications. Other than these efforts, the research interest has been broadened to incorporate additional constraints from industrial applications, including: a pair of activities must be separated by at least a

given duration (Moumene and Ferland 2009); activities can be split during scheduling under situations where resources may be temporarily unavailable (Buddhakulsomsiri and Kim 2006); a schedule-dependent setup time is required depending on the assignment of resources to activities overtime (Mika et al. 2008).

Because of the complexity of RCMPSP problems, heuristic-based methods become very promising to construct a feasible and robust algorithm. Most of the existing heuristics methods can be roughly classified into two categories: the priority rule-based methods and the meta-heuristic-based approaches (such as genetic algorithms). Mendes et al. (2009) proposed a genetic algorithm in which the chromosome representation is based on random keys and the priorities of the activities are defined by a genetic algorithm. Mika et al. (2005) adopted simulated annealing and tabu search for a multi-mode RCPSP with discounted cash flows.

In this paper, a complete local search with memory approach is proposed for the resource-constrained multi-project scheduling problem (RCMPSP). The objective function is to minimize the cost of facilities maintenance considering setup cost, idle cost, and resource rate.

The rest of the paper is structured as follows: Section 2 presents a problem statement; Section 3 proposes a forward and reversed schedule generation (FRSG) method; Section 4 and Section 5 describe the proposed schedule generation approach and a complete local search with memory algorithm; Section 6 shows some experimental results; and finally, Section 6 provides some concluding remarks.

2. Problem Statement

The foundation of our work is based on the concept of task network. A traditional task network is composed by a set of tasks and a set of precedence relationships between the tasks. Precedence constrains the schedule in that an activity cannot start until all of its predecessors have finished. However, activities do not get completed on their own; instead, they consume resources during their progress. The scheduling problem becomes difficult to solve when the required resources have limited capacities because allocating scarce resources among competing activities adds significant complexity to the optimization objectives. We can transfer the RCMPSP to a classical RCPSP problem by combining all projects as one super project which contains all tasks from different projects as its activities. The resultant RCPSP problem for the above super project is NP-hard in strong sense and it is described as follows.

Let $J = \{0,1,\cdots,n,n+1\}$ denotes the set of activities to be scheduled and $K = \{1,\cdots,k\}$ be the set of resources. Activities 0 and $n+1$ have a zero duration and represent two dummy activities – dummy source and dummy sink, respectively. The activities are interrelated by two types of constraints:

(1) Precedence constraints force each activity j to be scheduled after all predecessor activities P_j are completed;

(2) Activities require resources with limited capacities.

While being processed, activity j requires $r_{j,k}$ units of resource $k \in K$ during the whole period of its duration d_j. The assumption we made is that no preemption is allowed. Resource type k has a limited capacity of R_k available all the time. The

parameters d_j , $r_{j,k}$ and R_k are supposed to be integer, non-negative and deterministic. For the dummy source and the dummy sink, we have $d_0 = d_{n+1} = 0$ and $r_{0,k} = r_{n+1,k} = 0$ for all $k \in K$. The precedence constraint denoted by $A = \{(i, j) \mid j \in J, i \in P_j\}$ records all precedence relationships among activities.

Solving the RCPSP problem means finding a schedule for the activities, taking into account precedence and resource constraints, while minimizing a certain objective function. Figure 1 shows an example of a project network, where the activities are presented on nodes and precedence are on directed arcs. A project network is denoted as PN . The resource requirements are given to top of each node and the total available numbers of resources are provided at the bottom of the network.

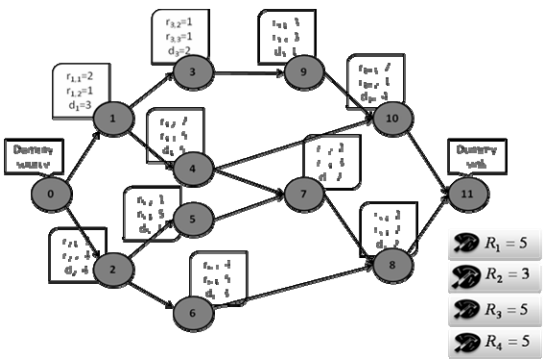


Figure 1 A project network example

In the FM system, solutions are represented in form of a precedence-feasible activity sequence $\pi(\pi_{[1]},\cdots,\pi_{[n]})$ where $\pi_{[i]} \in J$ and i is the index of an activity in the sequence. The *precedence-feasible activity sequence* is a sequence of activities satisfying the precedence constraints, i.e. any activity must have all its predecessors sequenced ahead. In the context of this paper, a precedence-feasible activity sequence is also called a valid sequence for short. For example, (1,4,2,3,5,6,7,8,9,10) and (2,5,6,1,4,7,8,3,9,10) are two valid sequences for the example project network in Figure 1.

Let $t_{[i]}$ represent the start time of activity $\pi_{[i]}$. A schedule for a valid sequence can be represented by a vector of start times $(t_{[1]},\cdots,t_{[n]})$. For the same example, Figure 2 shows a feasible schedule with the makespan of 17.

The RCPSP can be decomposed two sub-problems: (1) the schedule generation problem, in which a feasible schedule for a given valid sequence is calculated and (2) the sequencing problem, in which a valid sequence is found to have the optimal schedule. The schedule generation problem is embedded in the sequencing problem. A forward and reverse schedule generation method is developed for the schedule generation problem and a complete local search with memory is proposed for the sequencing problem.

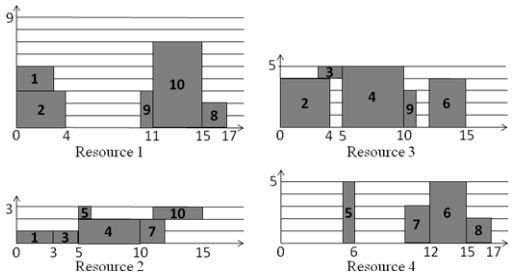


Figure 2 The Gantt chart of a feasible schedule with the makespan of 17

3. A Forward and Reverse Schedule Generation Method

Given a valid sequence, a schedule generation method is to generate a feasible schedule for the sequence and evaluate the obtained schedule. Two kinds of schedule generation schemes are adopted in the system: forward schedule and reverse schedule.

3.1 Forward Schedule Generation Procedure

A forward schedule S_F is a mapping where $\pi_{[1]},\cdots,\pi_{[n]}$ are mapped to a set of start times which are set to be as early as possible while obeying the resource constraints. The forward schedule generation procedure is described in Figure 3.

Procedure $FSG(\pi, A)$

/* π is a valid sequence and A is the set of all precedence constraints in the project*/

1. $t_{[0]} \leftarrow 0$;
2. For $i = 1$ to $n+1$
   Find the earliest feasible start time $t_{[i]}$ for $\pi_{[i]}$;
3. Return $t_{[0]},\cdots,t_{[n+1]}$

Figure 3 Procedure for calculating the forward schedule

3.2 Reverse Schedule Generation Procedure

The reverse schedule S_R is developed based on the forward schedule scheme by reversing all the precedence in the project network and the given valid sequence. A reversed project network PN^R is the network with all the precedence linkages reversed, i.e. an activity's predecessors in the original network become successors and its successors are changed to predecessors (as shown Figure 4). The reversed precedence constraint set A^R can be obtained by $A^R \leftarrow \{(j,i) \mid (i,j) \in A\}$. Similarly, a reverse sequence π^R is to reverse the order of activities in the valid sequence, i.e. $\pi^R_{[i]} \leftarrow \pi_{[n+1-i]}$. For example, the reverse of the sequence (1,2,3,4) is (4,3,2,1).

Theorem If π is a precedence-feasible sequence for the project network PN, then π^R must be a precedence-feasible sequence for PN^R.

Proof Suppose the index of an activity i in π and π^R is denoted as $index(i)$

and $index^R(i)$, respectively. For any $(i,j)\in A$, $index(i)<index(j)$ must be satisfied since π is a precedence-feasible sequence. Because PN^R is obtained by reversing all precedence constraints, i.e. $A^R \leftarrow \{(j,i)\,|\,(i,j)\in A\}$, for any $(j,i)\in A^R$, $index(i)<index(j)$ must be true. Since $index^R(i)=(n+1)-index(i)$, then $index^R(j)<index^R(i)$ must be true. Therefore, π^R must be a precedence-feasible sequence for PN^R. □

The procedure to generate a reverse schedule is described in Figure 5.

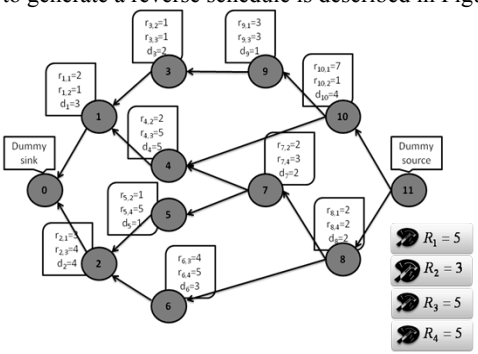


Figure 4 The reverse project network and reverse sequence

Procedure $RFSG(\pi, A)$

/* π is a valid sequence and A is the set of all precedence constraints in the project*/

1. $A^R \leftarrow \{(j,i)\,|\,(i,j)\in A\}$, $\pi^R_{[i]} \leftarrow \pi_{[n+1-i]}\,(i=0,\cdots,n+1)$;
2. $(t'_{[1]},\cdots,t'_{[n]}) \leftarrow FSG(\pi^R, A^R)$;
3. $C_{\max} \leftarrow t'_{[n+1]}$;
4. $t_{[0]},\cdots,t_{[n+1]} \leftarrow (C_{\max}-t'_{[0]}-d_{[0]},\cdots,C_{\max}-t'_{[n+1]}-d_{[n+1]})$
5. Return $t_{[0]},\cdots,t_{[n+1]}$

Figure 5 Procedure for calculating the reverse schedule

Step 4 in Figure 5 guarantees the timetable returned by $RFSG(\pi, A)$ is the feasible timetable of π for the project network PN.

3.3 The Definition of the Objective Function

The classical RCPSP considers makespan as its objective function, i.e., the completion time of the last activity. But in the real world, cost has a higher priority to consider. In the facilities maintenance management system, three economic factors are concerned, i.e., setup cost, idle cost, and resource rate.

Setup cost is the cost for preparing and initiating a resource. C_k^{setup} denotes the setup cost of a resource $k\in K$. If two consecutive activities are processed on the same resource with the waiting time less than a certain threshold, only one setup cost C_k^{setup} is charged. The waiting time threshold is denoted as λ^{setup}.

Idle cost is charged when a resource is not used by any of the activities. C_k^{idle} denotes the idle cost of a resource $k \in K$.

For certain types of resources such as crafts and labor, the resource rate is calculated based on payment rates that are checked out every time increment. Such kind of resources has no idle cost, but the length of their continuously working time affects greatly on the project budget. Resource rate is the cost for continuously using a resource per time increment. The total resource utilization cost is calculated based on time increments and a portion of the time increment will be rounded into a full time increment. C_k^{rate} denotes the payment rate and λ_k^{rate} denotes the time increment for a resource $k \in K$. For a resource k which keeps working for m time units, the total rate cost is $C_k^{rate} \times \lceil m / \lambda_k^{rate} \rceil$.

In order to take these three cost aspects into account for the optimization, the resource assignment interval list should be discussed first.

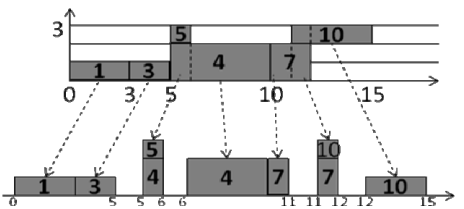


Figure 6 An example of the resource utilization distribution list

The resource utilization distribution list I_k is a set of binary vectors $<[s,e],l>$ which means the number of resources k being used during interval $[s,e]$ is l. I_k describes the profile of the Gantt chart on resources k. For the sake of convenience, two consecutive vectors do not share the same value of l, i.e., any two consecutive vectors $<[s_i,e_i],l_i>$ and $<[s_j,e_j],l_j>$ must have $l_i \neq l_j$. For example, $I_1 = \{<[0,5],1>, <[5,6],3>, <[6,11],2>, <[11,12],3>, <[12,15],1>\}$ (as shown in Figure 6) for the schedule in Figure 2.

Based on I_k, the total setup cost on resource k can be calculated by the function in Figure 7.

Function *TotalSetupCost*(k)
1. $TSC \leftarrow 0$;
2. For $i = 0$ to $|I_k| - 1$
  2.1 $TSC \leftarrow TSC + C_k^{setup} \times l_i$, $X \leftarrow 0$
  2.2 For $j = i - 1$ to 0
    If $s_i - e_j <= \lambda_k^{setup}$, $X_{overcharge} \leftarrow C_{setup}^k \times l_j$;
      If $X_{overcharge} > X$, $X \leftarrow X_{overcharge}$
    Else break;
  2.3 $TSC \leftarrow TSC - X$
3. Return TSC

Figure 7 Procedure for calculating the reverse schedule

The total idle cost on resource k can be calculated by $\sum_{i=0}^{|I_k|-1} C_k^{idle} \times (e_i - s_i) \times (R_k - l_i)$.

The total rate cost on resource k can be calculated by $\sum_{i=0}^{|I_k|-1} C_k^{rate} \times l_i \times \lceil (e_i - s_i) / \lambda_k^{rate} \rceil$.

Therefore, the objective function can be calculated as:

$$F \leftarrow \sum_{i=1}^{|K|} (TotalSetupCost(k) + \sum_{i=0}^{|I_k|-1} C_k^{idle} \times (e_i - s_i) \times (R_k - l_i) + \sum_{i=0}^{|I_k|-1} C_k^{rate} \times l_i \times \lceil (e_i - s_i) / \lambda_k^{rate} \rceil)$$

3.4 Forward and Reverse Schedule Generation Method

The procedure of the forward and reverse schedule generation method consists of three steps:

1) Calculate the forward schedule S_F of the given valid sequence and its objective function value.
2) Calculate the reverse schedule S_R of the given valid sequence and its objective function value.
3) The schedule with the smaller objective function value is selected as the final schedule of the given sequence.

4. The Complete Local Search with Memory Method

There are three containers in the algorithm: (1) NEWGEN, which accommodates the newly found valid sequences which will be explored in the current iteration; (2) NEIGHBOR, which accommodates the neighbors of the sequences in NEWGEN; and (3) DEAD, which accommodates all the explored valid sequences to avoid recalculating.

CLLM starts with a random valid sequence as the initial solution and puts it into NEWGEN. DEAD and NEIGHBOR are all empty at the beginning. The following process is iterated:

1) Generate valid sequence for NEWGEN.
   a. If NEWGEN is empty, the algorithm stops;
   b. The algorithm generates neighbors for all solutions in NEWGEN and check for their validness so that only the precedence-feasible neighbors are put into NEIGHBOR; if NEIGHBOR is not full. Two methods are used to generate potential neighbors: one-insertion and the partial pair-wise exchange. The former method simply picks up an activity and moves it to every possible slot once at a time; the latter one generates neighbors by just swapping two activities in the sequence.
2) Empty NEWGEN.
3) Look through sequences contained in NEIGHBOR and check whether they are "good" enough.
   a. Check each valid sequence in NEIGHBOR; if it is not in DEAD, we assume it is "good".
   b. Calculate a schedule for a "good" sequence using the forward and reverse schedule generation method.
   c. The schedules with objective function value lower than a certain threshold value are transported to NEWGEN for the next iteration and the others are

moved into DEAD. We notice that a small threshold value (for example, the best-so-far objective function value) turns the algorithm to a greedy search and stops very soon whereas a large-enough threshold value could lead to an enumerative search. Therefore, we use $F \times (\tau + 1)$ as the threshold value where F is the best-so-far objective function value and the speed of search and optimality of the solution can be adjusted by factor τ.

4) Empty NEIGHBOR.

If no improvement has been made for a certain number of successive iterations $N_{\max}$, the algorithm stops; otherwise go to the first step and repeat the process.

5. Computational Experiments

The proposed algorithm was implemented in Java on a Pentium 4 processor with the operating system, Windows XP. The algorithms are tested on the well-known benchmark instances (Kolisch et al. 1995). Three levels of the number of activities are selected at 30, 60, 90 for the J30, J60, J90 problem sets, respectively. Each of the set contains 480 instances.

The experimental results are evaluated by a percentage relative deviation to the initial solution (PRDI), defined as follows.

$$PRDI = \frac{F^I - F^{ALG}}{F^I} \times 100\%$$

F^{ALG} is the objective function value of a solution obtained by the proposed algorithm. F^I is the objective function value of the initial solution.

To determine reasonable parameters for the proposed CLM, 10 small instances (j301.1-j301.10) are tested with a variety of parameters. Those parameters are τ (the threshold value factor) and $N_{\max}$ (the maximum number of non-improved iterations). All experiments are repeated 10 times. Parameters are selected according to their effects on APRDI (average percentage relative deviation to initial solution) and CPU is the time requirement of the solutions, where APRDI is defined as follows.

$$APRDI = \frac{F^I - F^{AVG}}{F^I} \times 100\%$$

Where F^{AVG} is the average objective function value for an instance, which implies the overall performance of the algorithm.

The threshold value $F_{best} \times (\tau + 1)$ decides if a solution is good or not (F_{best} is best-so-far objective value). The algorithm becomes a greedy search when the threshold value is small (for example, the best-so-far objective value) and stops very soon, whereas the algorithm becomes an enumerative search if the threshold is large enough. Figure 8 indicates that the bigger τ the better results, the bigger τ the more time-consuming. To balance the efficiency and the effectiveness of the algorihm, according to the experiments, 0.1 is reasonable for τ.

$N_{\max}$ is one of the termination conditions. It exerts influence on both the efficiency and effectiveness of the algorithm. Figure 9 indicates that the larger $N_{\max}$,

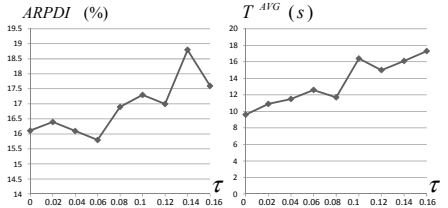


Figure 8 APRDI and the CPU time with different τ

the better the results, the more CPU time. Therefore, $N_{\max}$ is set to 50 which sets a good trade-off between the efficiency and the effectiveness.

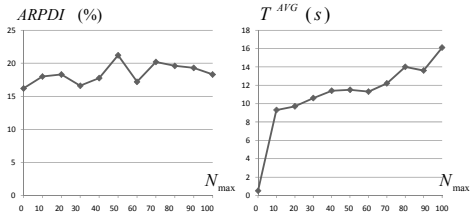


Figure 9 APRDI and the CPU time with different $N_{\max}$

Based on the above the parameters, all the total 1440 instances are tested with the results shown in Table 1. 4 measurements are taken into account, which are $ARPDI$, $PRDI^{best}$ (the largest PRDI value), T^{AVG} (the average CPU time, in seconds) and T^{best} (the best CPU time, in seconds).

Table 1 Experimental results

n	$ARPDI$(%)	$PRDI^{best}$(%)	$T^{AVG}(s)$	$T^{best}(s)$
30	15.2	40.6	27	0.7
60	14.1	37.8	128.7	9.4
90	13.2	34.6	266	41.9

Table 1 illustrates that the proposal algorithm can achieve the improvement of 15.2% in average for small instances of size 30, where the best improvement percentage is 40.6%. The CPU time requirement is 27 seconds in average and merely 0.7 second for some instances. For instances of size 60, the proposed algorithm can improve the initial solution by 14.1% in average and 37.8% at most. The CPU time requirement for J60 is 128.7 seconds in average and 9.4 at least. For the large instances of size 90, the proposed algorithm can achieve the improvement of 13.2% in average and 34.6% at most. The CPU time requirement for J90 is 266 seconds in average and 41.9 seconds at least.

6. Conclusions

In this paper, a complete local search with memory algorithm is proposed for the resource-constrained multi-project scheduling problem. The goal is to minimize the objective function value which involves applicable economic factors such as setup cost, idle cost, and resource rate. A generic meta-heuristic framework for the

considered problem is adopted by decomposing the problem into the schedule generation problem and the sequencing problem, which are then solved by an effective forward and reverse schedule generation (FRSG) method and the proposed complete local search with memory (CLM), respectively. The proposed algorithm has been tested on the well-known benchmark instances. Reasonable parameters of CLM are determined by experiments to get a good balance between effectiveness and efficiency. For each instance, the final objective function value found during the search process is compared to the one of the initial solution to show the improvement that the algorithm can achieve. Meanwhile, since the CPU time consumed by the complete search increases significantly with the problem size, computation time is chosen as another indicator for measuring the algorithm's performance. The experiment results also prove the applicability for using the proposed approach in facilities maintenance management.

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AN ANALYTICAL FRAMEWORK FOR INCORPORATING PROJECTS SUPPLY CHAIN PROBLEMS INTO PROJECT PLAN

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Abstract

The Supply Chain Management (SCM) field of research has developed a valuable set of concepts and strategies for integrating the core competencies of suppliers into the production systems, a trend followed by the construction industry. Research into quantifying the effects of upstream suppliers on the production rate of construction projects has been very limited. Literature for the construction industry generally discusses how SCM concepts can be adopted, or what problems and challenges inhibit such adoption without providing a framework to consider supply chain problems in early stage project planning. No analytical approach has yet been developed to help quantify the impact of upstream supply chain problems on the duration of construction projects. This paper presents an analytical framework for incorporating supply chain issues into project's plan and therefore assessing the impact of those issues on project's duration. A construction project case study is also presented for validation purposes.

INTRODUCTION

According to Chen and Paulraj (2004), the emergence of Supply Chain Management (SCM) research was based on advances in logistics, distribution and transportation, information technology, organization, purchasing, marketing, and production planning. The main objective in supply chain management is to integrate all different agents in the system in order to satisfy system level requirements (Simchi-Levi. et al. 2003).

In taking such a system-wide approach, designing and maintaining an efficient system becomes imperative, and challenges take on a huge significance. The possibility of conflicting objectives and goals among different members of a supply network, the dynamic and time-evolving nature of the system, and potential competition between different members of a network make it much harder to achieve a globally optimal situation.

In the context of construction industry, supply chain management is mainly concerned with managing the interfaces and relationships between the entities involved in delivering the projects with the aim to deliver the project on time and on budget. The entities involved in delivering a construction project usually include owner, general contractor, sub-contractors and industrial fabrication shops.

Researches into construction supply chain management can generally be divided into two categories of qualitative descriptive researches and case specific modeling researches. The first category of researches mainly describe the techniques and ideas that can be adopted from supply chain management into construction industry while the case specific researches focus on modeling the supply chain of a specific construction project.

This paper is an effort to address one of the major gaps in the construction supply chain body of literature with providing a framework to quantify the effect of construction project' supply chain issues on the project's plan.

Supply Chain Management in Construction

Although there have been studies addressing transportation and/or inventory in the construction industry, these issues have usually been studied in just one tier of the whole construction supply chain. Most studies in the area of construction supply chain have been qualitative (Davis 2008; Adetunji et al. 2008; Karim et al. 2006, Green et al. 2005; Jiang et al. 2005; Vaidyanathan et al. 2005; Cox et al. 2002; Palaneeswaran et al. 2003). These studies mainly focus on establishing a framework for applying supply chain ideas in construction industry. An example of such studies is the research conducted by Davis (2008) to determine the influence of relationship variables on construction projects' supply chains.

Some other researches in construction supply chain area focus primarily on utilizing technologies related to supply chain in construction (Min et al. 2008; Wang et al. 2007). Wang et al. (2007) discuss a Radio Frequency Identification (RFID) material management and control technology that can benefit construction projects. Min et al. (2008) present an agent-based construction supply chain simulator that is a modified version of the beer game widely utilized to understand the supply chain ideas in other industries. There have been limited examples of trying to model the supply chain of a specific construction project or company using simulation (Xue et al. 2007; Tserng et al. 2006; Walsh et al. 2004; Tommelein et al. 2003).

Although all of these studies have tried to highlight the benefits of adopting and implementing SCM ideas and techniques to the construction industry, they are specific to one project and based on several simplifying assumptions. For example, in the case presented by Walsh et al. (2004) the material demand histogram is assumed to be a straight line for the duration of the project, while in a real construction project material demand is a function of the project's progress, which is not generally linear. As helpful as these studies are, they still do not provide construction industry researchers and practitioners with a way to account for supply chain issues when developing a construction project's plan.

This paper introduces an analytical approach to incorporate supply chain issues of a construction project into the project's plan. The framework presented in this paper is applied to a construction project and the results were compared with the results of a validated simulation study.

Construction Supply Chain Issues

The three major flows in a typical construction project supply chain are: Financial flow, Information flow and Material flow. The success of a construction project is a direct result of effective management of these three streams. The duration of a construction project directly depends on its production rate while the project's production rate is a function of two main sets of factors.

The first set of factors is the factors can be classified as intrinsic factors. These factors include labor and equipment productivity, the combination of equipments and the site situation. The second set of factors influencing the production rate of construction processes and activities are the flows of money, information and material. Lack of budget, having incorrect or insufficient information and material shortage can directly affect the production rate of a construction process.

The main difference between the first and second sets of factors is that the second set of factors exists in relation to other agents involved in the construction project. In other words, those factors are construction supply chain factors and can be managed using supply chain management techniques and approaches.

Out of the three major flows that constitute a construction project's supply chain, material flow is of major importance and may have a substantial affect on the projects production rate and duration. Not having the right quantity of the required materials at the right time can stop construction processes and activities and impose additional costs on the project.

Construction Project' Material Supply Chain

In order to model the material flow of a typical bulk material for a construction project, the formulas used in supply chain management domain for modeling inventory are utilized. In supply chain management area, two main types of inventory policies are identified (Simchi-Levi et al., 2003).

Equation 1 (Simchi-Levi et al., 2003) presents the required inventory to cover expected customer's demand until new materials are received. In this equation, stock level (S) is calculated so that enough material is at stock to satisfy customers demand for the period equal to the supplier's lead-time.

$$S = L\mu + z\sigma\sqrt{L} \qquad \textbf{Equation 1}$$

Where S is the required inventory; L is production lead-time for the supplier; z is safety factor associated with the desired confidence interval; μ is mean daily demand and σ is variance of daily demand. In driving this formula, daily demand is assumed to follow a normal distribution.

In a construction project's supply chain, customers of any type of material are the construction processes and activities that require that material. For example in a residential or commercial construction project, the concrete foundation construction process represents a customer for certain types of material; concrete and rebar.

The stock level in a construction project is the inventory capacity available for that type of material at site and the lead-time is the time required for that type of material to be delivered to site. In the example of concrete foundation construction, the stock level of rebar is the quantity of rebar that can be held on construction site and the lead-time is the time from issuing the order to receiving the ordered quantity of rebar at site.

The two variables μ and σ are the mean and the variance of the construction process or activity demand for the material. The demand of a construction activity for a certain type of material directly depends on the intrinsic production rate of that activity. Higher production rate of a construction process or activity translates to a higher demand for materials. Consider for instant a paving project. If the intrinsic production rate of the paving activity increases from 1 km per day to 2 km per day then the daily demand for asphalt also doubles.

Construction Processes Production Rate

Production rate or throughput of a construction activity can be defined as the quantity of materials installed, removed or used in a certain period of time. For example production rate of concrete foundation construction is measured by the cubic meters or cubic yards of poured concrete per day or per hour. Another example is measuring the throughput of a pipeline construction project as linear meters of pipe installed per day.

Considering this definition for the production rate of construction activities, μ and σ can be replaced by μ_{Pr} and σ_{Pr} which are the mean and variance of the production rate (Pr) of the construction activity. Equation 1 will then be transformed to:

$$S = L\mu_{\text{Pr}} + z\sigma_{\text{Pr}}\sqrt{L} \qquad \textbf{Equation 2}$$

Base on that the following equation can be conferred:

$$\mu_{\text{Pr}} \le \frac{S}{L} \qquad \textbf{Equation 3}$$

Equation 3 presents an upper limit for the production rate of a construction activity or process. The upper limit is simply the ratio of the inventory capacity for the required material to the supply lead-time of that material.

Material Quality and Production Capacity

It is clear that some of the parameters that can affect the throughput of a construction process or activity are missing from Equation 3. The most important of these parameters are the quality of materials and the production capacity of the material supplier.

If the quality of the materials arriving at site is poor, the material is rejected and an order for a new replenishment is issued. So, in the case of having the same stock level or inventory capacity and the same lead-time, production rate of the construction process or activity receiving the poor quality material is less.

On the other hand, given the same condition for inventory capacity at site, material lead-time and quality of the material, production capacity of the supplier can impact the delivery of the material and therefore production rate of the construction activity. If supplier's production capacity is less than the ordered quantity of materials then it will take longer to deliver the ordered quantity to construction site. This in turn can affect the average production rate of the construction activities, which require that material.

Analytical Modeling of Material Quality

In order to model the effect of material quality on the average throughput of a construction process or activity, we assume that there is a quality control process in place. The quality of the material can be translated into the probability of rejection in

the quality control process. The worse the quality of material is, the higher the probability of rejection would be.

If the rejection probability is P, then the lead-time of the material can be calculated as:

$$L' = L(1-P) + P*(L+L')*(1-P) = L + PL' \quad \textbf{Equation 4}$$

$$L' = L \Big/ (1-P) \quad \textbf{Equation 5}$$

Incorporating Equation 5 into Equation 3, the upper bound for the average production rate of a construction process using materials with lead-time L and quality rejection probability of P is:

$$\mu_{Pr} \le \frac{S}{L'} \Rightarrow \mu_{Pr} \le \frac{S(1-P)}{L} \quad \textbf{Equation 6}$$

Analytical Modeling of Production Capacity

To model the impact of a capacitated production or manufacturing line for construction materials on the average production rate of a construction process, we have to differentiate between the two elements of delivery time namely production time and transportation time. If the production time is L_P, transportation time is L_T and it takes K production cycles to produce the whole quantity of the materials ordered, the order lead-time (L) can be re-written as:

$$L = KL_P + L_T \quad \textbf{Equation 7}$$

Equation 7 is correct whether the materials are shipped to the construction site as they are being produced or they are shipped in one delivery when the whole ordered quantity is ready. The upper bound for the average production rate of the construction activity for a capacitated production line is:

$$\mu_{Pr} \le \frac{S(1-P)}{L} \Rightarrow \mu_{Pr} \le \frac{S(1-P)}{KL_P + L_T} \quad \textbf{Equation 8}$$

Equation 8 is correct if the quality control happens at site. On the other hand if quality control process happens after each production cycle then it only affects L_P and not L_T. In that case, the upper bound for the average throughput of the construction activity would be calculated as:

$$\mu_{Pr} \le \frac{S}{K L_P \Big/ (1-P) + L_T} \Rightarrow \mu_{Pr} \le \frac{S(1-P)}{KL_P + L_T(1-P)} \quad \textbf{Equation 9}$$

Project Planning and Project's Supply Chain

Planning for a construction project involves the process of configuring activities, their durations and their dependencies. A construction project plan provides answers to the questions like what needs to be done and when and how it needs to be done. Determining the durations of construction processes or activities are a major part of the planning process.

In the previous parts of this article, an upper bound was calculated for the average production rate of a construction process or activity that required materials to be carried out. The total duration of that construction process or activity is the total time required for consuming (installing, removing or pouring) the total quantity of materials. For example, in an earth moving process, the duration equals the time needed to move the total quantity of the dirt.

On this basis, the total duration of a construction process or activity can be stated as:

$$D = TQ \Big/ \mu_{\Pr} \qquad \textbf{Equation 10}$$

Equation 10 simply states that the duration of a construction process or activity equals the total quantity of materials to be consumed (TQ) divided by the average production rate of that construction process or activity in terms of quantity per unit of time.

Using the upper limits of average production rate of a construction process provided in Equations 8 and 9, a lower limit for the duration of the construction process can be calculated as:

$$D \geq \frac{TQ * (KL_P + L_T)}{S(1-P)} \qquad \textbf{Equation 11}$$

$$D \geq \frac{TQ * (KL_P + L_T(1-P))}{S(1-P)} \qquad \textbf{Equation 12}$$

Equation 11 calculates the lower limit for the duration of the construction process when the quality control process is carried out at construction site while Equation 12 shows the same lower limit when the quality control process happens at the end of each production cycle.

Equations 11 and 12 can help incorporating a construction project's supply chain parameters into that construction project's plan by providing a lower limit for the duration of the processes and activities that should be completed in order to deliver that project.

Validation of the Analytical Framework

The analytical model presented in this paper by Equations 11 and 12 was validated against a supply chain simulation model of a construction project developed by the authors (2006). The simulation model itself was validated against the field data of the simulated construction project.

The project modeled by the authors (2006) was Glencoe tunneling project at Calgary, Alberta. The 935-meter Glencoe tunnel was being constructed with the use of pre-cast concrete liner segments. The tunneling project can be considered as the process of installing 935 meters of concrete liner segments. Therefore the main material to be modeled using the model provided in this article is the concrete liner segment.

The supplier of the segments had a quality control process to test the strength of the liner segments after 7 days of curing. The liner segments passing the test were shipped to the construction site while the ones failing the test were subjected to a second test after 14 more days of curing. Based on statistical analysis, probability of failing the tests was found to be 15%, transportation time was 2 hours and the capacity of production line was limited to 12 meters of liners per day. Table 1 shows the scenarios considered in the simulation model.

Table 1. Simulation results for Glencoe tunneling project duration by Ebrahimy et al. (2006)

Total Storage	Working Hours/Day			
	10	12	16	20
39	303	267	258	258
64	216	196	182	176
107	**205**	172	151	132
114	192	160	127	108
120	192	**158**	**125**	105
130	192	156	123	102
140	192	156	123	98
150	192	156	123	**97**
175	192	156	123	96
200	192	156	123	96

Equations 11 and 12 are conditioned to include the second quality test. The production lead-time (L_P) for this case is calculated as follow:

$$L' = 7*(1-0.15) + 0.15*(21*(1-0.15) + 0.15*(21+L')) \quad \textbf{Equation 13}$$

$$L' = 5.95 + 2.68 + 0.473 + 0.023*L' \Rightarrow L' = 9.3 \text{ days} \quad \textbf{Equation 14}$$

Using the production lead time from Equation 14 and adding transportation time of 0.1 days to it, the lower limit of the duration for each scenario in Table 1 can be calculated as shown in Table 2.

Table 2. Duration lower limit for Glencoe Tunneling Project

Total Storage	L	TQ	K	D_{LL}
39	9.4	935	1	249.33
64	9.4	935	1	151.94
107	9.4	935	1	90.88
114	9.4	935	1	85.30
120	9.4	935	1	81.03
130	9.4	935	1	74.80
140	9.4	935	1	69.46
150	9.4	935	1	64.83
175	9.4	935	1	55.57
200	9.4	935	1	48.62

Figure 1 compares the values provided in Table 1 to the lower limits provided in Table 2. As can be seen from the graph, for lower values of storage capacity,

simulation results gets closer to the analytical lower limit which is due to the fact that as the storage capacity decreases, its effect on the project's production rate increases.

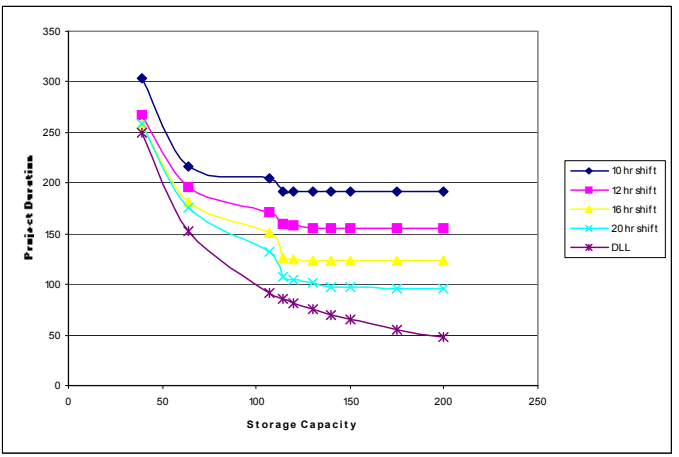


Figure 1. Duration lower limit vs. simulation results for Glencoe tunneling project

Conclusions and Recommendations

The mathematical model presented in this paper captures the effects of supply chain parameter on the production rate of a construction project. Using this modeling approach, the material intensive construction activities and processes can be modeled with their materials supply chains.

Based on this model, the factors considered of importance in replenishing a construction activity order for materials were inventory capacity at construction site (S), The quality of materials (1-P), production cycle time and transportation time (L_P, L_T) and the capacity of supplier production line.

Using these factors, an upper limit for the production rate of the construction process and activities and a lower limit for the duration of construction processes and activities were presented.

The modeling approach presented in this paper was validated against a simulation model developed for a tunneling project construction and the equations provided in this paper to calculate the lower limit of construction process durations proved effective.

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Analysis of Temporary Traffic Control Cost Items in Transportation Construction Bidding Process

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Abstract
Temporary Traffic Control Plans (TCP's), which provide construction phasing to maintain traffic during construction operations, are integral component of highway construction project design. Using the initial design, designers develop estimated quantities for the required TCP devices that become the basis for bids submitted by highway contractors. However, actual as-built quantities are often significantly different from the engineer's original estimate. The total cost of TCP phasing on highway construction projects amounts to 6–10% of the total construction cost. Variations between engineer estimated quantities and final quantities contribute to reduced cost control, increased chances of cost related litigations, and bid rankings and selection. Statistical analyses of over 2000 highway construction projects were performed to determine the sources of variation, which later were used as the basis of development for an automated-hybrid prediction model that uses multiple regressions and heuristic rules to provide accurate TCP quantities and costs. The predictive accuracy of the model developed was demonstrated through several case studies.

Keywords: Traffic Control Plans, Highway Construction, Competitive Bidding Process

Introduction

One of the unique characteristics of the transportation construction projects is that transportation structures must continue to function throughout the construction process. Maintaining the traffic during the construction operations is a challenging task. The same level of functionality of the structure needs to be maintained with limited capacity; but also, lane closures and shifts, frequent changes in speed limits, and on-going construction project activities impose great risks to the safety of the drivers and construction workers. The significance of the issue led to national standards development for proper device usage during highway construction. The United States Department of Transportation (USDOT) Federal Highway

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Administration (FHWA) has created a set of standards that specifies devices be used in order to guide State Highway Agencies (SHAs) in maintaining the traffic during construction operations (http://mutcd.fhwa.dot.gov/).

Highway agencies use the current MUTCD standards to prepare Temporary Traffic Control Plans (TCP's) for highway construction projects as part of the bid package for contractors' discretion. Highway projects' design and construction activities are generally completely differentiated; contractors bid on the completed design quantities provided by owners rather than on their own take-off quantities. The contracts are generally awarded on a competitive basis as the contractors bid with their unit costs on pay item quantities provided by owners (Jofre-Bonet and Pesendorfer 2000).

Accuracy of the TCP quantities

The quantity estimates provided by SHAs during bidding for contractors' discretion are also used in determining the engineers' estimates, which are owner estimates of construction costs that are used to assess contractor bids. TCP related cost items are often felt to be insignificant compared to actual construction operation expenses; yet, the reality is quite different as TCP costs account for 6-10% of the total project budget. Considering typical profit margins (3-4%) of the industry, TCP costs are of substantial importance and the accuracy of the TCP plans during planning phase is crucial. The study presented in this paper was initiated due to the recent fluctuations in TCP quantity and, as a result, cost estimations faced by a major SHA.

Inconsistencies in TCP quantity estimations can hinder successful completion of projects as well as creating unjust advantage to contractors that employ unbalanced bidding. TCP estimates are prepared in later stages of design process, generally, by contracted consulting firms. These professionals have expressed some concern about predicted TCP bid items not adequately reflecting actual quantities used, because the contractor has the flexibility to change the TCP phases provided they comply with the current MUTCD documentation (Ellis and Agdas 2009). They also expressed that it is inappropriate to expect contractors to justify changes from their estimates and original TCP schemes. Thus, contractors opposed to adapting a lump sum Maintenance of Traffic (MOT) bid item to present the overall TCP spending as an alternative because of the possible deviations from the original TCP estimates and the possibility of not being compensated for these changes.

It is unlikely that the current practice will change; however, provided project officials had tools to predict the possible changes in the original TCP quantities predictions provided by the consultants, the adverse effects caused by quantity fluctuations could be mitigated and better cost control could be achieved. There are multiple problems associated with this task as TCP quantities are dependent on a number of project specific factors as well as the TCP phasing chosen by contractors. Contractors are paid for TCP devices for their quantity and the duration they are present on the construction site. This creates a unique situation; because even if the contractor abides by the TCP design provided by the SHAs, overall TCP phasing costs can differ substantially because of schedule changes. Transportation construction project schedules can alter due to various factors including design changes, differing site conditions and adverse weather, and, in most cases, contractors

are accommodated for such delays. TCP costs are linearly correlated with the duration of the projects, and depending on TCP phasing of the contractor and employing unbalanced bidding substantial benefits can be realized.

Predicting TCP quantities at pre-bidding stage

TCP phasing can be done in numerous combinations depending on contractors' choice of planning, the standard MUTCD indexes used, and the project type. And provided the chosen TCP phasing is constructible, there is no basis for owners to deny contractors TCP design. However, this gives contractors great flexibility and allows them to use it to their advantage that can reduce the cost control and the fairness of the bidding process. It is unrealistic to assume that parametric-MUTCD standards based models to predict TCP quantities and costs by just using the project type would be accurate as the bidding behavior of contractors, duration of projects and possible phasing accommodations also contribute to TCP quantity and costs. Hence, predicting TCP quantities and costs is an unprecedented challenge; yet, using historic project data to identify relations within the bidding data is a viable alternative. Choosing proper project characteristics as input variables and TCP bid items as dependent variables can help identify quantity deviations from original design quantities. It must be understood that the proposed model cannot predict constructability and, therefore, only potentially addresses part of the SHAs' needs. The solution proposal was aimed at creating an estimation model for determining the MOT pay items and quantities with a secondary objective as to create a cost prediction model. The model is to be used as a pre-bid tool to satisfy both the consultant and contracting industry for predicting reasonable estimates of TCP quantities to provide assistance in the work program budget computations.

Literature review and current prediction methods

Prediction modeling has been one of the rather popular topics in construction research. Although discussions related to specifics of each prediction model is beyond the scope of this paper; two of the more frequently used methods were compared. The literature review revealed that regression models and neural network models have been the most commonly used methods in prediction model development. Regression models use independent variable(s) to identify the variability of the dependent variable; whereas the neural networks use adaptive learning, which mimics the human neural system to identify patterns within the data. Below are brief summaries of each method.

Neural networks

One of the most popular research topics in all Civil/Construction Engineering research field (Flood 2008), the neural networks use adaptive learning method to capture underlying patterns within the dataset (Vonk et al. 1997, Adeli and Karim 2001, Flood and Kartam 1994). There are multiple adaptive learning algorithms proposed in literature; yet, the common theme is using a training set and a proper learning algorithm to minimize the error (difference between the actual values and model predictions) produced by the model. To do so, error terms produced by the model are used to adjust the model variables in an iterative fashion to improve the

predictive ability of the models. The number of iterations depends on the choices made by the user. Before the neural networks gained mainstream popularity, application developments were mostly dictated by the algorithm and code development to do the data analysis. However, due to the recent increase in the system popularity, there are many software packages available for neural network model development.

Linear regression models

Regression predictions are developed around modeling the relation between independent variables (predictors) and the dependent variable using mathematical equations (Montgomery 2005). Although there are three more common regression types: linear, non-linear and logistics; linear regression models are the most common types used (Shannon and Davenport 2001). The generic linear regression equation depicts the main theme, fitting a straight line to the observed values of the dependent variable that is defined by observed values of independent variables.

Prediction model comparison

Accuracy

Although the predictive superiority of neural networks has been phrased in many publications, the greater effort requirement generally offsets this advantage (Hua 1996, Garza and Rouhana 1995, Agdas 2008). In addition, parameter selection for neural networks plays a great role in its performance, and there are no universally accepted benchmarks to choose proper parameters for different problems. On the other hand, regression models are relatively easier to develop and as the contribution of different independent variables can be traced. Model development is more streamlined and more efficient. Moreover, transportation construction projects are linear projects; thus, linear regression models are generally good enough fits to transportation construction data to enable analysis with acceptable levels of accuracy.

Identifying data relations

Neural networks are generally considered as “black boxes”, which is a term used to signify the fact that neural networks models do not disclose relations between variables; rather, they focus on mechanics of relations. Substantially important factors; such as, independency and relevance of independent factors (predictors) are generally not analyzed, which makes the selection of the predictive variables is the most important stage in model development. On the other hand, regression model development guidelines allow analysis of variable relations as well as their relevance to the predictive power of models being developed. In this study, a large data set covering over 10 years of construction data was analyzed; thus, the sheer size of the data makes the data mining and the screening quite tedious, favoring regression models over neural networks.

Extension to other applications

Finally, regression based prediction models are easier to be incorporated into different case based decision making applications. In this very case, the total number of prediction models to be developed makes it virtually impossible to have a practical

tool to address the problem stated earlier. Thus, the ability to have dynamic models was more desirable. Regression models are easier to develop and adjust depending on the data of interest, making them easier to be incorporated into other applications. The neural network prediction models, on the other hand, need standalone application platforms to be developed, and as they are data intensive and complicated, most of the time they can't be incorporated into other applications as regression models do. Linear regression models were chosen as the prediction methods because of their ability to explain variable interactions, acceptable accuracy, ease of development, and extensibility to other applications.

Data Analysis

The data used in this research was furnished by a major SHA, which contained over 4000 select highway projects completed over last decade. The database contained bid item details for the projects as well as the project characteristics (location, budget, length etc.). Due to the vast variety of bid items included within the database, substantial screening and filtering was necessary to reduce the data to manageable levels; the data was filtered for TCP related bid items and most frequent project types and transportation systems.

TCP related bid items

The master bid item list, the comprehensive list of bid items defined by the SHA of interest, serves as a reference guide to present transportation projects as a combination of a number of different bid items and the current list includes thousand of bid items, 70 of which are TCP related bid items. The bid items included; work zone signs, routing devices (barriers and barricades), temporary markings, and maintenance of traffic (MOT-a lump sum bid item used to compensate for the labor expenses required to successfully implement the TCP).

Project types and highway systems

Because different project types will have different TCP phasing requirements, the project type must be included as one of the variables in model development. SHAs use *Work Mix Code* (WMC) definitions to identify different project types (Ellis and Agdas 2009). The SHA furnished the data used in this analysis has over 130 WMC definitions; however, most of those projects are rarely conducted and there is little value in investing effort to analyze them. Instead, the most frequent 12 WMC definitions were chosen as the focus of interest.

Similar to WMC that are used to discriminate different project types, it is common for SHAs to use a similar approach to identify among different projects with respect to the type of the roadway they will be built on/around. This is, yet, another important factor to be taken into account in TCP phasing and quantity calculations as factors like number of lanes, two lane traffic, and existence of shoulder alongside the roadway will depend on the type of the roadway. Different roadway systems were identified by the variable *Transportation System* (TS) and the SHA of the interest in this research identified 9 different TS definitions. Similar to the WMCs, only a fraction of the TSs defined were observed within the database, and similar to the WMC definitions, TS descriptions were used as categorical variables and it is necessary to have a certain amount of data points available to have reliable statistical

analysis. Thus, only five TS descriptions were used in analysis. The combination of WMC and TS were used as the tool to identify truly unique project type/roadway system definition combination. The filtered dataset contained over 2000 projects completed over the last decade and was used for multiple regression models development.

Regression variables selection

In addition to the WMC and TS categorical variables, four continuous variables were chosen that are to affect the TCP quantities and associated costs to be included in the regression models; *Project Budget, Project Length*, *Project Location*, and *Project Duration.* These variables were chosen after analyzing the TCP quantities estimates and literature review.

Project budget

Total dollar value spent on a transportation project is one of the better indicators of the size of the project. Note that, the material and equipment spending will depend on the volume of the total work to be completed, thus using the length only as the project size would be misleading. Number of lanes, lane width, and thickness of the base material as well as the asphalt cover are all factors that the overall budget is highly correlated with.

Project length

The length of the project is one of the most significant factors contributing to the TCP quantities and costs as the total devices used within the construction zone is directly correlated to the length of the work zone

Project location

Although four different location types were defined within the database, they were subsidized to two types; urban and rural, in order to incorporate the categorical variables into the statistical equation without creating data subgroups. The sign spacing as well as the TCP device usage varies depending on the location of the projects; thus, the location will play an important role in TCP quantities and costs. Note that, although location is another categorical variable, there are only two possible values; thus, they can be treated like continuous variables and included in the regression models accordingly.

Project duration

As mentioned earlier, TCP costs are calculated for the devices that were on the construction site for a certain amount of time. It is important to account for the duration of the projects in TCP cost calculations.

Regression Models Development

Multiple linear regression models were developed to predict the TCP quantity requirements and associated costs that are for different project types. Linear models were chosen over other regression types (i.e. logistic regression) because of linear relation among variables chosen and TCP quantities (Field 2005).characteristics of

transportation construction industry as well. Models developed were of the following notation;

$$Y=\sum_{i=1}^{n}\beta_i X_i + \beta_0 + \varepsilon \quad (1)$$

Where Y is the TCP bid item quantity, X_i is one of the four independent variables used, β_i is the corresponding coefficient of the independent variable, β_0 is the intercept and ε is the error term that is used to assess the goodness of fit for the models developed (Foster 1998).

Fitness of the models developed

In order to assess the how well the developed prediction model relates to the dataset, coefficient of determination, R^2, was used. It is a value between 0 and 1, and is defined as a measure of how successful the model in explaining the variation within the data set. i.e. R^2 value of 0.9 will imply that the developed regression model can explain 90% of the variation within the data set. In the models developed benchmark for acceptable R^2 was set to 0.7 and all of the developed models met this requirement.

Accuracy of the developed models

In addition to the fitness of the model to the data set, the accuracy of the point predictions needed to be measured. There have been a number of error terms defined in the literature, but for this research, mean absolute percent error (MAPE) was adapted. MAPE is defined as the average absolute percent error of the given data set. The formula of the MAPE is as follows:

$$\frac{1}{n}\sum_{i=1}^{n}\frac{|A_i-P_i|}{A_i}\times 100 \quad (2)$$

Where, A_i is the actual quantity value for a given project data and P_i is the prediction value for the same data point. The main reason for selection was due to the fact that MAPE does not have a unit and allows different data sets with differing means be compared. The error term has been widely used in a number of different research areas including Civil Engineering (Hyndman and Koehler 2006, Pala et al. 2007).

Method employed in multiple regression models structure development

There are two main approaches in multiple regression models development. The first approach is to include all variables without any consideration to their contribution to the overall regression model. The other method is to evaluate different variables in terms of their contribution to the model and do an incremental development. Although there are many methods available for incremental inclusion of the independent variable in the final model, the method selected was a modified *Forward* selection. In regular *Forward* selection independent variables are entered into the regression equation according to their correlation with the dependent variable and their contribution is assessed by measuring the differences in R^2 value of the model (Brace et al., 2003). In this research, in addition to the improvement to R^2 value of the

model, the predictive accuracies of the models were tested as well. it is very unlikely that inclusion of an independent variable won't improve the R^2 value of a multiple regression model due to improved explanatory power induced by another variable, but the predictive accuracy coupled with the R^2 will indicate whether the variable is of value to the model or not. Note that, this will prevent inclusion of highly correlated independent variables (multi-co linearity effect), as in the case there is substantial correlation between the independent variables, the predictive accuracy of models will decrease substantially because of high correlation.

Heuristics rules to regulate regression predictions

The initial data analysis indicated severe outliers in almost each data group, a fact that was originally attributed to user errors. Omitting these outliers, however, has not improved the consistency of the predictions. Thus, it was concluded that the errors observed were not random user errors or systematic system errors than could be included into the models, but rather they were the variances induces by factors that weren't included in the database used for regression models. In order to account for this, simple heuristics rules were developed and adjustments to the original quantity predictions were made by using these. For instance, it was discovered after in rural highway projects most of the barricades can be replaced by cones; which might seem insignificant, yet barricades are one of the highest cost components of the TCP plans, and cones are cheaper to use in addition to ease in replacement. Some of these specific conditions that cannot be observed directly from the database are provided in Table 1. These factors were identified after conducting multiple surveys with SHA officials.

Moreover, although regression models have been used to predict various unknowns within construction research (Williams 2002, Sonmez 2008), one common warning using regression models is about the unreliability of predictions that use input variables outside the range of independent variables used in model development. Regression models are unpredictable in terms of their predictive powers in case of extrapolations of independent variables. In this research, the approach taken was to set minimum and maximum values to the TCP quantities using the proper MUTCD standards published by FHWA depending on the type of construction.

Table 1. Additional project specific information

Additional Project Information	TCP Items Affected
Number of travel lanes (Shoulder Modifications)	Barricades, Temporary Stripping, Reflective Pavement Markers, Advanced Warning Panel
Median (yes or no)	Work Zone Signs, Barricades, High Intensity Flashing Lights
Cross street frequency	Work Zone Signs, Barricades (Type I-II, Drums)
Edge Drop Off Conditions	Concrete Barrier, Barriers Light
Number of Signalized Intersections	Temporary Traffic Control/ Detection

Application Programming Interface (API) Development

An Application Programming Interface (API) development was necessary to efficiently use the models developed due to the vast number of regression models developed. Different regression models were developed for each TCP bid item for each unique WMC/TS combination provided there was enough data. Moreover, the regression models were developed for each TCP bid item and in order to find the TCP quantities related to any given project type, a compilation of regression models for the representing different TCP models would have been necessary. Thus, an API extending from MS Excel to MS Access was developed to use the regression models and data composition to determine the TCP bid items related to a given project, and to calculate the TCP costs using the bid item cost information published by the SHA (see Figure 1.). The communication channels between the programs were made possible by using the in-built Visual Basic for Applications (VBA) library within the software.

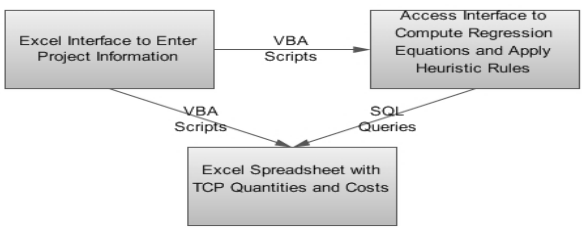


Figure 1. API framework

How to use the application

The API created, Maintenance of Traffic Estimation Software (MOTES), provides the users with a simple interface to predict the TCP quantities and cost, the term MOT was used instead of TCP due to being more common in the SHA documentation. The application interface is a graphic MS Excel spreadsheet that allows users to enter the necessary project information. Note that the tool designed to be a control/design tool for TCP phasing; and the information requested from users will be available at the time TCP design to start (Appendix Figure A1.).The VBA scripts use the entered project variables, the regression models, that are stored in a separate database file running Structure Query Language (SQL) queries to carry out the calculations-, and the heuristic rules embed to assure the accuracy of the regression predictions to calculate the TCP quantities. The quantities are later used with estimated duration and recent bid item cost averages to estimate the TCP costs. (Appendix Figure A2.).

Model Testing and Limitations

Although the accuracy of the regression models were tested through multiple regression models development and during heuristic rules introduction, the models developed needed to be tested with a data set that is not used in the models development. Eleven recent projects data were provided by the SHA to test out the accuracy of the TCP quantity predictions. TCP quantities of 8 out of 11 projects were predicted with acceptable levels of accuracy (i.e. MAPE<10%). Further data analysis of the data from different states is necessary to judge the applicability of the models

developed. Moreover, in order to apply the heuristic rules incorporated into the API development, further project specific information was needed, such as drop-off conditions and the number of the intersections included within the project location. Project specific information was provided by the SHA project officials who have been working on projects that have been used for model testing. Note that the same level of detail about projects is necessary to fully utilize the predictive powers of the application developed.

Conclusions

TCP's are integral parts of transportation construction projects. They play a vital role in assuring the safety of construction workers as well as roadway users, and also their costs can stack up to 10% of the overall project budget. The transportation construction bid item unit costs are closely monitored by SHA that generally take on the role of an owner; however, TCP quantities and costs show great variability mostly due to the flexibility the contractors have and the fluctuations from the original schedule. Provided the constructability of the phasing plans is approved, contractors can determine device quantities and labor costs associated with TCP plans. Because of the monetary value of the TCP plans; this flexibility can create cost related litigation, affect bid rankings and give unfair advantage to contractors that seek to maximize their profits via employing unbalanced bidding. Parameter based design phase TCP quantity predictions are not accurate due to the flexibility in TCP phasing design, behavioral decision making by contractors, and unforeseen changes to project duration.

The study represents a hybrid prediction model to estimate the TCP quantities and costs for a project that is at the design phase. The regression models were developed using the historic bid item data provided by a major SHA in an attempt to account for the variability of the factors that contribute to the TCP quantities. Project specific heuristics rules needed to be developed to account for TCP quantity variability induced by factors that were not recorded in the database used for regression models development. An API was developed in order to make TCP quantity estimations feasible at the design stages. The tool will enable the SHA official with a benchmark to assess the validity of the contractor TCP quantities and costs. Immediate benefits of using the application will be reduced risk of litigations, better bid selection, and fairer bid processes.

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Appendix

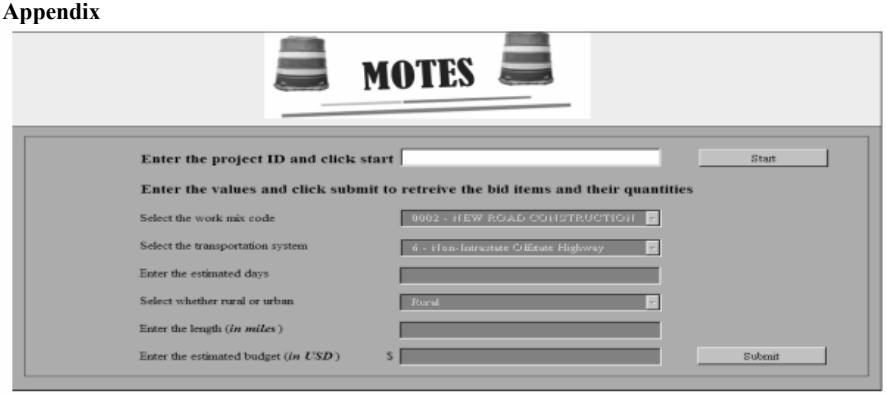
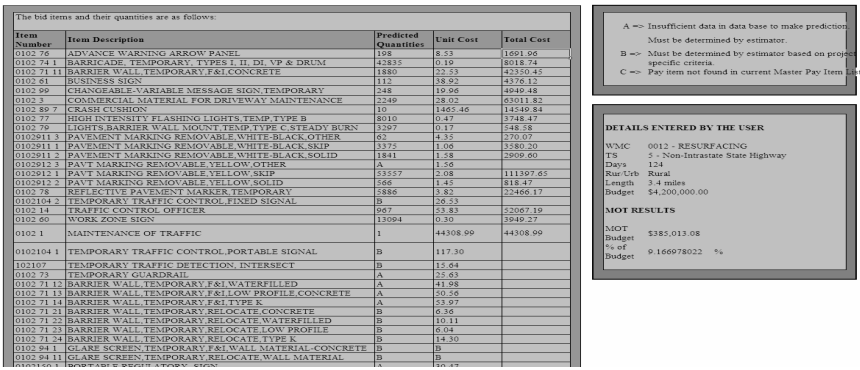


Figure A1. API input interface



The bid items and their quantities are as follows:

Item Number	Item Description	Predicted Quantities	Unit Cost	Total Cost
0102 76	ADVANCE WARNING ARROW PANEL	198	8.53	1691.96
0102 74 1	BARRICADE, TEMPORARY, TYPES I, II, DI, VP & DRUM	42835	0.19	8018.74
0102 71 11	BARRIER WALL, TEMPORARY,F&I,CONCRETE	1880	22.53	42350.45
0102 61	BUSINESS SIGN	112	38.92	4376.12
0102 99	CHANGEABLE-VARIABLE MESSAGE SIGN,TEMPORARY	248	19.96	4949.48
0102 3	COMMERCIAL MATERIAL FOR DRIVEWAY MAINTENANCE	2249	28.02	63011.82
0102 89 7	CRASH CUSHION	10	1465.46	14540.84
0102 77	HIGH INTENSITY FLASHING LIGHTS,TEMP,TYPE B	8010	0.47	3748.47
0102 79	LIGHTS,BARRIER WALL MOUNT,TEMP,TYPE C,STEADY BURN	3297	0.17	548.58
0102911 3	PAVEMENT MARKING REMOVABLE,WHITE-BLACK,OTHER	62	4.35	270.07
0102911 1	PAVEMENT MARKING REMOVABLE,WHITE-BLACK,SKIP	3375	1.06	3580.20
0102911 2	PAVEMENT MARKING REMOVABLE,WHITE-BLACK,SOLID	1841	1.58	2909.60
0102912 3	PAVT MARKING REMOVABLE,YELLOW,OTHER	A	1.56	
0102912 1	PAVT MARKING REMOVABLE,YELLOW,SKIP	53557	2.08	111397.65
0102912 2	PAVT MARKING REMOVABLE,YELLOW,SOLID	566	1.45	818.47
0102 78	REFLECTIVE PAVEMENT MARKER,TEMPORARY	5886	3.82	22466.17
0102104 2	TEMPORARY TRAFFIC CONTROL,FIXED SIGNAL	B	26.53	
0102 14	TRAFFIC CONTROL OFFICER	967	53.83	52067.19
0102 60	WORK ZONE SIGN	13094	0.30	3949.27
0102 1	MAINTENANCE OF TRAFFIC	1	44308.99	44308.99
0102104 1	TEMPORARY TRAFFIC CONTROL,PORTABLE SIGNAL	B	117.30	
102107	TEMPORARY TRAFFIC DETECTION, INTERSECT	B	15.64	
0102 73	TEMPORARY GUARDRAIL	A	25.63	
0102 71 12	BARRIER WALL,TEMPORARY,F&I,WATERFILLED	A	41.98	
0102 71 13	BARRIER WALL,TEMPORARY,F&I,LOW PROFILE,CONCRETE	A	50.56	
0102 71 14	BARRIER WALL,TEMPORARY,F&I,TYPE K	A	53.97	
0102 71 21	BARRIER WALL,TEMPORARY,RELOCATE,CONCRETE	B	6.36	
0102 71 22	BARRIER WALL,TEMPORARY,RELOCATE,WATERFILLED	B	10.11	
0102 71 23	BARRIER WALL,TEMPORARY,RELOCATE,LOW PROFILE	B	6.04	
0102 71 24	BARRIER WALL,TEMPORARY,RELOCATE,TYPE K	B	14.30	
0102 94 1	GLARE SCREEN,TEMPORARY,F&I,WALL MATERIAL-CONCRETE	B	B	
0102 94 11	GLARE SCREEN,TEMPORARY,RELOCATE,WALL MATERIAL	B	B	
0102 60 1	PORTABLE RESULT ATORY SIGN	A	30.47	

A => Insufficient data in data base to make prediction.
Must be determined by estimator.
B => Must be determined by estimator based on project specific criteria.
C => Pay item not found in current Master Pay Item List

DETAILS ENTERED BY THE USER

WMC	0012 - RESURFACING
TS	5 - Non-Intrastate State Highway
Days	124
Rur/Urb	Rural
Length	3.4 miles
Budget	$4,200,000.00

MOT RESULTS

MOT Budget	$385,013.08
% of Budget	9.166978022 %

Figure A2. API output interface

ASSESSMENT OF THE IMPACT OF INTER-ORGANIZATIONAL INTERACTIONS ON PROJECT METRICS

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ABSTRACT

The scale and complexity of capital intensive projects, along with the presence of multiple organizations and stakeholders with conflicting objectives, often cause expensive delays and cost overruns in such projects. This study develops a framework to measure the impact of organizational and stakeholder interactions on the performance metrics of the construction process of capital intensive projects. First, an inter-organizational network is developed to identify the key organizations involved in a specific project phase using social network analysis. Then, potential interactions between these key entities having a negative impact on the performance metrics of the projects are identified and simulated. A Monte Carlo simulation is used to identify significant interactions and to determine their overall impact on the time metric. Nuclear power plant projects, with a history of actual costs of more than 200% the estimated cost, is used as a test bed to verify and validate the research framework. The regulatory agency, the utility company, financing entities, designer and directly affected parties were identified as key entities for these types of projects. In addition, interactions between the utility company and financial entities were found to be significant.

INTRODUCTION

Capital intensive construction projects are capable of directly and/or indirectly affecting finances, society, environment and politics (Capka 2004, Flyvbjerg 2003). As a result, these projects typically involve a high number of stakeholders and

organizations who are involved in the project and who have the "ability to influence its outcome, either positively or negatively" (IFC 2007). Historically, capital intensive construction projects have been impacted by expensive delays and huge cost overruns (Flyvbjerg 2003).

BACKGROUND INFORMATION

Typical stakeholder analysis is based on the evaluation of the stakeholders' classification according to their standing, belief, characteristics on the process being analyzed and the assessment of attributes such as power, legitimacy and urgency (Mitchell et al. 1997, Olander 2006). Following Mitchell et al. (1997), power is linked to the use of coercive, utilitarian, or normative means to obtain their goals. Legitimacy is associated with appropriate actions according to socially established norms. Urgency is based on time sensitivity and criticality of the stakeholder relationship (Mitchell et al. 1997). Entities interacting in a project and having a high degree of power, low degree of legitimacy or low degree of urgency and conflicting objectives could affect the success of the project.

Prior research studies have analyzed the impact of organizational structures on construction project performance construction projects. Jin and Levitt (1996) have done extensive research regarding how organizational structure and dynamics of a working group within an organization affects team performance and hence, the duration, cost and quality of a project in the Virtual Design Team model. An agent based and discrete event simulation model was developed by this research group to model team dynamics on projects related to specific tasks within a project. Other studies have explored the applicability of social networks for analyzing construction project networks (Chinowsky, et al. 2009, Park et al. 2009, Son and Rojas 2009, Pryke 2004, etc.). These studies have considered the network structural attributes as metrics and conclude that social networks analysis is an efficient tool for analyzing working groups and project management strategies in construction projects.

Previous analyses of stakeholders and organizations (Olander 2006, Aaltonen et al. 2008, Newcombe 2003) have focused primarily on the impact of either external stakeholders or internal stakeholders. Significant stakeholders such as the regulatory agencies (internal stakeholders), and affected community and civic groups (external stakeholders) were not considered in the analysis of the impacts of organizational interactions on the metrics of construction projects. However, there is a need for analysis which incorporates the interaction between these two groups.

This study combines stakeholder theory, social network and risk analysis to evaluate the impact of the entities involved in a capital intensive project considering not only entities that are internal to the project but also those that are affected by the project (i.e., affected community, etc.). The paper describes a framework to assist planners in identifying and analyzing the impact of multiple stakeholders/organizations.

METHODOLOGY

In this study, an inter-organizational network is developed using Social Networks to identify the key organizations involved in a construction project. Then, a risk analysis is performed to evaluate the impact of potential interactions between these key entities on project metrics. The framework is then evaluated using a capital intensive project.

Inter-organizational network model

Network theory is an emerging powerful approach that has been used by researches and industry in different areas to analyze the interactions between entities (e.g., organizations, stakeholders, airports, Internet users, etc.). The network is comprised of nodes and links. Nodes represent the entities interacting in the network and contain information according to the analysis that is being performed (e.g. entity classification and attributes, etc.). Links represent the interaction between two nodes and carry information such as capacity and number of communications between nodes among others. Links are classified in edges and arcs. Edges depict directional relationships between nodes, while arcs just denote a connection between two nodes.

This study uses the principles of social networks which is a technique typically used for modeling: (1) important individual, event, place or group, (2) dependency of individual nodes, (3) leader-follower identification, (4) bonding between nodes, (5) vulnerabilities identification, (6) key players in the network, (7) potential threat from the network, and (8) efficiency of overall network (Hussain and Ortiz-Arroyo (2008)). The inter-organizational network model identifies the key entities involved in capital intensive projects, and is used to calculate the structural attributes of the network and entities.

describes network/entity metrics typically used in a social network analysis.

Risk Analysis and Monte Carlo Simulation

A risk analysis is performed to identify and evaluate potential interactions having a negative impact on project metrics. Data availability linking inter-organizational interactions with project metrics is often a limitation in this type of problem. Usually, impacts of the interactions are not well documented, or are difficult to trace. Data related to the interactions and metrics could be collected using interviews, focus groups and surveys deployed to subject matter experts (SMEs) who are representatives of identified key entities. Previous studies have found that experts provide accurate probability estimates (Charniak 1991). The likelihood and impact of potential negative interactions can be estimated using the probability encoding technique as described by Spetzler (1975), which allows “extracting and quantifying individual judgment about uncertain quantities”. The data can then be analyzed using tools typically used in risk analysis such as Monte Carlo Simulation and Probability-Impact analysis. This study uses Monte Carlo Simulation since it allows the modeler to evaluate possible scenarios sampling from the estimated probability distributions and finding the most significant interactions having an impact on project metrics.

Table 1. Network Structural Metrics

	Metric	Definition / Algorithm	Impact on the analysis
Network	Density	Number of links in the network divided by the number of all possible links.	• This metric can be used to compare the networks of different phases of the target process. • For undirected networks, the density represents the probability that any given link between two random entities is present (Hanneman and Riddle, 2005)
Entity	Degree	• Number of connections and entity has to other entities. • Entities with high degree communicate/exchange information with greater number of entities.	These entities could be more involved in the process and therefore have a greater impact on the policy-making process/ performance metrics.
	Degree Centrality	• Measure of centrality. • Proportion of entities that are connected to the node being evaluated. (Wasserman and Faust, 2004)	The centrality provides a measure of importance or power of the entity.
	Clustering coefficient	• How well connected the neighborhood of the entity is. • The clustering coefficient is calculated by dividing the number of triangles centered in the entity by the number of triples (two nodes connected to a center node) centered in the entity.	• A value of 1 means that the neighborhood is fully connected. • A value close to 0 means that there are hardly any connections in the neighborhood. (Li, et. al 2009)

Different methodologies can be used to identify key entities in a network. For instance, previous research have used different measures of centralities (e.g., betweeness centrality, degree centrality) and clustering coefficient to determine the importance of an entity in a network. The methodology used in this case for predicting the key entities was proposed by Hussain and Ortiz-Arroyo (2008) and integrates a Bayesian posterior probability statistical analysis for each entity and the calculation of overall network entropy developed by Shannon (1948).

CASE STUDY

New nuclear power reactors are one of the largest capital intensive projects in the U.S. The current total estimated construction cost of these facilities ranges from $2,930 to $4,745 per kilowatt in 2007 USD (Du and Parsons 2009). Furthermore, there are national security concerns surrounding these projects that make them even more complex, costly and challenging. The increase in cost for nuclear power plants constructed during the decades of 1960s and 1970s surpassed 100%. Stakeholders and involved organizations have played a significant role in the delay and the increase in cost when these nuclear power plants were constructed. According to Department of Energy reports (2001) these delays were often caused by issues such as engineering and management problems, a cumbersome regulatory process and public opposition.

Data Collection and Analysis

Data collection activities include interviews with subject matter experts, data gathering regarding previous projects and projects currently undergoing the regulatory review process. These activities are described in Table 2.

Table 2. Types of data collected

Data Source	Type of data/information	Use of the data
Interviews with Subject Matter Experts (SMEs)	- Historical antecedents. - Data availability issues. - Interaction between entities.	- Problem delineation and data collection. - Estimate of impacts on project metrics (time).
Data from Previous Projects	Litigation processes and issues of previous nuclear power plants projects (causes and duration of the litigation process/issues, and who were involved).	- Identification of potential conflictive interactions. - Impact of these interactions.

Inter-organizational Network Model for Nuclear Projects

A conceptual inter-organizational network, as shown in Figure 1 was created. Organizations involved in nuclear projects (such as applicant, designer and the Nuclear Regulatory Commission (NRC)) were identified from documentation of current Combined License Applications (COL) available online (nrc.gov). In addition, the Report of the Public Communications Task Force (NRC 2003) of the NRC identifies external stakeholders for the agency and the level of communication between these stakeholders and the NRC. A link between two entities means that those two entities are likely to interact during the process. In this case, weights are not considered in links.

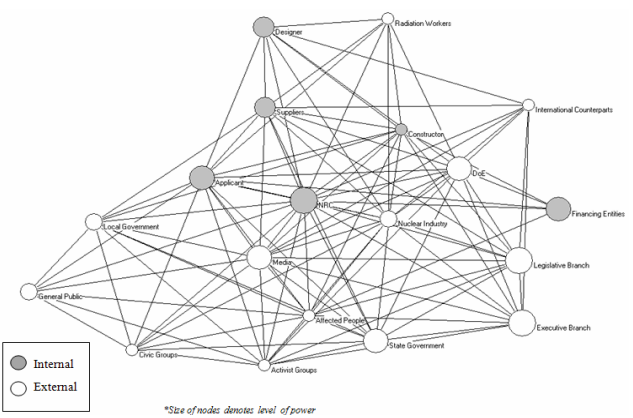


Figure 1. Inter-Organizational Network

The structural attributes were calculated for each of the organizations considered in the 'analysis and are shown in Table 3. The density of the network is 0.62, implying the probability that there is a link between two randomly chosen entities is 0.62. The

NRC and the Applicant/Licensee are likely to interact with a higher number of entities and have the highest centrality. This is expected, since the NRC and the applicant are involved in all project phases to ensure their objectives are met. Centrality is often interpreted as an indicator of importance of the entities in the network. In addition, these two entities are highly powerful in the process, and therefore their conflictive interactions could have a significant impact on project metrics. On the other hand, the clustering coefficients of these two entities are not the highest in the analysis. In the case of State Governments, for example, the clustering coefficient is 1, meaning that the entities linked with this organization (such as local government and affected community) are also linked with each other. This is not surprising for governmental agencies which are usually linked within themselves and offer service to the general public.

Table 3. Structural Attributes of Inter-organizational Network

	Entity	Entity Structural Attributes		
		Degree	Degree Centrality*	Clustering Coefficient
1	Nuclear Regulatory Commission	18	1.00	0.58
2	Applicant(utility company/licensee/owner)	15	0.83	0.62
3	Financing Entities	5	0.28	0.80
4	Designer	8	0.44	0.86
5	Constructor	12	0.67	0.62
6	Supplier	12	0.67	0.71
7	Civic Groups	9	0.50	0.92
8	Directly Affected Parties	13	0.72	0.69
9	Activists Groups	12	0.67	0.77
10	State Governments	7	0.39	1.00
11	Local Government	10	0.56	0.80
12	Legislative branch (Federal)	12	0.67	0.79
13	Media	11	0.61	0.80
14	Nuclear Industry	10	0.56	0.82
15	Executive branch	13	0.72	0.64
16	International Counterparts	15	0.83	0.69
17	General Public	15	0.83	0.67
18	Department of Energy and Federal Governments	8	0.44	0.86
19	Radiation Workers	7	0.39	0.95
Network Attributes	**Average Degree**	11.15	**Density**	0.62

When applying the Bayesian posterior probability method, the entities having the greatest uncertainties (smallest entropies) in the conceptual model and therefore identified as key actors of the process are entities 1:NRC, 2: Applicant, 4:Designer, 3: Financial entities and 14: directly affected community, in that order. The first four entities are internal to the process, while the last one is external to the process.

Risk Analysis of Potential Negative Interactions

To demonstrate the methodology, an example is provided using input from a subject matter expert who provided information about potential conflictive interactions for a pair of entities, from the applicant's point of view. In addition, the SME provided estimates of the likelihood of these interactions to occur during a nuclear project in the

pre-construction phase and the estimated optimistic, most probable and pessimistic durations which could be the result of these interactions. In capital intensive projects, delay is easily translated into the cost project metric since: (1) the delay can increase in the interest expense on construction financing resulting in capitalized costs of the project, (2) expected revenue is delayed since the project cannot be operated, and (3) there may be cost increases in labor and materials due to inflation (Nevitt and Fabozzi 2000).

A Monte Carlo Simulation is run to identify: (a) the interactions which would have a higher negative impact on the duration of the process, and (b) the distribution of these durations. Table 4**Error! Reference source not found.** shows the results obtained from a Monte Carlo Simulation run. Column (1) lists the identified interactions between the identified key entities. Column (2) lists the probability of occurrence of this interaction on the project. The information on column (2) and (3) are estimates from the SMEs. Column (4) calculates the frequency of occurrence of that interaction on this project considering the probability of occurrence (column (2)). For example, for this particular project, there were no conflictive interactions between the financing entity and the applicant and there was one between the applicant and the NRC. Column (5) shows the delay produced as a result of the occurrence of a specific interaction on this project and is defined by a PERT distribution having the parameters listed in Column (3). The overall impact of that interaction is shown in column (6). For instance, for this particular project, the total impact on the time metric of the project produced by the interactions of the key entities is 179 days.

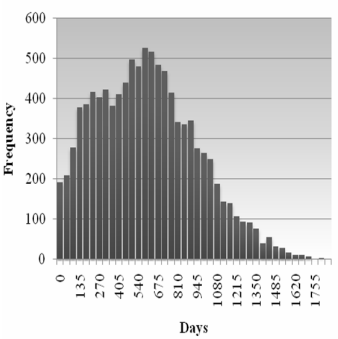
A simulation (10,000 iterations) was performed to determine the impacts on the time metric of the project. Figure 2 shows the results for the interactions between the applicant and the NRC. The range of values corresponds to the delay of the project as a consequence of the potential interactions. Figure 2(a) shows the distribution of delays when considering all the interactions and represents the impact of these interactions on the time metric. The range of values can be represented using a gamma distribution with a mean of 578 that could be used for estimating project duration. Figure 2(b) shows that the interactions having the largest impact on the duration of the project are the interactions between the applicant and financing entities followed by interactions with NRC and designer.

CONCLUSIONS AND FUTURE WORK

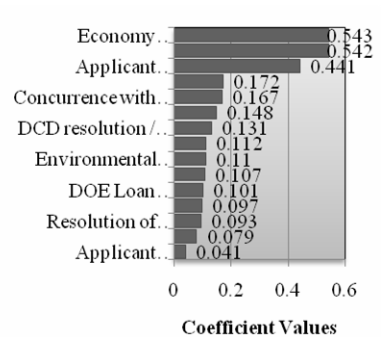
The assessment of impacts of stakeholders and organizations in a construction project are crucial to ensure project success. This paper describes a framework to identify and assess the impacts of the entities involved in capital intensive projects. Using social network analysis, an inter-organizational network is developed to identify the key organizations in a project. Then, potential interactions between these key entities having a negative impact on the performance metrics of the projects are identified for the pre-construction process of a capital intensive project. Input from subject matter experts is used to determine the estimated probability and the expected impact of each of these interactions. A Monte Carlo simulation is used to identify significant negative interactions that have a significant impact on the duration of the project.

Table 4. Results from a Monte Carlo Simulation Run

Interactions (1)	Probability per project (2)	Days			Frequency/ project (4)	Impact (days) (5)	Impact of interaction (days) (6)
		O	M (3)	P			
Applicant – NRC							
Significant technical issue – COL	15.0%	30	120	360	0	324	0
Environmental Issue – COL	25.0%	30	90	120	0	102	0
Design Certification Approval	35.0%	60	120	180	0	123	0
Resolution of Requests for Additional Information (RAIs)	25.0%	30	60	180	1	103	103
Applicant – Designer							
Design Control Document (DCD) resolution	45.0%	30	90	150	0	91	0
Site Specific Requirements	25.0%	30	90	120	0	108	0
Concurrence with DCD RAIs	35.0%	60	120	180	1	76	76
Applicant - Financing Entities							
Economy influence on financing	35.0%	180	360	720	0	361	0
Applicant financial position	25.0%	180	360	480	0	332	0
Department of Energy Loan Guarantees	35.0%	180	360	720	0	446	0
Applicant - Affected Community							
Community opposition	5.0%	0	180	360	0	261	0
Lack of Agreement on Taxes	15.0%	30	60	180	0	134	0
Total							**179**



(a) Distribution of durations (days) due to interactions



(b) Tornado diagram: Total delay regression coefficients

Figure 2. Results of Risk Analysis

In its initial phase, the study has provided means to improve the current understanding of inter-organizational impacts on project metrics. The methodology however is highly dependent on available data and if data is not available, on the accuracy of the data provided by SMEs. Therefore, it is crucial to find SMEs who are involved in the type of project being analyzed and not to rely on a single SME.

Since the occurrence of interactions is also uncertain, future research will integrate inter-organizational network and fuzzy logic theory to model these uncertainties. In addition, since the influence of stakeholders is not static throughout a project, multiple inter-organizational networks will be constructed and compared to analyze the changes structural attributes of the networks, during different phases of the project. The results of this study can provide strategies to reduce and mitigate negative inter-organizational impacts on capital intensive projects, and serve as a basis for inter-organizational policy development and decision making processes.

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Front End Planning for Infrastructure Projects

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ABSTRACT

Infrastructure capital projects are at the center of efforts to invest in the recovery of the economy, both domestically and internationally, and are seen as a primary growth engine of the construction industry today. Sadly, many of these projects are unsuccessful due to poor early project planning. Front End Planning (FEP) is a critical process for uncovering project unknowns, while developing adequate scope definition and a structured approach for the project execution process. FEP assists in identifying and mitigating issues such right-of-way concerns, utility adjustments, environmental hazards, logistic problems, permitting requirements and so on. This paper will outline ongoing research funded by the Construction Industry Institute (CII) focused on front end planning of infrastructure projects. This investigation, which includes input from domestic and foreign planning experts from over 30 organizations using as reference over 60 capital projects, provides an understanding of the critical issues that must be addressed during FEP of infrastructure projects. Critical success factors for FEP of infrastructure projects will be shared, including key planning process steps, along with guidance to practitioners involved in planning infrastructure projects.

KEYWORDS

Front End Planning, Infrastructure, Risk Management, Planning

INTRODUCTION

In recent years, a high percentage of the annual construction-related capital spent by public and private owner organizations is on infrastructure work in both foreign and domestic markets. Estimates by Engineering News Record for 2008 were at $225 billion for new construction and repair/renovation of aging infrastructure. This represented a 10 percent increase over 2006 expenditures (ENR 2007). Although this

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2008 forecast probably did not occur because of the economic downturn, it does show the extent of expenditures in this sector.

Recent failures in infrastructure projects, such as the bridge collapse in Minnesota, steam line failure in New York City, and the public outcry to invest in traditional and alternative energy infrastructures to reduce the price of energy have highlighted the precarious condition of the nation's infrastructure. Studies have shown a poor success rate on many large infrastructure projects (Flyvbjerg et al. 2003; NRC 2003). As the economy has slowed, government economic stimulus efforts, both foreign and domestic, are focusing on infrastructure investments to revitalize economic conditions. Consequently, a large and growing volume of construction work is focused on infrastructure projects. The increased demand for more sustainable infrastructure, calls for greater control in the front end planning (FEP) process. In order to provide the construction industry with an adequate tool to solve the current conditions, the Construction Industry Institute (CII) formed a research team with the purpose of creating a front end planning tool specifically designed to address the unique circumstances that surround infrastructure projects.

While addressing (FEP) of industrial and building projects, previous CII-research efforts have not focused on infrastructure work directly, and little research has been performed in the area of FEP for infrastructure projects. The research project outlined in this paper is a continuation of the research/development thread conducted by CII over the past 18 years, extending to this important industry sector. The objective of this paper is to portray the importance of developing a tool for front end planning of infrastructure projects, and to describe the process the CII research team is using to develop the FEP tool, including initial findings.

IMPORTANCE OF FRONT END PLANNING

Front end planning is defined as "the process of developing sufficient strategic information with which owners can address risk and decide to commit resources to maximize the chance for a successful project" (CII 1994). Figure 1 shows the CII phase gated front end planning process. Front end planning generally occurs up until phase gate 3 on the model, just prior to design and construction of the project. Front end planning is arguably the single most important process in a capital facility project life cycle. It is focused on creating a strong, early link between the business or mission need, project strategy, scope, cost, and schedule and maintaining that link unbroken throughout the project life (CII 2008a). Anecdotally, many companies concede that good front end planning is rare, but it is desired for every project and essential for optimal project execution.

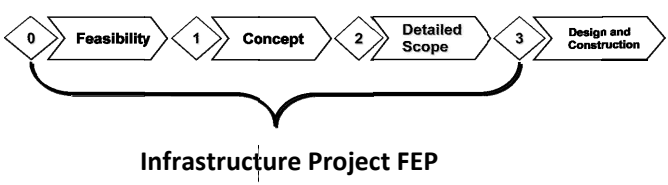


Figure 1. Front End Planning Process

CII research indicates that well performed FEP has helped reduce total design and construction cost by as much as 20 percent, reduce total design and construction schedule by up to 39 percent, improve cost and schedule predictability and increase the chance of meeting the project's environmental and social goals (CII 1994).

RESEARCH METHODOLOGY

The overriding hypothesis of this development effort is that there are FEP process steps and data that can be defined that will add value to a capital project, in this case an infrastructure type project. This process and associated variables will positively influence success of a project and a project team (and an organization) must perform this process effectively in order to have a more successful project venture. The development methodology to test this hypothesis has been used successfully in past efforts of this type (Dumont and Gibson 1996; Cho et al. 1999; Gibson and Whittington 2008).

Research focused on FEP for infrastructure projects began in October 2008. CII brought together a team of 20 industry professionals representing hundreds of combined years experience in infrastructure projects, pre-planning, estimating and related fields. This team was comprised of highly experienced members from 20 different owner organizations, contractors, and suppliers along with the academic team.

WHAT IS AN INFRASTRUCTURE PROJECT?

One of the first tasks undertaken in this research effort was to develop an agreed-upon definition of an infrastructure project. Many definitions were reviewed and the team spent several meetings refining the definition that is given below:

> "A capital project that provides transportation, transmission, distribution, collection or other capabilities supporting commerce or interaction of goods, service, or people. Infrastructure projects generally impact multiple jurisdictions, stakeholder groups and/or a wide area. They are characterized as projects with a primary purpose that is integral to the effective operation of a system. These collective capabilities provide a service and are made up of nodes and vectors into a grid or system (e.g., pipelines (vectors) connected with a water treatment plant (node))."
>
> Vectors examples:
>
> - Electrical Distribution/Transmission systems:
> - Pipelines
> - Highways
> - Canals
> - Railway systems
> - Tunnels
> - Telecommunication lines
> - Wide Area Networks
>
> Nodes/Centralized facilities examples:
>
> - Dams
> - Power Generation Facilities
> - Steam or chilled water production

- Marine, Rail or Air Terminals
- Water/Waste Water/ Solid Waste Processing

In the context of systems, an infrastructure in this definition provides the needed services and connections (vectors) that enable industrial facilities and buildings to function effectively. If any of these vectors are disrupted, the entire system will fail to function effectively unless redundancy is provided. A diagram illustrating this concept is given in Figure 2.

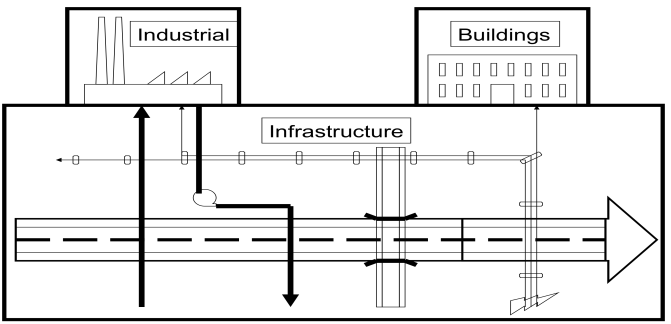


Figure 2. Infrastructure Interrelationship Diagram

WHAT IS THE PDRI?

Beginning in 1994, the Construction Industry Institute (CII) began to develop a tool used in the front end planning process. This tool is known as the Project Definition Rating Index or PDRI. The first PDRI was intended for use on industrial projects. After successful research and testing, the PDRI for industrial projects went through three revisions to give us the current edition. It became evident to the developers, that there was a need for a similar tool for building projects. In 1999, the Project Definition Rating Index for building projects was developed (Dumont and Gibson 1996; Cho et al. 1999).

The PDRI is a tool designed to measure the degree of scope definition in a project. This tool is composed of a comprehensive checklist of scope definition elements to be evaluated based on level of completeness by project representatives before detailed design and construction. After all elements have been assessed, an index is calculated that gives the relative level of definition for the project. A lower score indicates a more complete scope definition. (CII 2008a; CII 2008b)

The CII research team met multiple times over the course of nine months to draft the PDRI for infrastructure. The original basis of the tool was provided by a front end planning risk tool entitled the Advance Planning Risk Analysis (APRA) tool developed for Texas Department of Transportation (Caldas et al. 2006). The draft PDRI consists of 3 sections broken down to 13 categories and further into 68 elements focused on scope definitions for infrastructure projects. These 68 elements are organized in checklists, an excerpt of which can be seen in Figure 3 which shows the elements that make up the category entitled Project Strategy. Each element is

further detailed with a description as shown in Figure 4, in this example for public involvement (element A.4).

SECTION I - BASIS OF PROJECT DECISION							
CATEGORY Element	Definition Level 0	1	2	3	4	5	Score
A. PROJECT STRATEGY							
A.1 Need & Purpose Documentation							
A.2 Investment Studies & Alternatives Assessments							
A.3 Key Team Member Coordination							
A.4 Public Involvement							
						CATEGORY A TOTAL	

Definition Levels

0 = Not Applicable
1 = Complete Definition
2 = Minor Deficiencies
3 = Some Deficiencies
4 = Major Deficiencies
5 = Incomplete or Poor Definition

Figure 3. Excerpt from PDRI Project Score Sheet

A.4 Public Involvement

Public involvement is an integral part of project development and should be planned and managed. Most infrastructure projects have to afford some level of public involvement to inform the public of project scope issues and to measure public attitudes regarding the development process. The level of public involvement is dependent upon a number of social, economic, and environmental factors, along with the type and complexity of the project. Community involvement efforts may include meetings with key stakeholders, including affected property owners, public meetings, and public hearings. Issues to consider include:

- ❑ Policy determinations regarding public involvement
- ❑ Notification procedures and responsibilities
- ❑ Identification of key stakeholders
- ❑ Identification of utility providers
- ❑ Types of public involvement:
- ❑ Press releases and notices
- ❑ Public meetings/hearings
- ❑ Individual or group meetings with affected property owners
- ❑ Local support and/or opposition
- ❑ Public involvement strategies after project approval
- ❑ Available website content
- ❑ Input of public involvement information into any typical deliverables such as a "Environmental Impact Statements", "Public Hearing Notices," or other
- ❑ Other user defined

Figure 4. Example Element Descriptions

Table 3 gives a listing of the 68 elements that were identified and defined as part of this development effort. Each of these elements is grouped topologically under categories, with the categories grouped within the three sections.

Table 3: PDRI SECTIONS, Categories, and Elements

SECTION I. BASIS OF PROJECT DECISION

A. Project strategy
A1. Need & purpose documentation
A2. Investment studies & alternatives assessment
A3. Key team member coordination
A4. Public involvement

B. Owner/operator philosophies
B1. Design philosophy
B2. Operating philosophy
B3. Maintenance philosophy
B4. Future expansion & alteration considerations

C. Project funding and timing
C1. Funding and programming
C2 Preliminary project schedule
C3. Contingencies

D. Project requirements
D1. Project objectives statement
D2. Functional classification and use
D3. Evaluation of compliance requirements
D4. Existing environmental conditions
D5. Site characteristics available vs. required
D6. Dismantling & demolition requirements
D7. Determination of utility impacts
D8. Lead/discipline scope of work

E. Value analysis
E1. Value engineering procedures
E2. Design simplification
E3. Materials alternatives considered
E4. Constructability procedures

SECTION II. BASIS OF DESIGN

F. Site Information
F1. Geotechnical characteristics
F2. Hydrological characteristics
F3. Surveys and mapping
F4. Permitting requirements
F5. Environmental documentation
F.6 Environmental commitments & mitigation
F7. Property descriptions
F8. Right-of-way mapping and site issues

G. Location and geometry
G1. Schematic layouts
G2. Horizontal and vertical alignment
G3. Cross-sectional elements
G4. Control of access

H. Associated structures & equipment
H1. Support structures
H2. Hydraulic structures
H3. Miscellaneous elements
H4. Equipment list
H5. Equipment utility requirements

I. Project design parameters
I1. Capacity
I2. Safety and hazards
I3. Civil/structural
I4. Mechanical/equipment
I.5 Electrical/controls
I.6 Operations/maintenance

SECTION III. EXECUTION APPROACH

J. Land acquisition strategy
J1. Local public agencies utilities contracts and agreements
J2. Long-lead parcel & utility adjustment identification & acquisition
J3. Utility agreement & joint use contracts
J4. Land appraisal requirements
J5. Advance land acquisition requirements

K. Procurement Strategy
K1. Project delivery method & contracting strategies
K2. Long-lead/critical equipment & materials identification
K3. Procurement procedures and plans
K4. Procurement responsibility matrix

L. Project control
L1. Right-of-way & utilities cost estimates
L2. Design & construction cost estimates
L3. Project cost control
L4. Project schedule control
L5. Project quality assurance & control

M. Project execution plan
M1. Safety procedures
M2 Owner approval requirements
M3. Documentation/deliverables
M4. Computing & CADD/model requirements
M5. Design/construction plan & approach
M6. Intercompany & Interagency coordination & agreements
M7. Work zone and transportation plan
M8. Project completion requirements

Using structured focus groups (also known as research charrettes) a purposive, expert sample of workshop participants was solicited by the authors to provide input into this tool. These workshops were held in London, Houston, New York and Los Angeles in which 64 industry professionals representing 37 organizations, 15 owners and 21 contractors, with over 1400 years of individual experience in infrastructure projects have participated. Table 1 provides a listing of workshops, while Table 2 provides a list of organizations that participated in the workshops. Individuals in these workshops represented the viewpoints of 37 contractors/consultants and 27 owner organizations. An attempt was made to ensure that representatives had experience in one of three categories of infrastructure projects: projects that conduct energy such as transmission lines, people and freight projects such as highways or railroads, or fluids projects, such as pipelines or channels.

Table 1. Workshops and Participants

Location	Date	Number of Participants
Washington, DC, USA	July 16, 2009	16
Sunbury, UK	August 11, 2009	8
London, UK	August 13, 2009	7
Houston, TX, USA	September 16, 2009	13
New York, NY, USA	October 14, 2009	12
Los Angeles, CA, USA	October 20, 2009	8

Table 2. Workshop Participating Organizations

Owners	Contractors
Architect of the Capital	AECOM
British Petroleum	Booz Allen Hamilton
Chevron	CH2M HILL
Conoco Phillips	CSA Group
European Investment Bank	D' Orange Ltd
Exxon Mobil	European Construction Institute
National Institute of Standards and Technology	Fluor Enterprises
Port of Long Beach	Jacobs Engineering
Salt River Project	KBR
Sempra Global	KPFF
Smithsonian Institution	Mustang Engineering
UK Highways Agency	P2S engineering
UK Network Rail	Parsons
U.S. Army Corp of Engineers	Pathfinder LLC
U.S. Department of Energy	Phoenix Constructors
	Project Resource Company
	PSEG
	S & B Infrastructure Group
	Syngenta Engineering
	The RBA Group
	Worley Parsons

The authors realized that the 68 elements that make up the PDRI for Infrastructure were not weighted equally. That is to say that there are individual elements among the 68 total elements that will have a greater effect on the overall level of preparedness for a project, and in turn the success of a project. With this in mind, the project team relied on participants in these research charrettes to develop relative weights to each

of the 68 elements within the PDRI. Charrettes began with an explanation of the PDRI tool, purposes and goals of the research, its background, and desired end product. Participants provided background information that included their contact information, company, position, as well as the participant's total years of project management, planning or estimating experience, types of projects, and the percentage of work experience involving infrastructure projects.

Participants were asked to give feedback to the score sheets, descriptions, and efficacy of the draft PDRI as the charrette progressed. These data were used to update and modify the structure to better represent industry terminology and risk profile for these types of projects.

The workshops proceeded with each participant using an infrastructure project that they had recently been involved in as a reference for providing relative importance values. This project would be used as a reference throughout the charrette to assign values to the defined elements. The workshop facilitator then reviewed each element within the 13 categories giving a detailed definition and description of the element while answering questions. Assuming that scope development for the project had been completed, the workshop participants were instructed to apply what they felt to be an appropriate cost contingency to each element, given two circumstances: 1) the element was undefined or 2) it was completely defined. The weighting was based on their opinions as to the relative impact that each element has on the overall accuracy of the project's total installed cost (TIC) estimate.

The data collected from the workshops will be used to develop the final working version of the PDRI score sheet. By normalizing the responses from the workshop participants, the research team will create a scoring system from zero to 1000 points. The detailed description of this process is beyond the scope of this paper, but follows the model developed by Cho et al. (1999). Within the next year, the research team will meet several times to adjust the PDRI according to the feedback received in the various workshops as well as observations made as the tool is applied to past projects and tested on current or future projects. The team's end product will be a comprehensive score sheet that can be used to evaluate the level of completeness or definition for individual project scopes.

Feedback was received in the form of comments on the score sheet itself as a well as a separate handout for general comments or suggestions for improvement. These suggestions led to refinement of the element descriptions and will be further used as a guide for the future use of the PDRI tool on actual projects.

INITIAL RESULTS

An analysis of the data collected through the various workshops supported the theory that some elements were of relatively higher importance than other elements. The following are assessments from the initial data when normalized. The top ten elements (of 68) for infrastructure projects based on input from the workshop participants:

1. Need & Purpose Documentation: The need for a project may be identified in many ways, including suggestions from operations and maintenance personnel, engineers, planners, local elected officials, developers, and the public. Documentation

should result in assessing the need and purpose of a potential project based on factual evidence of current and future conditions, including why the project is being pursued.

2. Investment Studies & Alternatives Assessments: Various studies address possible alternatives when the solution is unknown. These findings will avoid unnecessary expenditures on preliminary engineering and related costs and will also confirm the viability of proceeding with the selected option and typically take the form of feasibility/route studies or major investment studies.

3. Contingencies: The contingency management process should effectively communicate the contingency magnitude and confidence level to all appropriate stakeholders. It is important to have estimates of the proper accuracy, consistency, and clarity at the right phase of the planning process. Contingencies are forecasted and adjusted throughout the planning process based on the level of confidence in the current estimate accuracy.

4. Design & Construction Cost Estimates: The project cost estimates should address all costs (excluding right-of-way acquisition and utility adjustment costs) necessary for completion of the project.

5. Preliminary Project Schedule: A preliminary project schedule should be developed, analyzed, and agreed upon by the major project participants. It should include milestones, unusual schedule considerations and appropriate master schedule contingency time (float), procurement plan (long-lead or critical pacing equipment/material and contracting), and required submissions and approvals.

6. Funding & Programming: As part of the funding and programming process, initial cost estimates must be prepared, assessing funding provided for planning, design, construction, right-of-way acquisition, utility adjustment, maintenance, and other project expenses. Strategic measures must be in place for determining the sources, levels, and forms of funding available to the project, as it competes against others for limited funds, whether public or private.

7. Existing Environmental Conditions: Decision making requires an understanding of existing environmental conditions which must be obtained from a variety of sources, including previous surveys, geographic information systems, and resource agency databases. Identifying problematic issues at an early stage in the project development process enables better decision making as well as adequate time to address and mitigate these concerns.

8. Design Philosophy: A list of general design principles should be developed to achieve a successful project that fulfills the functional requirements and assimilates into the existing infrastructure system.

9. Capacity Study: Capacity studies are required for scope definition of most infrastructure projects. These studies provide a description of the related process flows and interactions allowing the planning team to ensure adequate facility capacity, while guarding against over- or under-design.

10. Evaluation of Compliance Requirements: A fundamental part of decision making is an understanding of adherence requirements to various local, regional, and national plans. As part of project development, determine, document, and understand applicable requirements. Compliance should be assessed with existing plans, codes, and standards, national, regional or local requirements and utilization of design standards.

A study of the element rankings when compared to the rankings given in the PDRI for buildings and industrial projects, highlighted elements of equally high importance as well as confirmed the uniqueness of infrastructure projects. Some issues that were found in all three top ten lists include: the importance of marketing and business planning, evaluation of site conditions, and identification of all needs and uses of the facility. Unique characteristics of infrastructure projects include in this top ten list include: contingencies, design philosophy and funding.

CONCLUSIONS

The authors will continue to work on the results of the workshops held over the past several months in conjunction with the research team. Further data will be collected to understand the efficacy of the developed tool.

It should be noted that several of the themes that have emerged and are identified in these initial results are unique to infrastructure projects and must be addressed by the project team. First, these projects typically involve a larger number of key stakeholders than building or infrastructure projects. These interfaces must be managed. Second, these projects are typically horizontal in nature and cross multiple jurisdictions. This fact means that non-homogeneous jurisdictional and technical conditions exist that must be addressed, such as compliance requirements, funding sources, and right of way procurement difficulties.

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Implementation of Building Information Modeling (BIM) in Modular Construction: Benefits and Challenges

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Modular Construction consists of one or more structure units fabricated in a manufacturing plant away from the jobsite. In the building industry, prefabricated modules are normally completed with trim work, electrical, mechanical and plumbing installed. Previous studies have proved that Modular Construction provided many advantages to the built environment, including the reduction of need for workforce, the reduction of onsite Green House Gas (GHG) emissions, and the improvement of construction schedule and product quality; however the extensive demand of pre-project planning and coordination among members of cross-interdisciplinary professionals have significantly impeded the application of this technique. With the recent development of Building Information Modeling (BIM), these challenges could be overcome through the BIM platform. Through case studies the benefits and challenges of implementing BIM in modular construction are clearly identified.

Keywords: Building Information Modeling, Coordination, Prefabrication, Building Systems.

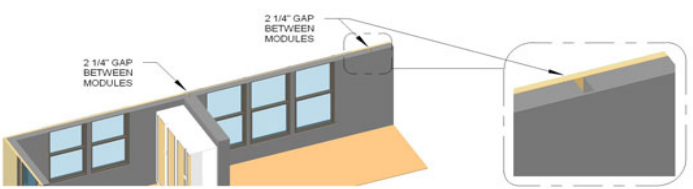
Introduction

Modular construction refers to factory-built building units completely assembled or fabricated in a manufacturing plant away from the jobsite, then transported and assembled on site (Pasquire, 2002). Modular building normally consists of multiple rooms with three-dimensional units, which are constructed and pre-assembled complete with trim work, mechanical, electrical and plumbing components installed (O'Brien, 2000). A large portion of construction research conducted in the United States and globally discusses that the use of modular construction provides many significant advantages, including: 1) the reduction of overall project schedules, 2) the improvement of product quality, 3) increased onsite safety performance, 4) a

reduction in the need for onsite skilled workers, and 5) a decrease in the negative environmental impact caused by construction operations (Gann, 1996; Hsieh, 1997; Edge, 2002; Gibb, 2001; Venables, 2004; Lu, 2007). However, the coordination and fabrication of the Mechanical, Electrical and Plumbing (MEP) systems in modular construction has always being one of the most challenging tasks encountered in the delivery process of modular constructions (Tatum, 2000; Korman, 2001; Lu, 2008).

The MEP coordination and fabrication process involves defining the locations for components of building systems, in where are often congested spaces, to avoid interferences and to comply with diverse design and operations criteria. There are three primary reasons contributing to the challenges of MEP fabrication in modular construction. First, the process is highly fragmented between design and construction firms. Second, the level of technology used in different coordination scenarios has historically varied significantly between engineers and construction contractors. Third, historically the process did not provide a model for use by specialty contractors plan prefabrication (Korman, 2001).

Using Building Information Modeling (BIM) to coordinate, document and fabricate MEP systems in modular constructions appears to be an effective approach to overcome these challenges. In 2009, Maine based Modular Construction Company KBS has successfully delivered their recently awarded modular project by integrating BIM technology into the design and construction process for the New Street Project, Cambridge, MA, as presented in Figure 1 (KBS, 2009).



(a) Architecture BIM Model to present modular wall details



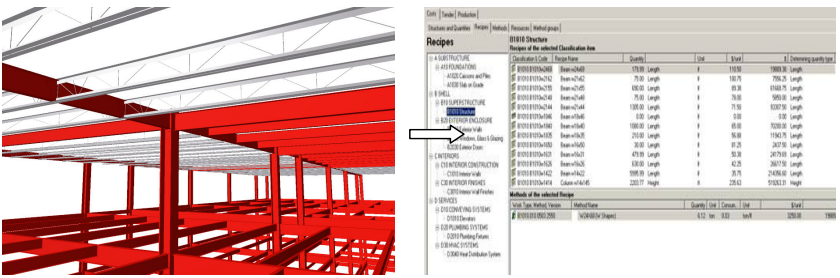


(b) Installation prefabricated Roofs (c) Prefabricated Wall Panels

Figure 1: BIM application in Modular Construction Projects (Tocci & KBS)

BIM Background and Applications

BIM is commonly defined as the process of creating an intelligent and computable three-dimensional (3D) data set and sharing the data among the various types of professionals within the design and construction team. With BIM technology, an accurate virtual model of a building is constructed with precise geometry and relevant data needed to support the procurement, fabrication, on-site installation activities, as presented in Figure 2 (Eastman et al, 2008).



(a) Structural Steel BIM Model (b) Automatic Quantity Takeoff from BIM Model

Figure 2 BIM Model Applications in Cost Engineering
(Courtesy of: Holder Construction Co, Atlanta, Georgia, USA)

The use of BIM technology allows for the creation of intelligent contextual semantic digital models in terms of building elements and systems, such as spaces, walls, beams, columns and MEP systems, whereas 3D CAD technology is limited to generating drawings in graphical entities in terms of lines, arcs and circles. In addition, BIM technology allows for a creation of a model that contains information related to the building physical, functional and procurement information. For instance, the BIM model would contain data about the geometry, location, its supplier, operation and maintenance schedule, flow rates, and clearance requirements for an air-handling unit (CRC Construction Innovation, 2007).

Using BIM technology allows designers, engineers, and construction contractors to visualize the entire scope of a building project in three dimensions. Therefore, BIM technology is not only defined by simply creating a 3-D data set for internal analysis. When most professionals refer to a 3-D model today, they are only referring to a digital 3-D data set that contains geographical representations of objects placed in relation to each other. BIM technology is also known as the process of using a 3-D model and associated data set to improve collaboration among project participants. Using this collaborative approach, designers and builders can plan, in precise detail, the location and clearances required for a complete and successful project.

The implementation of BIM systems in modular construction normally involves in the following process:

- *Visualization*: ability to create a 3D presentation of building modules geometry, location, space, contained systems in relation to each other
- *Modeling*: ability to generate a 3D rendering tool to present the final product and finishes to owners, designers and constructors
- *Code reviews*: allows for building officials and fire officials could use the 3D models with related data for code compliance reviews
- *Fabrication/ shop drawings*: facilitates for the generation of detailed shop drawings could be easily produced once the BIM model is completed
- *Communication*: facilitates simultaneously creation of construction documents, product imagery, rapid prototypes, exterior envelope, interior finishing, and MEP fixtures of building modules. Through this single information platform, BIM promote collaborations among the design team, consultant, constructors and the clients
- *Cost estimating:* provides for cost estimating, material quantifications, and pricing to be automatically generated and modified while changes are applied for each building module
- *Construction sequences:* provides a complete construction schedule for material ordering, fabrication, delivery and onsite installation of each building systems. With the integration of 3D rendering, 4 D (3D model + scheduling information) could be easily generated during the project design and construction phase
- *Conflict, interference and collision detection:* ability to determine building system interferences which can be visually presented. For instance, an air distribution duct for the HVAC system physically interfering with a concrete beam

Today, there are many examples of BIM software. NavisWorks™ is a software program that interprets all of the other software programs used by various specialty contractors and design engineers. NavisWorks™ is to software what the Rosetta Stone was to interpreting languages. This software has the potential to unlock and or interpret the other 2-D CAD drawings. This program only identifies the clashes and the individual specialty contractors need to revisit their own software programs and revise them in order to resubmit. NavisWorks™ will then reanalyze the new shop drawings and hopefully there are fewer or no clashes. Obviously, when there are multiple specialty contractors involved in a project, the challenge is to create an environment whereby everyone has worked out the details successfully.

There are many3-D graphical representation software programs available for architects and engineers to model their project in BIM platform as well. Graphisoft's ArchiCAD™ allows one to draw in 3-D or import a 2-D drawing and create a 3-D model. This program allows you to toggle back and forth from 2-D to 3-D with the click of a mouse. AutoDesk™ is a 2-D drafting program coupled with Revit™ creating the 3-D model.

MEP Coordination in Modular Construction prior to BIM technology

Without the use of BIM system MEP coordination, prefabrication phase in modular construction begins after the design and preliminary routing of all building systems (mechanical, plumbing, electrical, etc.) is complete. The design is considered complete when engineers have sized all components (e.g., HVAC duct, pipe, conduits), completed the engineering calculations, and produced the diagrammatic drawings. Representatives from each of the specialty contractors (primarily HVAC wet and dry, plumbing, electrical, and fire protection) meet to discuss their particular designs and drawings, which indicate the proposed routing for each system to follow to service each required location. Most specialty contractors refer to these contract drawings as schematic design drawings. The engineers' stamp that the engineer provides only insures that the design of the systems will work functionally. It does not ensure that the system will actually fit within building.

In this scenario, the design consultant remains the engineer of record (EOR) and retains liability for the system functionality; however, these drawings are not detailed enough to either fabricate components or construct the systems. The required size of components, such as conductor wire, duct dimensions, and pipe diameter are called out on the drawings, but no scaling of the components is shown in the drawings. It is the specialty contractor's responsibility to build the particular building system from these design documents. This requires that the contractor produce shop drawings, also known as fabrication drawings. The shop drawings include the detailed information required by the specialty contractor to fabricate and install a particular building system.

During coordination meetings, the participating specialty contractors compare preliminary routing for their systems to identify and resolve conflicts. The MEP trades use a sequential comparison overlay process to compare their design drawings until they resolve all interferences. This often requires preparing section views for highly congested areas to identify interferences. The preliminary shop drawings that each specialty contractor brings to the meeting indicate the path preferred for each branch of the system to reach the required locations and perform essential functions. Architectural, structural, and diagrammatic drawings constrain this routing. Within these constraints, specialty contractors route systems based on the lowest cost; however, they generally do not consider the other systems. They also decide which specialty contractor(s) will revise their design and submit requests for information regarding problems that require an engineering resolution. The product of this process is a set of coordinated shop drawings that the specialty contractors submit to the design engineer for approval that the system functionality has not been compromised.

Using BIM for MEP Coordination in Modular Construction

Historically, there has been a wide variation in the level of technology used in the MEP coordination process. At the low-tech end of the spectrum, specialty contractors drafted plan-views on translucent media and prepare section-views when necessary. At the other extreme, progressive contractors have used 3D CAD to improve the process. With the recent development of BIM, the process has gravitated toward the use of

BIM software.

There are many locations in buildings that repeatedly cause coordination problems. These include building corridors, points of entry and exit, openings in shear walls, and vertical utility chases. Reserving space for access is more easily accomplished using BIM models. However, often times resolving interferences most frequently entails determining which building system has priority. In these cases priority is typically determined by evaluating the functionality of each system. In the event of interferences or clashes, the newly proposed route must be evaluated to determine if the new route changes the systems' functionality. If it is determined that the new route affects the functionality of the system performance, it is given priority over another system.

The need for MEP coordination grows out of the lack of detailed design provided for fabrication and installation of building systems, and exists regard-less of the project delivery process used. The current conditions in the design and construction industry drive current practice for MEP coordination. The use of BIM technology has created an opportunity to improve the current process by changing the way design engineers and construction contractors interact with each other during the coordination process. BIM offers parties involved in MEP coordination to take the opportunity to align goals and define requirements during the construction of the model. In addition, when historically MEP design consultants have not considered constructability issues and made assumptions about constructability or ignore the issue totally, the use of BIM allows a mechanism for dialogue between specialty contractors who install the system and design engineers who design the system.

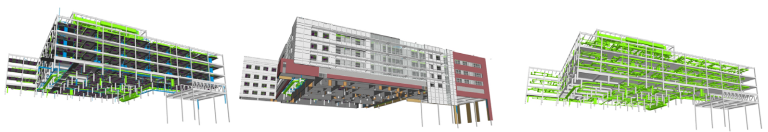
Benefits and Challenges of BIM Implementation: Case Studies

The following case studies document the implementation of BIM in two different types of commercial projects. Specific examples of using BIM facilitating MEP coordination in Modular Construction are discussed as well. The project and owners name are anonymous for confidentiality purpose. The construction manager was Rogers Builders, headquartered at Charlotte, NC. The company has over 350 associates and nationally ranked among Top 100 CM-at-Risk firm by Engineering News Record (ENR) and Top 10 Healthcare General Contractors by Modern Healthcare for the last 10 Consecutive years. The company has implemented BIM system for every project they have built since 2007, with no premium cost to the owner side. Rogers Builders maintain that the cost for development and maintenance of BIM model with in-house resources is controlled at 0.1% of total project cost.

Case Study 1: Healthcare Expansion Project, Charlotte, North Carolina, USA

Project Scope: $44Million, 110,000 SF healthcare expansion project
Modular Construction: prefabricated concrete panels are used for floor slab
Delivery Methods: CM @ Risk
Contract Type: Cost Plus with Guaranteed Maximum Price

Design Assistant: No Design Involvement
BIM Implementation Cost: $44000
BIM Implementation Saving: $220,000
BIM Platform: Naviswork™



(a) Structural BIM Model (b) Architecture BIM Model (C) MEP BIM Model

Figure 3 BIM Models in Healthcare Expansion Project
(Courtesy of: Rogers Builders, Charlotte, NC, USA)

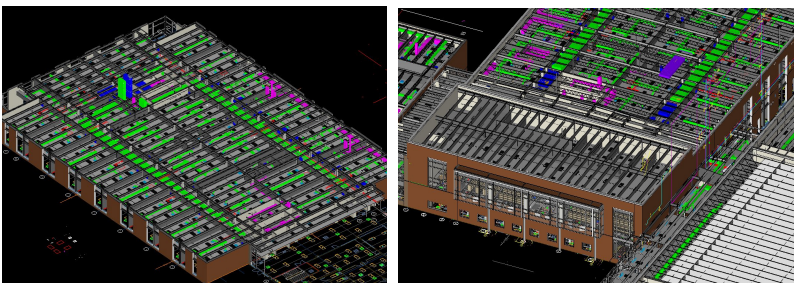
For this project, the BIM model produced architecture, structural systems and MEP systems. It was developed to provide a dynamic platform for inter-disciplinary collaborations as presented in Figure 3. Through the entire project management phase, Roger Builders used the BIM models for cost engineering, subcontractor buyout, MEP coordination and clash detection. The specific benefits have been identified by using BIM model in this project includes:

- Clearly defined subcontractor's work scope
- Automatic quantity extraction of structural steel and major MEP systems
- Facilitate shop drawing of structural steel and MEP systems
- 560 clash conflicts between MEP systems and the structural systems were identified prior to the fabrication of the MEP and structural systems

Case Study 2: High School Project, Gastonia, North Carolina, US

Project Scope: $38 Million, 220,000 SF High School Project
Modular Construction: Prefabricated classroom with rough-in MEP installation
Delivery Methods: Design- Build
Contract Type: Cost Plus with Guaranteed Maximum Price
Design Assistant: Extensive Design Involvement
BIM Implementation Cost: $38000
BIM Implementation Saving: N/A
BIM Platform: Naviswork™

A comprehensive BIM model with overlapped architecture, structural, MEP model has been created by Rogers Builders BIM specialists at the design phase of the project, as presented in Figure 4.The BIM model was used extensively for design coordination, subcontractor work scope clarifications, cost engineering, MEP coordination and project sequencing.



(a) 1st Floor BIM Model (b) 2nd Floor BIM Model

Figure 4 High School B Project BIM Model
(Courtesy of: Rogers Builders, Charlotte, NC, USA)

All MEP coordination was conducted through the BIM platform. It is very beneficial to have fully integrated architecture, structural systems, and MEP systems in single 3D file, which reduces change for human error and provides a visual check for interferences for clash detections. By using the BIM model for this project, 258 conflicts were identified and eliminated during the design phase, as presented in Figure 5 and Figure 6. Each classroom module was accurately manufactured offsite with rough-in plumbing pipes and electrical conduits installed. The finishing MEP and furnishing process began after the installation of each classroom module.

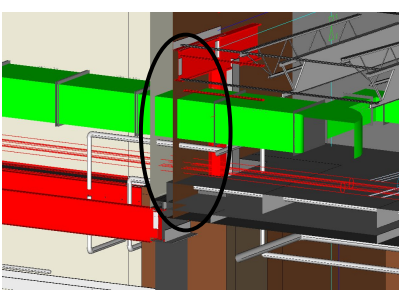


Figure 5 Ductwork Conflicts Structural Steels



Figure 6 Ductwork conflicts with Bar Joists

(Picture Courtesy: Rogers Builders, Charlotte, NC, USA)

Through these case studies, the researchers identified that the most effective use of BIM models was for design coordination, walk-through animation and clash detections. This was more so for modular construction project which requires extensive design coordination especially for MEP systems.

The greatest challenge of using BIM in construction project is the implementation process itself, regardless of the software capabilities. Development of accurate BIM model requires extensive resources and in-depth knowledge of construction methods and process. Most small or medium firm could not afford the special team and man-

hours to aligning BIM, as Rogers Builders employs several in-house BIM specialists to develop, maintain and operate BIM models for each project. A dual system of AutoCAD™ and BIM system functioning at same project is another major challenge of BIM implementation. Construction managers normally need to spend tremendous time and man hours to educate major subcontractors, materials suppliers and even some architecture firms to integrate BIM systems into their work platform.

Other than finance and organizational issues, the project team has experienced legal challenges as well. The use of BIM technology encourages multi-disciplinary collaboration, which contrasts to defining responsibility to each party and then assigning liability issues among the parties. In addition, using BIM models instead of traditional contract documents raises questions on insurance coverage and confidentiality exposure. Ownership and control of the model, use and distribution of the model, and intellectual property rights are some of the issues that need to be addressed while BIM implementation being adopted in construction industry.

Conclusion

The current construction delivery model does not support modular construction techniques due to extensive project planning and MEP coordination involved, even though modular building technologies offer tremendous advantages to the construction industry. With the increased integration of BIM in construction project, incorporating modular building technologies into project becomes more effective and desirable because the entire planning, design, shop drawings development, manufacturing and construction process could be streamlined. Physical conflicts between the structure, mechanical, electrical and plumbing systems can be easily identified early in the design process and resolution is expedited and the building trades are not restricted to only relying on paper plans and written specifications. Further research is suggested to focus on the organizational and legal issues evolved with implementing BIM models in construction projects.

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Improved Procedures for Business Accommodation on Transportation Construction Projects

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Abstract
Highway construction projects have direct impacts on adjacent businesses. The nature and the degree of impact depend on individual business characterization and project specific factors. The type of business is also a relevant factor in predicting the impact of transportation construction projects. This paper presents the results of research focused on developing an in-depth understanding of these relationships. The study includes project case studies of three transportation construction projects in Florida. Surveys were conducted with all adjacent businesses, which were combined with analyses of the business accommodation procedures employed by State Highway Agencies (SHAs) nationwide to provide measure the efficiency of present rules. The results include an analysis of differing priorities for different classification of businesses and development of design and construction management best practices to better accommodate businesses during highway construction. A pilot project that employed business accommodation principles devised in this research, and improvements to business accommodations observed were compared to cases where no measures were taken.

Introduction

A common theme with both the national and state level highway agencies strategic plans is the reduction of traffic congestion though improvements to our transportation infrastructure. Implementation of renewal and enhancements projects ultimately involves construction. However, construction operations are also a source of congestion, adversely impacting traffic. Consequently, a great deal of attention is given to construction related traffic congestion. A significant body of research exists focusing specifically on predicting and managing work zone caused congestion. Traffic Control Plans are now specifically designed to provide for efficient and safe passage of motorist through and around construction work zones.

The reality is that adjacent businesses are also affected by highway construction operations. Highway construction can cause significant economic loss to local businesses. A survey of businesses conducted of businesses adjacent to Reconstruction of the Dallas North Central Expressway Texas found that impact to businesses during construction was substantial, but offset by economic improvement post project (Harrison and Waldman 1998). A survey of businesses adjacent to the Widening of State Highway TX-21 in Texas, found that 52% of the businesses reported a decline in sales during the construction period (Wildenthal and Buffington 1996). Current design and construction procedures attempt to address business concerns to varying degrees. Access to businesses is recognized as a critical need. However, the subject of Business Accommodation is a relatively new and complex area. A preliminary analysis of the subject suggests that different types of businesses have different concerns with regard to the impact of adjacent highway construction operations. All business problems may not be solved by simply providing motorist access from the through traffic lanes in the work zone. More information is needed concerning the specific needs of different types of businesses with regard to adjacent highway construction operations. Given an increased understanding of business requirements, strategies are needed for accommodating business needs during construction. The objective of this study was to develop an in-depth understanding of the needs of adjacent businesses during highway construction and to develop strategies for accommodating those businesses needs.

Data Collection

The primary data collection approach in this study was to obtain information directly from businesses located on highways which were under construction in Florida. Business input was obtained through one-on-one interviews with business managers. The information obtained was analyzed and the resulting synthesis produced common themes and needs. Given the definition of business needs, strategies for improving business accommodation were developed (Ellis and Washburn 2005). In order to test the developed strategies, a pilot project was conducted. The same business survey format used in data collection stage was used to assess the benefits of implementing the proposed strategies.

Project A: The project included widening San Jose Blvd., Jacksonville, Florida from 4 to 6 lanes, adding new sidewalks throughout the project area, providing right turn lanes in both directions,
and building four foot bike lanes. The project was estimated to take 2.5 years to complete at a cost of $11.7 million. This was not a limited access roadway, therefore business accesses were located along the length of the roadway.

Project B: Project included widening Mahan Drive, Tallahassee, Florida from two lanes to four lanes with a median and left turn access points. The project included improved drainage structures, added bike lanes, and installation of a new traffic signal. The total cost of the project was estimated at 5.1 million dollars and construction time was estimated at 20 months.

Interviews with Business Managers

Multiple visits to the businesses along the roadway projects were accompanied with interviews with business managers about their experience with the current construction project were completed. The interview format used was simple yet structured surveys. Managers were asked to provide an opinion of the project activity overall, and were then asked to provide their comments. The advantage of this face to face process was that the research was able to achieve a 96% response rate with a total of 77 business mangers.

Table 1 provides the results of the interviews with business managers on Project A & B. Possible issues related to businesses were determined studying the project characteristics and physical requirements stemming from surrounding environments in order to complete projects successfully. 75% of the businesses around Project A stated that they believe the project had a negative impact on their businesses. The most common complaint was lack of business access to survey participants respective their businesses. The second most outstanding issue was the traffic congestion caused by construction activities, which in participants' opinion caused their potential customers to take alternative routes. It should be noted that our interview team found many of the adjacent businesses were either temporarily or permanently closed due to ongoing construction projects. This appears to support the reduction in sales of from 10% to 25% reported by several of the businesses.

Similar to survey results of Project A, survey results of Project B indicated major dissatisfaction of the business owners with the project. 66.7% of the participants stated that the project had a negative impact on their business. The most outstanding problem was, again, determined to be the lack of business access. The second most common complaint was the traffic congestion caused by the construction, which in participants' opinion caused their potential customers to take alternative routes. However, no closed businesses were found around Project B.

Table 1 Survey results with business managers on Projects A & B

Issues	**Project A**	**Project B**
Extended project schedule	16.7%	0.0%
Business access	54.2%	33.3%
Traffic congestion	25.0%	11.1%
Poor communication between businesses and construction professionals	20.8%	16.7%
Utility shortages without notice	16.7%	5.6%
No business signs directing customers to businesses	12.5%	5.6%
Overall impact of the Project		
Positive	4.2%	8.3%
Neutral	20.8%	22.2%
Negative	**75.0%**	**66.7%**

Survey Findings

Clearly, businesses were not happy with the experience of having the roadway on which they are adjacent under construction. Most of their concerns were related directly to project features, which were perceived to affect their sales. Access from the roadway to their respective businesses was determined to be the most outstanding issue. Both project A and B were performed with similar approaches to business accommodation. Community information meetings were held prior to the start of each project. However, communication with businesses during construction generally had to be initiated by business owners. Access to businesses was not a contract requirement, but was a secondary consideration during construction and traffic control plan phasing requirements resulted in significant congestion at times during construction. Figure 1 provides a photograph of a poor access situation on one of the projects. The business access entrance is not visible to the approaching traffic.



Figure 1. Photograph of a typical poor business access

Following summarizes the critical accommodation issues for businesses interviewed:

- Access for vehicle and pedestrian traffic to their business during construction
- Communications between project management and business managers
- Traffic congestion adjacent to the business, which may cause potential customers to take alternative routes
- Utility outages
- Business signs temporarily located in the right of way to guide customers

Understanding Individual Business Characteristics

In the past construction managers have tended to consider grouping all businesses together assuming that they all have same project related issues. Research in this

study indicates that this is not the case. Different types of businesses have significantly different accommodation needs.

Impulse Businesses: Impulse retail businesses depend on customers that visit their businesses when they see them and have the impulse to buy. These are the typical drive-by type retail businesses. Fast food restaurants such as McDonalds are good examples. Visibility to drive by customers is a critical issue for these businesses. Customers are likely to find identical services at other businesses in adjacent areas. Therefore, difficult access and congestion may encourage customers to avoid the project location. This category of business is particularly sensitive to access and congestion management.

Destination Businesses: Destination businesses have an established customer base. Customers return because they have an established relationship with the business, or the business offers a unique product or service so that customers will seek them out. An example of a destination business would be a rental car agency location. Customers visit because they have made previous appointments. The road construction is an annoyance but not a deterrent. Consider the following comment obtained from the study interviews:

Dian Ivory Photographic Studio – "Our customers are loyal mothers who have scheduled their appointments weeks in advance to have their babies photographed, therefore, nothing is going to stop them from keeping their appointments."

Visibility is not a major issue for destination businesses, but they do need access for their customers.

Seasonal Businesses: Most retail businesses achieve a significant portion of their annual sales during the holiday season. Given the option, most would prefer not to have their sales disturbed during this period. Other examples of seasonal businesses also exist. For example, income tax preparation services. One of the surveyed businesses was a florist that had their utilities turned off on the day before Valentine's Day.

Nighttime Businesses: Businesses that are open predominantly at night have a completely different relationship with the construction activities, which are predominantly in the day time. Nighttime businesses are not disrupted by the work activity.

Preliminary Development of Business Accommodation Strategies

Given the understanding accommodation needs acquired in the study survey phase, strategies for mitigating the negative impacts of construction were developed. The most important strategies are discussed in this section.

Communications with Businesses

- *Development of a Project Web Site*: Project websites can provide excellent visual tools for communicating the scope of the completed project, and up to date scheduling information.
- *Development of a Pre-Construction Business Inventory*: Prior to construction, businesses needs are to be identified, contact information of owners needs to be verified, and businesses should be categorized with respect to their specific accommodation needs. This inventory should be handed off to project personnel who can employ this tool in maintaining communication with businesses during construction.
- *Conduct Routine Visits to Businesses*: Regular business visits as well as when special situation visits can improve the much needed communication among parties.

Access Management

Access management issues must be considered during the design phase of the Traffic Control Plan. Additionally, maintaining business access must be made a contractor requirement by including a clause within the project documentation. State Highway Agency project engineers must monitor and enforce access issues during construction. Access for nighttime deliveries must also be considered. For example, restaurants like McDonalds receive their food deliveries at night by semi-trailer. An access that would accommodate their retail customers may not be adequate for their deliveries.

Congestion Mitigation

Traffic Control Plans should be predicated on a comprehensive traffic study of the affected area. While traffic plans have traditionally focused on maintaining flow through the project, it is also important to consider the roadway corridor functions. In addition to intersection evaluations, turning movement counts at drive ways and median openings should be collected. Use of on-street parking, which may be affected by construction, should be noted.

Business Signage

As noted in the survey results, many businesses have been significantly affected by their visibility to drive by customers. Construction site operations can reduce or prevent drivers from seeing the signs of businesses. Temporarily mounting business entrance signs at access points improve driver awareness of specific businesses along the construction corridor.

Utility Outage Coordination

Management of this issue simply requires basic common sense project management. Notices of outages are coordinated with businesses at least 48 hours in advance. To the extent possible outages are not scheduled during business hours.

Implementing the Findings via the Pilot Project

Given the preliminary strategies developed in the preceding study phase a sample project was used to determine the effect of the accommodation strategies on business satisfaction. The project was a typical widening project similar in scope and business

composition to the two projects previously studied. Survey input was obtained through one-on-one interviews with business managers as used previously on the projects in the initial phase.

Pilot Project Description: The project included widening of SR 121, Macclenny, FL with a length of approximately 1.6 miles. The project was estimated to require 400 days to complete with a cost of $5.8. The project consisted of SR 121 from I-10 to just south of US 90 and SR 228 from South Boulevard to just north of McIver Street, approximately 1.6 miles. The total cost of the project was $5.8 million. The scope of work included widening the road, adding a turning lane, reconstructing a bridge on the project, improving drainage structures, and resurfacing the road. This was not a limited access roadway; therefore business accesses were located along the length of the roadway. Perhaps the most significant difference in the project management approach taken in this project was that, business accommodation measures were adopted as a project priority by the SHA team and by the contractor. The following unique business accommodation measures were implemented on the project:

- A dedicated Public Information Office was assigned to the project.
- A comprehensive inventory of businesses was developed prior to construction.
- A project website was developed prior to construction.
- Weekly visits were made to businesses and managers were given contact information for key project management personnel.
- Business access and congestion management was a consideration in the design of the Traffic Control Plan (modifications were made during construction as needed).
- The requirement to maintain business access was included in the contractor's scope of work.
- A specification for temporary business signs was developed and implemented.
- Utility outages were scheduled in advance with business managers.

Findings from the Pilot Project

Table 2 provides the results of the interviews with business managers on the Pilot Project. The surveys used were essentially the same as the ones used to collect data on the two former projects. The improvements to businesses functioning were apparent after implementing the benchmark measures proposed by the research team. Favorable opinions rose to 45.8%. Level of Communication among parties was significantly improved (There were no reported issues with communications). Business access was again the most outstanding issue for adjacent businesses; however, improvements over the two earlier projects were apparent. There were no instances where access was not available; it just was not as easy as it was prior to construction. Traffic congestion problem was also mitigated. There were no reported issues with utility outages. Figure 2 provides a photo of a business access and sign in place. The specification was revised subsequent to the project to require pole mounting of the signs.

Note that, the business access and traffic congestion are generally dictated by the physical characteristics of the project and the construction site layout. Regardless of the efforts given to eliminate these effects, it is not possible to eliminate all the problems. However, the other major issues (mainly communication based problems) were addressed successfully.

Table 2. Survey results of the Pilot Project

Issues	**Pilot Project**
Extended project schedule	0.0%
Business access	22.9%
Traffic congestion	14.3%
Poor communication between businesses and construction professionals	0.0%
Utility shortages without notice	0.0%
No business signs directing customers to businesses	0.0%
Overall impact of the Project	
Positive	45.8%
Neutral	14.3%
Negative	**54.3%**



Figure 2. Photograph of a typical temporary business entrance sign

Conclusions and Recommendations

Research has shown that adjacent highway construction can negatively impact businesses. Businesses in this study reported a 5% to 25% decline in revenue during the construction project.

While it can be argued that business will improve after the roadway improvement is complete, many small businesses cannot survive until the project is complete. Especially in these economic conditions, it is essential that highway construction agencies develop engineering and business practices to embrace business accommodation on their projects.

This study has indentified critical business accommodation needs for businesses adjacent to highway construction projects. Additionally, this study has suggested at least a preliminary understanding of how the characteristics of different businesses affect their accommodation needs. Specific business accommodation measures were developed to satisfy the identified business needs. These measures were implemented in a trial project resulting in significant improvements in business satisfaction with the project.

Future Research

With regard to work zone traffic control plans the Manual for Uniform Traffic Devices provides that "*The needs and control of all road users … shall be an essential part of highway construction, utility work, maintenance operations, and the management of traffic incidents.*" (FHWA 2003). Applicability of similar national standards development approach to business accommodation should be analyzed as a viable alternative to current practices.

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Modeling Cash Flow Profiles with Singularity Functions

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Abstract
The ability to plan and manage cash flows is critical for the survival and long-term economic success of construction contractors. Profiles arise from the interplay of outflows, e.g. labor, equipment, and materials, and inflows, e.g. progress payments less retainage, which very in frequency and are subject to payment terms. Their complex zigzag shape was previously only modeled with simplifications. Approaches included discrete values at specific points in time; averaged S-curves, e.g. from regression; or envelopes of extreme values. Yet neither is suited for cumulative costs of variable schedule activities. This paper therefore describes how cash flow profiles can be flexibly and accurately modeled with singularity functions, which originated in structural engineering. Their components define ranges of behavior between cutoff values. Emphasis is placed on expressing common payment terms, which are illustrated with an example that is validated with the literature. This new approach augments project planning toward an integrated model.

Introduction
The success of construction contractors relies upon sound financial management of their portfolio of projects. While profits or losses materialize in the balance sheet only at completion of a project, cash is a tangible and depletable (yet reversible) resource whose scarcity can cause disruptions or even the eventual bankruptcy of a firm. Cash is thus considered the most important element within construction projects (Hwee and Tiong 2001). The complex behavior of cash flows arises from an interplay of many transactions that depend on time, events, or prior costs. Forecasting and managing them therefore requires proper models and tools. Building upon previous work on analyzing linear schedules (Lucko 2009), this paper presents a new approach to accurately represent cash flows while also facilitating an intuitive understanding.

Importance of Cash Flows
Careful "cash flow management is critical… to the heart of the financial viability of a construction company" (Kenley 2003, p. 162). "The prudent contractor therefore... takes the cash flow issue very seriously" (Touran *et al.* 2004, p. 719), as obtaining a

bank loan can be difficult for a risky business like construction. Capital enables the vital debt-to-income ratio, which is indispensable to achieve profitability (Chen *et al.* 2005). Its lack may even lead to eventual bankruptcy (Harris and McCaffer 2001).

Previous Limitations

Previous studies faced the challenge of the "'sawtooth' effect [that] is very difficult to model. It is quite suitable for representing real data, but for any form of modelling, forecasting or simulation it cannot be represented" (Kenley 2003, p. 168). Oscillating cash inflows and outflows thus were simplified as discrete values (Khosrowshahi and Kaka 2007), empirical averaged S-curves (Park *et al.* 2005) without peaks, which was deemed inaccurate (Kaka and Evans 1998), or envelopes (Hwee and Tiong 2001).
"Due to a lack of accurate prediction models… [Texas DOT] usually estimates payments as uniform distributions over the project duration" (Jarrah *et al.* 2007, p. 235). Complexity also stems from variable cash flows occurring at either the activity, project/program, or company levels (Navon 1996) and complicates optimizing them.

Analytical Approach

Singularity functions offer an elegant way to model and analyze complex phenomena. Used in structural analysis, they alleviated the need to solve many separate equations and boundary conditions and instead expressed the entire scenario with one equation of connected ranges that start wherever any variable of interest changes its behavior.

Definition of Singularity Functions

Singularity functions are range-based and contain at least one basic term of Eq. 1. Its pointed bracket operator is a case distinction that 'activates' it only from *a* onward.

$$y(x)=s\cdot\langle x-a\rangle^{n}=\begin{cases}0 \text{ for } x<a\\ s\cdot(x-a)^{n} \text{ for } x\geq a\end{cases} \qquad \textbf{Eq. 1}$$

where x is the independent variable on the horizontal axis, y is the dependent variable on the vertical axis, a is the cutoff x-value, n is the order of the curve segment that is modeled, and s is a scaling factor. Thus e.g. $n = 0$ is a step with constant height s at a and $n = 1$ a ramp with slope s from a. For example, a linear equation $y(x) = m \cdot x + b$ of slope m from intercept b gives the singularity function $y(x) = b \cdot \langle x - 0\rangle^{0} + m \cdot \langle x - 0\rangle^{1}$ with two terms that separately model the initial intercept and subsequent slope.

Superposition Principle

It is possible to describe any complex shape by additive *superposition* in analogy to structural analysis that modeled e.g. several point and distributed loads along a beam. An unlimited number of basic terms of Eq. 1 can be included in one singularity function. Modeling such complex shape divides its geometry into a group of range segments of basic behaviors. For illustration, the low-complexity shape of Figure 1 is modeled explicitly by Eq. 2. Any higher order terms could be included analogously.

$$y(x)=1\cdot\langle x-0\rangle^{0}+\frac{1}{1}\cdot\langle x-0\rangle^{1}-\frac{1}{1}\cdot\langle x-1\rangle^{1}-1\cdot\langle x-2\rangle^{0}-\frac{1}{2}\cdot\langle x-2\rangle^{1} \qquad \textbf{Eq. 2}$$

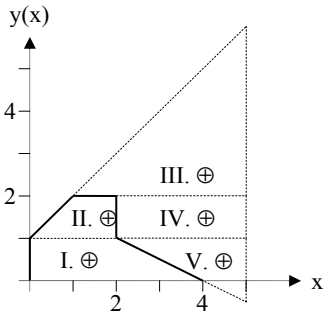


Figure 1: Shape Modeled with Singularity Function

The edge of a shape, shown as a thick solid line, is composed by adding several areas whose borders are shown as dashed thin lines. The signs in Figure 1 indicate positive and negative areas, i.e. added upward or downward on the *y*-axis. Horizontal stripe I is added first, then triangle II. Triangle III, horizontal stripe IV, and triangle V are subtracted. These five areas match with the five basic terms of Eq. 2. The height in the *y*-direction is always correct, even if basic terms with the same *a* are switched, e.g. if triangle II were added before stripe I. The dashed rightmost edge indicates that from their cutoffs *a* onward all basic terms remain active until infinity on the *x*-axis.

Simplification of Terms and Sorting

Eq. 1 acts like an off-on switch and singularity functions are evaluated *cumulatively*. The further one moves into the positive *x*-direction the more terms become active. Note that basic terms contribute *changes* to the behavior of the overall singularity function. Several basic terms *i* can be *simplified* using Eq. 3 into one term by adding their s_i if – and only if – they have identical values of their cutoff *a* and exponent *n*.

$$s_1 \cdot \langle x-a \rangle^n + s_2 \cdot \langle x-a \rangle^n = (s_1 + s_2) \cdot \langle x-a \rangle^n \qquad \textbf{Eq. 3}$$

Despite their name, singularity functions are right continuous and defined at all *x*-values (or fall to zero). They can be differentiated and integrated normally (Lucko 2009). For clarity and ease of the manual calculations, it is much recommended that all basic terms are sorted from left to right by their *x*-value and within that by their *n*.

Cash Outflows

Expenses, or cash outflows from the viewpoint of a contractor, are incurred for every line item, e.g. to pay labor, rent equipment, purchase materials, and cover overhead of the contracting firm. As in most models (Elazouni and Metwally 2005), costs in this paper are assumed to be simplified as growing linearly for each activity individually, but could also consist of many small transactions. Such growing cash outflows can be modeled as one singularity function per activity, plus one function that describes any non-activity costs, e.g. overhead. The rate at which money is spent over time becomes

their 'cost slope.' For a more detailed model the individual costs can be modeled with Eq. 2. Each expense would be one basic term of Eq. 1. Both such models, linear outflows or the detailed stepped outflows, require that a final change term is included, which deducts all previously accumulated costs again if fluctuations over time are of interest (in analogy to a density function) instead of only the cumulative total cost.
Additional cash outflows occur from financing interest that is assessed by the lender in regular intervals of integer time units, e.g. months and is applied directly *after* the end of each period. A new variable ε is introduced to correctly model this minute increment of time, which is set to an infinitesimally short duration. Otherwise, the singularity function for interest would incur a logical impossibility of having to evaluate the overdraft at the same point in time at which the interest itself is added.

Cash Inflows

Contractors add profit on their bills to the owner. Assuming that profit is applied evenly to all cash outflows, they are multiplied by a factor of $1 + p$, where p is the profit percentage. Otherwise, each type of costs could have a different value for p.
Bills, i.e. requests for progress payments, extend a payment period to the owner that ends with the due date. Unless early payment discounts are offered, owners will often seek to pay bills as late as possible to continue earning interest on their cash holdings. Such *billing-to-payment-delay b* is modeled by adding b to each billing date in the singularity function. Contractors must bear expenses for extended durations that can reach 90 days (Setzer 2009) and require financing. Such delays result from 'pay when paid' (Blyth and Kaka 1999) provisions. They especially affect subcontractors, who accumulate their expenses into a bill to the general contractor, who bills the owner, who in turn sends the payment less a retainage to the general contractor at the end of the contractually permissible payment period, and it is finally passed on downward.
Payments, or cash inflows from the viewpoint of a contractor, are received at a steady frequency whereas outflows grow continuously. Expenses must be aggregated into an individual regular payments that are (a) delayed by b, (b) reduced by the retainage if such is withheld, and (c) are stepped at each period. These modeling objectives can be accomplished with *floor and ceiling functions*. They were defined by Iverson (1962) for a programming language that used the operators and to round a real number downward or upward to integers. For modeling cash inflows, is applied to the time variable of the singularity function. Deducting them from the cumulative total of cash inflows and outflows ensures that the correct expenses are billed after each period.
A *retainage r* of 5% to 10% of the bill is typically withheld by the owner to provide an incentive for the contractor to finish the work. It is released only after substantial completion (Touran *et al.* 2004), which burdens subcontractors beyond their own portion of the work. It is modeled by setting up two singularity functions, one of $1 - r$ while retainage is withheld and another one of r to give the retained amount itself.

Cash Flow Example

The example of Figure 2, analyzed by Halpin and Woodhead (1998) in tabular form, illustrates how to model cash flows. Table 1 summarizes the activity dates and their unit costs. It assumes $p = 25\%$ profit on all costs and $r = 10\%$ retainage until the project exceeds $125,000 in value and is released with the final payment. Overhead is

$5,000 monthly (dashed line). The billing delay *b* is one month, shown as arrows. It causes a lag in Figure 2 between the outflow (without and with profit, upper solid and dotted lines) and stepped inflow curve, whose difference is also shown below the time axis. The vertical *z*-axis for cost and a horizontal *y*-axis for time are consistent with linear schedule analysis (Lucko 2009). The interest *i* is "1% per month for the amount of the overdraft at the end of the month" (Halpin and Woodhead 1998, p. 123). The model for the costs of each activity plus overhead creates five equations. Only Eq. 4 of activity *A* is shown for brevity. Its costs are added from its start and then subtracted again at its finish; otherwise they would continue to accrue until infinity on the *y*-axis.

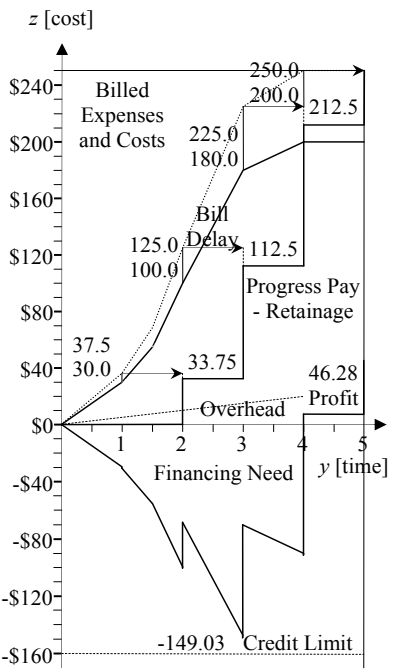


Figure 2: Cash Flow Example (Halpin and Woodhead 1998)

Table 1: Activity List for Cash Flow Example (Halpin and Woodhead 1998)

Activity	Duration	Start	Finish	Total Cost	Unit Cost
A	2.0 mo.	0.0 mo.	2.0 mo.	$50,000	$25,000/mo.
B	2.0 mo.	1.0 mo.	3.0 mo	$40,000	$20,000/mo.
C	1.5 mo.	1.5 mo.	3.0 mo.	$60,000	$40,000/mo.
D	2.0 mo.	2.0 mo.	4.0 mo.	$30,000	$15,000/mo.
Overhead	4.0 mo.	0.0 mo.	4.0 mo.	$20,000	$5,000/mo.

$$z(y)_A = \$0 \cdot \langle y - 0\,mo. \rangle^0 + \frac{\$25{,}000}{1\,mo.} \cdot \langle y - 0\,mo. \rangle^1 - \frac{\$25{,}000}{1\,mo.} \cdot \langle y - 2\,mo. \rangle^1 \quad \textbf{Eq. 4}$$

The total costs without profit are given by the superposed and simplified Eq. 5, which is the upper solid line in Figure 2. Multiplying it by 1.25 gives the costs with profit.

$$z(y)_{cost+OH} = \$0 \cdot \langle y - 0\,mo. \rangle^0 + \frac{\$30{,}000}{1\,mo.} \cdot \langle y - 0\,mo. \rangle^1 + \frac{\$20{,}000}{1\,mo.} \cdot \langle y - 1\,mo. \rangle^1 + \frac{\$40{,}000}{1\,mo.} \cdot \langle y - 1.5\,mo. \rangle^1$$
$$- \frac{\$10{,}000}{1\,mo.} \cdot \langle y - 2\,mo. \rangle^1 - \frac{\$60{,}000}{1\,mo.} \cdot \langle y - 3\,mo. \rangle^1 - \frac{\$20{,}000}{1\,mo.} \cdot \langle y - 4\,mo. \rangle^1 \quad \textbf{Eq. 5}$$

Billing

For brevity, the zero intercepts in Eqs. 4 and 5 will be omitted in further calculations. Billing equations for *A* and other activities plus overhead are derived by inserting the floor operator into Eq. 4 to give Eq. 6, which breaks the linear growth into steps.

$$z(y)_{A,bill} = \frac{\$25{,}000}{1\,mo.} \cdot \langle \lfloor y \rfloor - 0\,mo. \rangle^1 - \frac{\$25{,}000}{1\,mo.} \cdot \langle \lfloor y \rfloor - 2\,mo. \rangle^1 \quad \textbf{Eq. 6}$$

Adding the individual singularity functions like Eq. 6 gives the total billed costs of Eq. 7, which steps up at the end of each month. Converting Eq. 7 into stepped form with exponent $n = 0$, shifting the cutoff a by one period from expenses that grow from the start of each period to their billing that occurs at the end of that same period, and multiplying it by $1 + p = 1.25$ gives the billed costs with profit of Eq. 8. *C* that starts only at 1.5 months is automatically correctly incorporated into the subsequent bill.

$$z(y)_{cost+OH} = \frac{\$30{,}000}{1\,mo.} \cdot \langle \lfloor y \rfloor - 0\,mo. \rangle^1 + \frac{\$20{,}000}{1\,mo.} \cdot \langle \lfloor y \rfloor - 1\,mo. \rangle^1 + \frac{\$40{,}000}{1\,mo.} \cdot \langle \lfloor y \rfloor - 1.5\,mo. \rangle^1$$
$$- \frac{\$10{,}000}{1\,mo.} \cdot \langle \lfloor y \rfloor - 2\,mo. \rangle^1 - \frac{\$60{,}000}{1\,mo.} \cdot \langle \lfloor y \rfloor - 3\,mo. \rangle^1 - \frac{\$20{,}000}{1\,mo.} \cdot \langle \lfloor y \rfloor - 4\,mo. \rangle^1 \quad \textbf{Eq. 7}$$

$$z(y)_{cost+OH,\,profit,\,bill} = \$37{,}500 \cdot \langle y - 1\,mo. \rangle^0 + \$87{,}500 \cdot \langle y - 2\,mo. \rangle^0 + \$100{,}000 \cdot \langle y - 3\,mo. \rangle^0$$
$$+ \$25{,}000 \cdot \langle y - 4\,mo. \rangle^0 \quad \textbf{Eq. 8}$$

Payment

It is found that the retainage of 10% is applied until including 2 months, whereafter $125,000 of value is exceeded and the full 100% of the billed costs with profit are paid. Eqs. 9 and 10 model the factors for the payment less retainage and the retained amount that is released in the final payment and are applied to the billed costs of Eq. 7. One time period is added to the cutoff *a* of their second term for the billing delay *b*.

$$z(y)_{less\ retainage} = (1 - 0.1) \cdot \langle y - 0\,mo. \rangle^0 + 0.1 \cdot \langle y - (2\,mo. + 1\,mo.) \rangle^0 \quad \textbf{Eq. 9}$$

$$z(y)_{retained\ amount} = 0.1 \cdot \langle y - 0\,mo. \rangle^0 - 0.1 \cdot \langle y - (2\,mo. + 1\,mo.) \rangle^0 \quad \textbf{Eq. 10}$$

The multiplication of a singularity function for payments multiplied by the retainage function of Eq. 9 uses the operator $\otimes$, which *modifies* the multiplication of Eq. 11 in that the result is not a single value, but a modified singularity function for payments. In other words, only half of all pairwise terms within the multiplication are executed.

$$\begin{aligned}&\left((1-0.1)\cdot\langle y-0\,mo.\rangle^0 + 0.1\cdot\langle y-(2\,mo.+1\,mo.)\rangle^0\right)\otimes\left(\$37{,}500\cdot\langle y-(1\,mo.+1\,mo.)\rangle^0 + \$87{,}500\right.\\ &\left.\cdot\langle y-(2\,mo.+1\,mo.)\rangle^0 + \$100{,}000\cdot\langle y-(3\,mo.+1\,mo.)\rangle^0 + \$25{,}000\cdot\langle y-(4\,mo.+1\,mo.)\rangle^0\right) = \$33{,}750\\ &\cdot\langle y-2\,mo.\rangle^0 + \$78{,}750\cdot\langle y-3\,mo.\rangle^0 + \$100{,}000\cdot\langle y-4\,mo.\rangle^0 + \$25{,}000\cdot\langle y-5\,mo.\rangle^0 \quad \textbf{Eq. 11}\end{aligned}$$

Evaluating Eq. 11 with a regular multiplication operator *after* the final payment date at $y_{max} + b + 1$ mo. = 6 mo. gives (0.9 + 0) · \$37,500 · 1 + (0.9 + 0) · \$87,500 · 1 + (0.9 + 0.1) · \$100,000 · 1 + (0.9 + 0.1) · \$25,000 = \$237,500 as the total payments less retainage. Since the singularity function for payments multiplied by the retained amount function of Eq. 10 is a numerical value, the multiplication operator of Eq. 12 is unmodified. This dollar value is finally released at the time $y_{end} = y_{max} + b = 5$ mo. Eq. 13 finally gives the total cash flows before the terms for the interest i are added. Note that profit is left out of all of the expense terms, as it need not be financed itself and that the duration ε is added to all payment dates to facilitate calculating interest.

$$\begin{aligned}&\left(0.1\cdot\langle y-0\,mo.\rangle^0 - 0.1\cdot\langle y-(2\,mo.+1\,mo.)\rangle^0\right)\cdot\left(\$37{,}500\cdot\langle y-(1\,mo.+1\,mo.)\rangle^0 + \$87{,}500\right.\\ &\left.\cdot\langle y-(2\,mo.+1\,mo.)\rangle^0 + \$100{,}000\cdot\langle y-(3\,mo.+1\,mo.)\rangle^0 + \$25{,}000\cdot\langle y-(4\,mo.+1\,mo.)\rangle^0\right) = (0.1-0)\\ &\cdot\$37{,}500\cdot 1 + (0.1-0)\cdot\$87{,}500\cdot 1 + (0.1-0.1)\cdot\$100{,}000\cdot 1 + (0.1-0.1)\cdot\$25{,}000\cdot 1 = \$12{,}500\end{aligned}$$

Eq. 12

$$\begin{aligned}z(y)_{cash\ flows} &= \frac{\$30{,}000}{1\,mo.}\cdot\langle y-0\,mo.\rangle^1 + \frac{\$20{,}000}{1\,mo.}\cdot\langle y-1\,mo.\rangle^1 + \frac{\$40{,}000}{1\,mo.}\cdot\langle y-1.5\,mo.\rangle^1 - \$33{,}750\\ &\cdot\langle y-(2\,mo.+\varepsilon)\rangle^0 - \frac{\$10{,}000}{1\,mo.}\cdot\langle y-2\,mo.\rangle^1 - \$78{,}750\cdot\langle y-(3\,mo.+\varepsilon)\rangle^0 - \frac{\$60{,}000}{1\,mo.}\cdot\langle y-3\,mo.\rangle^1\\ &- \$100{,}000\cdot\langle y-(4\,mo.+\varepsilon)\rangle^0 - \frac{\$20{,}000}{1\,mo.}\cdot\langle y-4\,mo.\rangle^1 - (\$25{,}000+\$12{,}500)\cdot\langle y-(5\,mo.+\varepsilon)\rangle^0\end{aligned}$$

Eq. 13

Interest

Financing interest that is added to the overdraft balance is more complex to model than continuous expenses or periodic payments due to its compounding nature, i.e. any interest draws interest itself, which causes the singularity function that includes interest to become *self-referential* to earlier points in time. Again the aforementioned duration ε ensures that interest is charged directly *after* when the overdraft balance is assessed. Since variations in the overdraft balance are caused by (but also enable)

when the schedule activities occur, creating a separate closed-form equation that only modeled interest would impractically assess financing on each line item separately. Eq. 13 gives the overdraft balances that must be financed, still excluding any charges from compound interest *i* itself. These self-referential terms are 'added' to Eq. 13 to give Eq. 14 and refer to earlier terms on the time axis, leading to a 'nested' equation.

$$z(y)_{cash\ flows} = \frac{\$30{,}000}{1\,mo.}\cdot\langle y-0\,mo.\rangle^{1} + \frac{\$20{,}000}{1\,mo.}\cdot\langle y-1\,mo.\rangle^{1} + \frac{\$40{,}000}{1\,mo.}\cdot\langle y-1.5\,mo.\rangle^{1} - \$33{,}750$$
$$\cdot\langle y-(2\,mo.+\varepsilon)\rangle^{0} - \frac{\$10{,}000}{1\,mo.}\cdot\langle y-2\,mo.\rangle^{1} - \$78{,}750\cdot\langle y-(3\,mo.+\varepsilon)\rangle^{0} - \frac{\$60{,}000}{1\,mo.}\cdot\langle y-3\,mo.\rangle^{1}$$
$$-\$100{,}000\cdot\langle y-(4\,mo.+\varepsilon)\rangle^{0} - \frac{\$20{,}000}{1\,mo.}\cdot\langle y-4\,mo.\rangle^{1} - (\$25{,}000+\$12{,}500)\cdot\langle y-(5\,mo.+\varepsilon)\rangle^{0}$$
$$+i\cdot\Big(z(y=1\,mo.)\cdot\langle y-(1\,mo.+\varepsilon)\rangle^{0} + z(y=2\,mo.)\cdot\langle y-(2\,mo.+\varepsilon)\rangle^{0} + z(y=3\,mo.)\cdot\langle y-(3\,mo.+\varepsilon)\rangle^{0}$$
$$+z(y=4\,mo.)\cdot\langle y-(4\,mo.+\varepsilon)\rangle^{0} + z(y=5\,mo.)\cdot\langle y-(5\,mo.+\varepsilon)\rangle^{0}\Big) \qquad \textbf{Eq. 14}$$

Results

Evaluating Eq. 14 under consideration of its sorted terms correctly gives all end-of-month balances as per Table 2, which gives identical results to the tabular calculation of Halpin and Woodhead (1998). For simplicity, all debt balances are positive and all surpluses are negative. Additionally calculated values at ε after each end of a time period are listed underneath their preceding values for brevity. This duration ε thus distinguishes between assessing and charging interest. The maximum amount that must be financed, i.e. the *credit limit* up to which a bank would have to approve this contractor is \$147,553 and occurs at 3 months. This value increases to \$149,028.53 if the compounded interest amount of \$1,475.53 is charged exactly at the ends of each month, not incrementally thereafter. Interest reduces the initial profit from \$50,000 to \$46,318.68 and is shown as steps in the lower half of Figure 2. Financing ends after receiving a large payment at 4 months. The credit limit is the maximum of all values.

Table 2: Cash Flow Values (calculated from Halpin and Woodhead 1998)

Item	Timing	1 mo.	2 mo.	3 mo.	4 mo.	5 mo.	Total
Direct Cost	On End	25,000	65,000	75,000	15,000	0	180,000
Indirect Cost	On End	5,000	5,000	5,000	5,000	0	20,000
Total Cost	On End	30,000	70,000	80,000	20,000	0	200,000
Cumulative Cost	On End	30,000	100,000	180,000	200,000	N/A	200,000
Plus 25% Profit	On End	7,500	17,500	20,000	5,000	0	50,000
Total Billing	On End	37,500	87,500	100,000	25,000	0	250,000
Cumulative Billing	On End	37,500	125,000	225,000	250,000	N/A	250,000
Less 10% Retained	On End	0	3,750	8,750	0	N/A	12,500
Delayed Payment Release Retained	On End	0	33,750	78,750	100,000	25,000 +12,500	250,000
1% Period Interest	At ε	300	1,003	1,476	903	0	N/A*
Total Cash Flow	On End	30,000	100,300	147,553	90,279	-8,819	N/A
	At ε	30,300	67,553	70,279	-8,819	-46,319	N/A

* Note that interest is compounded, i.e. draws interest itself.

Conclusions

The previous example has served to introduce the possibilities for financial modeling and analysis that singularity functions newly bring to the construction engineering and management field. The comparison of the results showed correct results for all times, while introducing clearer distinctions for minute details such as when interest is assessed versus when it is charged. Tabular computations that provided discrete values at integer times only and other previous simplified approaches that used S-curves or envelopes can be replaced by one comprehensive singularity function.

Its additive nature – despite the necessity for self-referential interest in the recursive end terms – allows adding different types of costs, e.g. steps from initial mobilization, many small transactions or an overall growth function, defining specific ranges over which they apply, and converting them into regular bills including profit at periodic, user-defined intervals. Regarding inflows, the important payment terms of billing delays, owner's retainage, and compound interest from financing have been demonstrated with singularity functions. Realistically the interest should be included in the bills to the owner. Additional terms, e.g. the fees that banks assess on unused credit were not included in the original example and have been omitted for brevity. They could theoretically be calculated with the difference of the credit limit and the total cash flow function of Eq. 14. Extending this thought, it is also possible to create target curves for cash flow that can be used in an optimization. Different levels of detail, whether within activities, e.g. to separately track materials, equipment, and labor cost, or beyond projects, e.g. to manage a portfolio of them, are also possible.

Singularity functions are right-continuous and defined for all x-values, which makes them independent of user-selected time units. They can be implemented in computer software, e.g. Microsoft® Excel spreadsheets or the scientific analysis environment MATLAB®. They clearly separate their components as per Eq. 1, are segmental, and versatile with regard to the shapes that they can model. This makes them a suitable tool for use in construction engineering and management education to enhance the understanding of financial and engineering economics concepts. Examples of a scale and complexity like the one presented in this paper can be evaluated manually, supported by – but not dependent upon - the graphical representation of cash flows.

Future Research

The new approach for modeling intricate financial concepts with singularity functions opens various avenues for future research, including investigating conceptual details, e.g. unused credit fees and payment processing calendars, modeling different ways to assess interest exactly, e.g. based on average daily balances instead of end-of-period balances, modeling different cash flow strategies and scenarios, e.g. self-performing work versus outsourcing and the impact of different payment terms. Research also needs to investigate its user-friendliness for practice, possible conceptual limitations, and how be best integrate this cash flow model with its underlying linear schedule for an overall optimization. Other related items for future research are time-cost tradeoff to shorten project durations and progress measurement in earned value management.

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Modeling Resource Profiles with Singularity Functions

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Abstract
Resources are productive agents on construction projects and are therefore of special interest in project planning. Algorithms use heuristic or evolutionary approaches to (a) allocate resources underneath an availability ceiling to determine the minimum possible project duration or (b) leveling resources of noncritical activities within the fixed project duration toward a smooth profile of an even workflow. However, adding one or several types of resources in histogram bins is scale-dependent, disconnected from the underlying schedule, and computationally inefficient, as any change requires a recalculation. This paper therefore describes how such profiles can be modeled with singularity functions, which have been applied to linear scheduling, as cumulative additions over time. An example demonstrates how the activities and their resources remain coupled during an optimization procedure, e.g. resource leveling. Resources are extracted directly from productivities of their activities. The new approach also allows defining mathematical expressions for specific desirable or available profiles.

Challenges of Resource Planning and Control

Resource is a broad term that can include materials, labor, and equipment that are directly involved in the productive activities on a construction project, as well as a wide range of less tangible items, e.g. permits, access, information, and money that function as conditions or enabling factors for actual execution. As used in this paper it refers to any specialized labor, e.g. crafts; other types are rare in the literature (Smith-Daniels and Aquilano 1984). Labor combined with heavy equipment is called a crew.
Optimizing the use of limited resources is an important objective of project managers. Main approaches are *allocation* (Lambourn 1963) that determines the project duration by placing resources of activities under an availability ceiling and *leveling* (Galbreath 1965) that shift resources within float from peaks into valleys in their histogram.
Resource leveling (Harris 1990), toward which the new model described in this paper is applied, is an *NP*-complete (Son and Skibniewski 1999) problem of algorithmically 'smoothening' a resource profile to a rectangle to create an uninterrupted progress of the project and minimize costs of hiring, training, and firing plus avoid any decreased morale among the laborers from a potentially high turnover. Besides construction

engineering and management (e.g. Kandil and El-Rayes 2006), operations research and management science studies (Brucker *et al.* 1999, Herroelen *et al.* 1998), rarely cross-cited in construction research, also examined the similarly complex *resource-constrained project scheduling problem*, e.g. with standard problem sets (Kolisch and Sprecher 1996). Resource-constrained schedules are *NP*-hard (Błażewicz *et al.* 1983).

Previous Limitations for Linear Scheduling

Several studies applied resource leveling to linear scheduling. Mattila and Abraham (1998) incurred rounding errors in integer linear programming of delays and lower productivity. Yang and Ioannou (2001) used a pull approach to avoid idleness. Yang and Chang (2005) modeled probabilistic durations but again allowed only constant productivity. Yen (2005) worked on combining resource allocation and leveling using heuristics and meta-heuristics, but noted its one-directional model, inefficient model of variable productivity, and large number of variables. Georgy (2008) used a similar genetic algorithm to minimize daily changes. None of the approaches could derive its resource model directly from its linear schedule for an integrated optimization. Their different limitations can be overcome by applying the flexible singularity functions.

Basic Operator of Singularity Functions

The basic operator that composes the individual terms that make up each singularity function is written as a case distinction as per Eq. 1. The pointed brackets were first used by Wittrick (1965), while singularity functions had been independently defined by Föppl (1927) and Macaulay (1919) for structural analysis, e.g. of beams under a combination of vertical loads. The operator is zero (inactive) for all x-values smaller than the cutoff value a. Beginning at a, it gives the value of evaluating the bracketed term normally and remains active until infinity in the positive direction of x. The x-axis is horizontal and the y-axis is vertical. The exponent n determines the overall behavior, e.g. constant, linear, quadratic, etc. and the factor b provides its scaling, e.g. for the height of a constant, the slope of a linear growth, or the shape of a parabola.

$$b \cdot \langle x-a \rangle^n = \begin{cases} 0 \; for \; x < a \\ s \cdot (x-a)^n \; for \; x \geq a \end{cases} \qquad \textbf{Eq. 1}$$

Additive Superposition and Simplification

Basic operators are assembled into a complete singularity function based on ranges of behavior in the variable of interest, $y(x)$. Each change in the behavior is modeled by adding a new term as per Eq. 1. A singularity function thus can contain an unlimited number of terms that cumulatively describe the entire gradient of $y(x)$ for any two-dimensional shape as long as it qualifies as a true function, i.e. only one output value $y(x)$, which can be zero, exists for each input x-value. Note that discontinuities, e.g. vertical steps, can be modeled, so that the singularity (i.e. points of change) functions occasionally are also called discontinuity functions. This important ability directly enables modeling the components and analyzing the resource profile in this paper.

Superposition refers to the cumulative nature of singularity functions. Keeping the components separated into ranges, i.e. segments, and within them into the behaviors of different exponents creates unique flexibility to model complex shapes. Extensions

to Eq. 1, e.g. to allow behavior depending on x itself or logarithms, are possible, but have not been described in the literature and will be investigated in future research. *Sorting* all terms in a singularity function by their cutoffs a and within that by their exponent n increases the clarity, especially of manual calculations. It also facilitates *simplifying* any terms whose factors b can be added if their a and n are both identical. Simplification also reduces the required storage for computer calculations, wherein an increasing number of values from active terms would be kept for growing x-values.

Differentiation and Integration of Basic Operator

Singularity functions have a fundamental advantage over other methods for modeling any discontinuous shapes, e.g. vectorization (Russell and Caselton 1988). As per Eqs. 2 and 3, they can be differentiated to calculate its rate of change or integrated for the area underneath the function, e.g. the total resource consumption of a resource profile.

$$\frac{d}{dx} b \cdot \langle x-a \rangle^n = n \cdot b \cdot \langle x-a \rangle^{n-1} \qquad \textbf{Eq. 2}$$

$$\int b \cdot \langle x-a \rangle^n = \frac{b}{n+1} \cdot \langle x-a \rangle^{n+1} + C \qquad \textbf{Eq. 3}$$

Singularity Functions in Linear Scheduling

Lucko (2009) presented a novel use of singularity functions to model an entire linear schedule, which is particularly suited for any projects with a linear geometry and/or repetitive operations (Mattila and Park 2003). Its criticality analysis had six steps:

1. Writing all activities and their buffers as singularity functions with a zero intercept.
2. Sequentially stacking activities and buffers alternatingly with a conservative finish-to-start relationship, i.e. the maximum of a predecessor is the intercept of a successor.
3. Calculating pairwise differences between adjacent buffer and activity equations.
4. Differentiating these difference equations to find their minima, i.e. critical points.
5. Consolidating the schedule to its minimum possible duration under consideration of all constraints by deducting the minimum differences and rewriting all intercepts.
6. Determining the continuous critical path from the critical points. An analysis of the different float types (Lucko and Peña Orozco 2009) can be performed subsequently.

Modeling Individual Resource Consumption

Each activity consumes resources, e.g. laborers, to produce a certain physical output. Assuming that its resource rate r, which can be measured e.g. in number of laborers, remains constant over time for an activity, Eq. 4 models this individual consumption.

$$r(y) = r \cdot \langle y-a_S \rangle^0 - r \cdot \langle y-a_F \rangle^0 \qquad \textbf{Eq. 4}$$

where $r(y)$ is the resource consumption, y is the time on the horizontal axis, r is the individual resource rate of an activity, a_S is the start time of said activity, and a_F is its finish time. More complex consumption patterns could thus be modeled additively.

Under this new approach each activity contributes a *horizontal strip* to the resource profile. Prior studies, e.g. Georgy (2008), Mattila and Abraham (1998), and Galbreath (1965), all used vertical strips as histogram bins for each time unit, e.g. workdays. An extra algorithm step of adding daily aggregated resources (Russell and Dubey 1995) was required to calculate the so-called improvement factor (Hiyassat 2000, Martínez and Ioannou 1993) for each possible time shift of the noncritical activities within the profile. The new model does not split the resources from their activities. It facilitates an optimization, e.g. to level the profile by shifting noncritical activities or segments thereof, which only modifies the particular cutoff value a. Adding the expressions of Eq. 4 for all activities gives the complete resource profile for the construction project.

Modeling Measure of Resource Levelness

The *first moment of area*, used to calculate the centroid of complex shapes and in its extension to the second moment of area for the bending stiffness of cross-sections in structural engineering, is a generally used measure by which to compare the different possible constellations of a resource profile and select the one with minimum moment (Harris 1990), i.e. an increased levelness. It is the area of a regular geometric shape multiplied by the length of the lever from its center of gravity to the axis around which a rotation is imagined, in this case the horizontal y-axis. Complex shapes can be decomposed into simpler ones, e.g. rectangles. Note that each activity adds not one but two horizontal strips to the resource profile and accordingly also to the moment. One strip beginning at its start is positive; one beginning at its finish is negative.

Modeling the moment must correctly consider both the area and lever of an activity's contribution to the resource profile. The area, i.e. resource consumption, of an activity is always constant, but could be 'split' into segments at different heights when adding it onto an existing uneven profile. Another complication is caused by any concurrent activities whose levers cannot be determined from their resource rate alone. Using the singularity function that expresses the entire resource profile provides the solution.

Eq. 5 models the moment of a resource profile as the sum over the products of each newly added strip multiplied by the cumulative total height (including said strip) of the profile up to that time but *minus half* the height of said strip to reach its center of gravity. Note again that each activity contributes two strips to the total summation.

$$M = \sum_{i=1}^{2 \cdot k} \left(r_i \cdot \langle y_k - a_i \rangle^1 \cdot \left(\left(\sum_{j=1}^{i} r_j \right) - 0.5 \cdot r_i \right) \right) \qquad \textbf{Eq. 5}$$

where M is the first moment of area, i is a running index of all activities that are sorted by their start time up to their total count k, j is a running index within i, r is the individual resource rate of an activity, and a is a start or finish time of said activity. The pointed brackets in Eq. 5 calculate the length of the strip from its start time until the maximum finish time y_k, i.e. the rightmost edge of the entire resource profile. The summation nested inside Eq. 5 can also be rewritten as a recursive expression of $r(y)$.

Modeling Changes in Resource Profile

Two possible ways exist by which a complete activity changes its contribution to the profile while maintaining continuity, shifts and resource changes. They modify Eq. 4

to Eq. 6 by adding a shift s to its cutoff a and changing the resource rate r. The total 'area' R, which can be measured e.g. in labor-days, is maintained via the activity duration. Additionally, these changes can affect individual activity segments. Shifting them creates interruptability. Even more complexity is introduced if intact activities are permitted to become interruptible at any point in time (Ioannou and Srisuwanrat 2007) and are possibly subject to additional calendar-related constraints, both which is not considered in this analysis example and will be investigated in future research.

$$r(y)=r\cdot\langle y-(a_S+s)\rangle^0-r\cdot\langle y-(a_S+(R_{\text{var}}/r)+s)\rangle^0 \qquad \textbf{Eq. 6}$$

where s is the shift to the cutoff for the start of the activity and R_{var} is the variable resource content of said noncritical activity segment as the product of its duration multiplied by its resource rate r, i.e. the area of its contribution to the resource profile.

Resource Example

For brevity and due to this paper focusing on new modeling concepts, only resource leveling is presented in the following example. The related resource allocation could be performed with analogous concepts and will be investigated in future research.
Originally presented by Mattila and Abraham (1998) for a real road building project, the example of the linear schedule was analyzed for critical segments as shown on the left side of Figure 1. Table 1 lists its parameters as needed for the resource leveling.

Table 1: Activity List and Critical Ranges

Name	Type	Activity Duration	Work Amount	Start Time	Finish Time	Start Amount	Critical Time	Critical Amount
A	Full	5	50	0	5	0	0 to **2**	0 to **20**
B	Bar	3	N/A	0	3	42	N/A	N/A
C	Full	15	50	2	17	0	2 to 17	0 to 50
D	Block	3	4	10	13	8	N/A	N/A
E	Full	8	50	12	20	0	**17** to 20	**31.25** to 50
F	Partial	2	20	20	22	30	N/A	N/A
G	Full	13	50	20	33	0	20 to 33	0 to 50
H	Full	5	50	30	35	0	**33** to 35	**30** to 50
I	Full	3	50	35	38	0	35 to 38	0 to 50

Boldface values in Table 1 indicate critical points, i.e. where a change from critical to noncritical occurs or vice versa. Permutations of activities or segments thereof are shown as dotted lines and straight or curved arrows in Figure 1 to indicate different possible contributions to the resource profile. Table 2 lists the float that enables time shifts and resource rates to vary for individual activities. The resource rates count the shared type of equipment, trucks. Underlined values indicate the initial configuration of each activity as shown in solid lines in Figure 1. The areas R in the profile have the unit of resources multiplied by duration, i.e. truck-days. The work amount in this road building example was measured as length in surveying stations [30.48 m ≈ 100 ft].

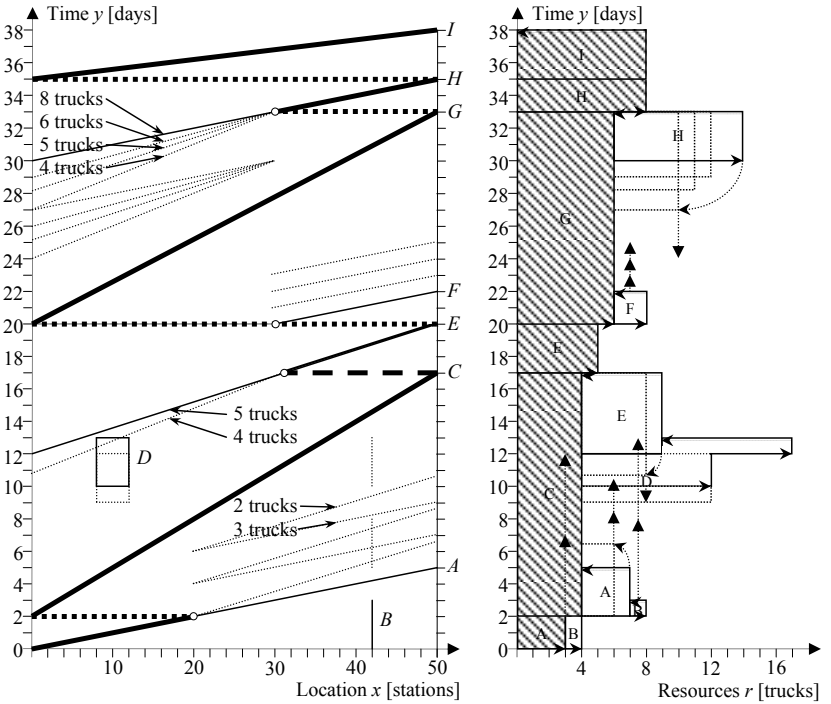


Figure 1: Linear Schedule (Mattila and Abraham 1998) and Resource Profile

Table 2: Float, Time Shifts, and Resource Rates

Name	Slope	Float	Shift	Resources	Fixed Area	Variable Area
A	5/50	Partial, late	0, 2, 4	2, 3	6	9
B	N/A	Fully	0, 5, 10	Constant 1	0	3
C	15/50	Fixed	N/A	N/A	60	0
D	N/A	Fully	0, -1	Constant 8	0	24
E	8/50	Partial, early	Constant 0	4, 5	15	25
F	5/50	Fully	0, 1, 2, 3	Constant 2	0	4
G	13/50	Fixed	N/A	N/A	78	0
H	5/50	Partial, early	0, -3	4, 5, 6, 8	16	24
I	3/50	Fixed	N/A	N/A	24	0

Fixed Profile of Critical Activity Segments

All critical activities give contributions that remain fixed during the resource leveling and are shaded on the right side of Figure 1. Eq. 7 models this consumption pattern by adding the contributions from all critical activity segments as per Eq. 4 and Table 1.

$$r(y)_{fixed} = 3\cdot\langle y-0\rangle^0 + 1\cdot\langle y-2\rangle^0 + 1\cdot\langle y-17\rangle^0 + 1\cdot\langle y-20\rangle^0 + 2\cdot\langle y-33\rangle^0 - 8\cdot\langle y-38\rangle^0 \quad \textbf{Eq. 7}$$

Note that the resource profile on the right side of Figure 1 is rotated by 90 degrees. This orientation enabled the *y*-variable of its linear schedule to be minimized (Lucko 2009). It would be beneficial to transpose the time axis of the profile, or histogram, to become horizontal to visualize optimizing the variable of interest *r*. However, it is not required, as singularity functions are *independent* of their graphical representation.
It is possible to directly extract *r* from the known unit productivity of each activity in the linear schedule once the transposition or 'axis flip' has been performed so that, unlike in Figure 1, the slope of each activity curve is proportional to its productivity.

Variable Contributions from Noncritical Activity Segments
Noncritical activities have float that can be consumed by shifts *s* or by changed *r* that extend an activity's duration. Either parameter may vary during the resource leveling. Eqs. 8 through 13 apply Eq. 6 to all of the noncritical segments of late *A*, *B*, *D*, early *E*, *F*, and early *H* based on their possible integer values for *s* and *r* as per Table 2. Eq. 6 is modified to model the change in the start – not finish – time of the early *E* and *H*.

$$r(y)_A = r_A\cdot\langle y-(2+s_A)\rangle^0 - r_A\cdot\langle y-(2+9/r_A+s_A)\rangle^0 \quad \textbf{Eq. 8}$$

$$r(y)_B = 1\cdot\langle y-(0+s_B)\rangle^0 - 1\cdot\langle y-(0+3/1+s_B)\rangle^0 \quad \textbf{Eq. 9}$$

$$r(y)_D = 8\cdot\langle y-(10+s_{lD})\rangle^0 - 8\cdot\langle y-(10+24/8+s_D)\rangle^0 \quad \textbf{Eq. 10}$$

$$r(y)_E = r_E\cdot\langle y-(17-25/r_E+0)\rangle^0 - r_E\cdot\langle y-(17+0)\rangle^0 \quad \textbf{Eq. 11}$$

$$r(y)_F = 2\cdot\langle y-(20+s_F)\rangle^0 - 2\cdot\langle y-(20+4/2+s_F)\rangle^0 \quad \textbf{Eq. 12}$$

$$r(y)_H = r_H\cdot\langle y-(33-24/r_H+s_H)\rangle^0 - r_H\cdot\langle y-(33+s_H)\rangle^0 \quad \textbf{Eq. 13}$$

Moment from Critical and Noncritical Activity Segments
Resource rates *r* and shifts *s*, i.e. interruptions between activity segments, can vary in integer counts as per Table 2. These given values are assumed to not violate buffers between activities. Performing the resource leveling thus seeks a minimized moment among all possible permutations of $s_A = \{\underline{0}, 2, 4\}$, $r_A = \{2, \underline{3}\}$, $s_B = \{\underline{0}, 5, 10\}$, $s_D = \{\underline{0}, -1\}$, $r_E = \{4, \underline{5}\}$, $s_F = \{\underline{0}, 1, 2, 3\}$, $s_H = \{\underline{0}, -3\}$, and $r_H = \{4, 5, 6, \underline{8}\}$, which gives $3 \cdot 2 \cdot 3 \cdot 2 \cdot 2 \cdot 4 \cdot 2 \cdot 4 = 2{,}304$ possible permutations; larger examples can have millions of permutations. Using Eqs. 7 through 13 it is now possible to compose Eq. 14 for the moment based on Eq. 5. All these change terms are sorted, simplified, and extended by the length of the strip from its start until the maximum *y*-value and the appropriate lever. However, a correction variable becomes necessary for the case that a positive

and a negative strip have the same cutoff value a. Adding them would cancel out their contributions to the moment, which would give too short a lever. Correcting this issue is accomplished by introducing an infinitesimal duration εthat is subtracted from the cutoff values of all strips that are a 'downward' step in the resource profile, i.e. those strips with a negative sign. Alternatively, it could be added to the cutoff value of all the 'upward' steps, which would also keep downward and upward steps separate. This prevents any simplification toward an incorrect moment. The value of $\varepsilon$is set to be extremely small, e.g. $1 \cdot 10^{-6}$, to not influence any significant digits of the moment.

$$
\begin{aligned}
M = {} & 3\cdot\langle 38\rangle^{1}\cdot[r(0)-1.5]+1\cdot\langle 38-s_B\rangle^{1}\cdot[r(0+s_B)-0.5]+1\cdot\langle 36\rangle^{1}\cdot[r(2)-0.5] \\
& +r_A\cdot\langle 36-s_A\rangle^{1}\cdot[r(2+s_A)-0.5\cdot r_A]-1\cdot\langle 35-s_B\rangle^{1}\cdot[r(3+s_B-\varepsilon)-0.5] \\
& -r_A\cdot\langle 36-s_A-(9/r_A)\rangle^{1}\cdot[r(2+s_A+(9/r_A)-\varepsilon)-0.5\cdot r_A]+8\cdot\langle 28-s_D\rangle^{1}\cdot[r(10+s_D)-4] \\
& +r_E\cdot\langle 21+(25/r_E)\rangle^{1}\cdot[r(17-(25/r_E))-0.5\cdot r_E]-8\cdot\langle 25-s_D\rangle^{1}\cdot[r(13+s_D-\varepsilon)-4] \\
& -r_E\cdot\langle 21\rangle^{1}\cdot[r(17-\varepsilon)-0.5\cdot r_E]+1\cdot\langle 21\rangle^{1}\cdot[r(17)-0.5] \\
& +1\cdot\langle 18\rangle^{1}\cdot[r(20)-0.5]+2\cdot\langle 18-s_F\rangle^{1}\cdot[r(20+s_F)-1]-2\cdot\langle 16-s_F\rangle^{1}\cdot[r(22+s_F-\varepsilon)-1] \\
& +r_H\cdot\langle 5-s_H+(24/r_H)\rangle^{1}\cdot[r(33+s_H-(24/r_H))-0.5\cdot r_H]-r_H\cdot\langle 5-s_H\rangle^{1} \\
& \cdot[r(33+s_H-\varepsilon)-0.5\cdot r_H]+2\cdot\langle 5\rangle^{1}\cdot[r(33)-1]-8\cdot\langle 0\rangle^{1}\cdot[r(38-\varepsilon)-4]
\end{aligned}
\qquad \textbf{Eq. 14}
$$

All strips end at the maximum y-value of 38 days. Eq. 14 can be evaluated for any permutations of s and r as per Table 2, e.g. for the initial permutation with zero shifts and the maximum number of trucks (i.e. s_A =0, r_A = 3, s_B = 0, s_D = 0, r_E = 5, s_F = 0, s_H = 0, and r_H = 8). All *possible* simplifications *must* be performed and for clarity are underlined: M = (3 + 1) · 38 · [4 - 1.5 - 0.5] + (1 + 3) · 36 · [8 - 0.5 - 1.5] - 1 · 35 · [8 - 0.5] - 3 · 33 · [7 - 1.5] + 8 · 28 · [12 - 4] + 5 · 26 · [17 - 2.5] - 8 · 25 · [17 - 4] - 5 · 21 · [9 - 2.5] + 1 · 21 · [5 - 0.5] + [1 + 2] · 18 · [8 - 0.5 - 1] - 2 · 16 · [8 - 1] + 8 · 8 · [14 - 4] - 8 · 5 · [14 - 4] + 2 · 5 · [8 - 1] - 8 · 0 · 0 = 1,287 truck-days times trucks. This value is validated by a manual calculation of the right side of Figure 1 and found to be correct.

Conclusions

The new model can be efficiently used in any type of optimization procedure toward resource leveling, using e.g. a heuristic or evolutionary algorithm that is applied to the parameters s and r. For brevity, details of such solution will be described under future research. The new model has been implemented in a computer application and can be used in conjunction with any schedule, but is especially suited for linear scheduling. It is planned to integrate the output of the model with a genetic algorithm, whose optimized configuration for the leveled resource profile will be validated against the results provided by Mattila and Abraham (1998). On the input side, the model can be integrated with an existing software tool for performing a criticality and float analysis of linear schedules with singularity functions. Overall, this model thus provides a link between different analytical functions of project management. It opens an analytical avenue for modeling non-linear, discontinuous characteristics of complex phenomena as e.g. encountered in resource planning in an integrated, coherent, and exact manner.

Future Research

The model for modeling and optimizing resource profiles that has been presented in this paper is a stepping stone toward research on integrated project management. The resources were derived directly from their underlying activities in the linear schedule, thus maintaining a mathematical link between the schedule and its resource profile. Future research will extend the model and its analytical capabilities toward different behaviors of resources within activities, e.g. to model a learning effect, using several different types of resources with their respective availability and cost constraints and different weights or priorities, and investigating its application to resource allocation, where different availability ceilings can also be modeled with singularity functions.

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Activity Overlapping Assessment in Construction, Oil and Gas Projects

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Abstract

Increasing demand for project completion in a shorter duration has led to various methods of schedule compression techniques, that a well known among them is fast tracking that refers to overlapping activities that normally would be done in sequence. Fast tracking (overlapping) can reduce the execution time of a project while at the same time can result in rework, extra costs and increased risks as evident by many construction projects. In order to limit the risks of fast tracking and to gain maximum advantage, a tradeoff between benefits and losses of activity overlapping is required. Such a tradeoff requires a systematic and practical approach. For this purpose an analysis has been conducted over the inherent nature of overlapping to develop a new framework for optimizing activity overlapping in construction projects. The main objective of this paper is to introduce such a framework and the hypothesis behind it. The paper will also include the theoretical justification of the suggested framework to verify that the framework can be both reliable and practical to be used by project managers to find the optimum overlapping between activities to reduce the negative risks including sources of cost overruns and time delays.

1- Introduction

Today's construction businesses rely on first-to-market product strategies to gain competitive advantages and increase profit margins (Hastak et al. 2008). This is

particularly true for oil and gas projects that are considered type of industrial construction. It has become increasingly important for energy companies to reduce the investment payback time, to turn a profit as early as possible and to reduce the period of risk exposure. Completing projects in an efficient and timely manner is of interest to the contractors as well, because the shorter the duration of the project, the greater the number of projects that can be completed in the same time frame and ultimately the greater the profit.

The demand for project completion in a shorter duration has led to various methods of schedule compression. According to Project Management Body of Knowledge (PMBOK), schedule compression techniques include crashing and fast tracking. In crashing, cost and schedule tradeoffs are analyzed to determine how to obtain the greatest amount of compression for the least incremental cost. Crashing does not always produce a viable alternative and can result in increased cost. In fast tracking, phases or activities that normally would be done in sequence are performed in parallel. An example would be to construct the foundation for a building before all the architectural drawings are complete. Fast tracking can result in rework and increased risk. This approach can require work to be performed without completed detailed information, such as engineering drawings. It results in trading cost for time, and increases the risk of achieving the shortened project schedule (PMBOK 2004). In this light, fast tracking is the same as overlapping dependent activities in the project schedule, and this definition is the focus of this paper as well. However, sometimes practitioners in the construction, oil and gas industries have a different perception of fast tracking. To them, fast tracking means utilizing any exceptional techniques to reduce the execution time of projects (Eastham 2002). Although such a perception may include overlapping, it entails a broader range of techniques and therefore is not discussed in this paper.

In this paper, in response to the need for managing the increased risks of fast tracking, a new framework to assess and optimize activity overlapping in construction as well as oil and gas projects is introduced; further, the hypothesis behind the framework is explained. The framework has been developed by means of an in depth analytical study on the inherent nature of overlapping, and after conducting a comprehensive literature review to identify the existing approaches to overlapping assessment. The results of the literature review revealed that there was a gap in previous studies on overlapping. No study could be found that made a distinct and direct relation between activity overlapping in the project schedule and the big picture of the project (business objectives of the project). To fill such a gap, the new framework was developed. The framework utilizes a risk analysis process to assess the selected overlaps and to determine the optimum degree of overlapping.

2- Overlapping Principles

A typical construction project consists of many activities that have to be performed in a specific order to complete the project. Each activity is dependent on one or more

activities. Generally, there are two types of dependency: Information dependency and resource dependency. When two activities have information dependency, one activity requires information (raw data, specifications, drawings, etc.) from a second activity, before the first activity can be started. When two activities have resource dependency, it means that they are using the same resource. For example both activities have to be performed by a designated designer or specific equipment. In either case, overlapping dependent activities can generate extra risk for the project. If two activities have no dependency of any type on each other, then their overlapping will not be risky.

When two activities with information dependency are overlapped, the basis of overlapping is the early release of preliminary information by the predecessor activity to the successor activity. This relation is shown in figure 1: Activity B that is a successor to activity A should normally start after activity A is finished. But if for some reason, activity A may release preliminary or incomplete yet useful information to activity B, then activity B can start sooner than expected. Therefore the two activities may proceed in parallel. Then, as soon as activity A is completed, it may release its final information to activity B; from that point, activity B will proceed with the final information from activity A.

In order to determine the extent to which two activities are overlapped, Dehghan (2009) suggests evaluating *degree of overlapping* as per the following equation:

Degree of overlapping = (time duration of the overlapped fraction ÷ total duration of the shorter activity) × 100 (Eq. 1) (Dehghan 2009)

In the formula, the shorter activity can be either the predecessor (upstream) or the successor (downstream) activity. For example in figure 1, the upstream activity (activity A) has a shorter duration compared to the downstream activity (activity B), and the degree of overlapping is (10 ÷ 40) × 100 = 25%. According to equation 1, 0% overlapping represents the time when no overlapping exists between two activities, and 100% overlapping represents the time when two activities are fully overlapped.

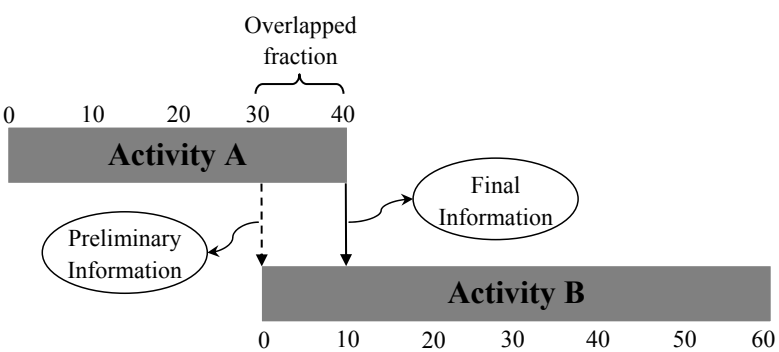


Figure 1- Basis of overlapping and degree of overlapping

3- Problems with overlapping

Fast track projects are increasingly being experienced by the oil & gas industry and fast tracking is becoming the norm for executing energy projects worldwide (Knecht 2002). The unique advantage of fast tracking or overlapping is the timesaving it generates in the project, which consequently results in a long list of benefits such as earlier operation, earlier income, time to market, increased market share, tax reductions, reduced pay back period, increased prestige, etc. Such benefits generally have their roots in the business objectives of the project. Therefore, there is an increasing intention to overlap project activities to compress the schedule and thus to reduce the execution time. However, companies still face serious shortcomings and challenges when compressing their projects schedules with this method. The main problem lies in extra risks generated, with the risk of rework probably the greatest. Overlapping can result in more changes, which consequently can result in more rework; more rework can increase expenses and lengthen execution time of the project. Further, sometimes overlapping necessitates utilizing exceptional work procedures, which can adversely affect project quality requirements and jeopardize safety. This means that too much overlapping cannot be applied, because only reasonable levels of risk can be tolerated. If too much overlapping is implemented, then the time saving benefits might be offset and even superseded by the losses originated from rework and cost. Therefore, the question is how much overlapping is desirable or which degree of overlapping is optimum. The answer to this question is the main goal of this research, i.e. to develop and validate a systematic and structured approach and a conceptual framework to assess and determine the optimal overlapping that brings the maximum advantage to the project.

4- Hypothesis

Decision on if a specific degree of overlapping is desirable can be made on the basis of a tradeoff between its positive and negative impacts. Some of the parameters affecting such a tradeoff have been shown in the influence diagram in figure 3.

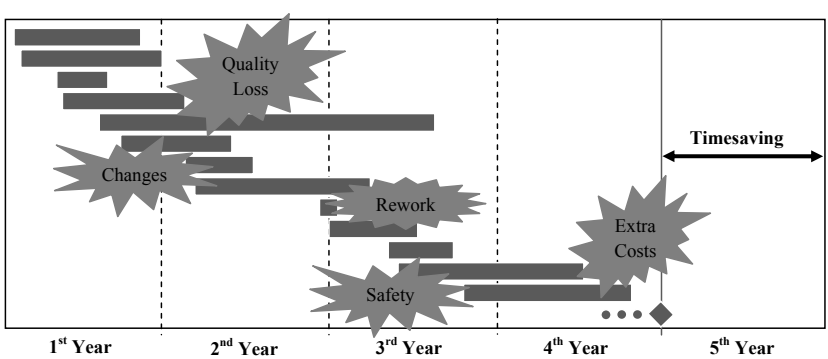


Figure 2- Activity overlapping reduces project duration and generates extra risks

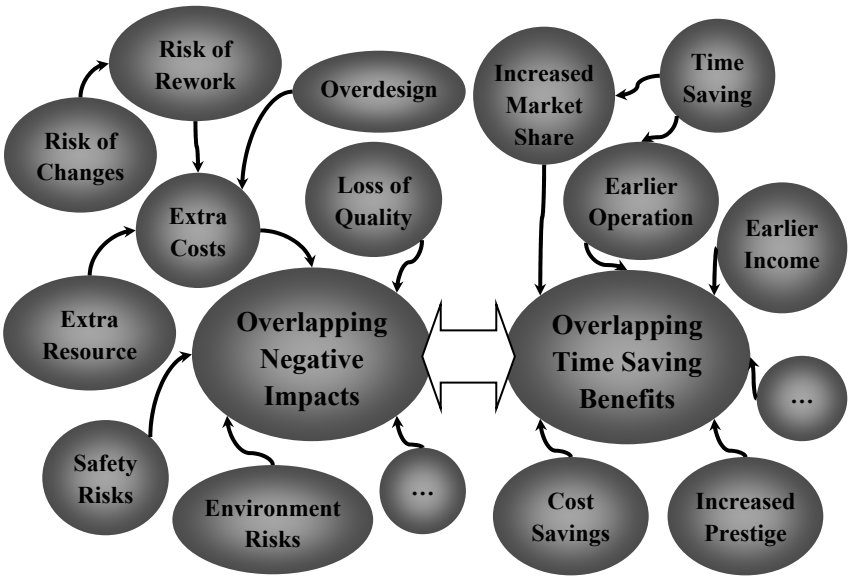


Figure 3- Tradeoff between negative consequences and timesaving benefits of overlapping

Needles to say, in the real world, there are much more parameters than those shown in the diagram. If the overlapping results in a remarkable timesaving that its benefits surpass the negative impacts, it is advised to overlap. Otherwise, if the risks associated with the overlapping are so high that the advantages are neutralized, then such an overlapping should be avoided.

Figure 4 shows how the tradeoff is implemented on a sample overlapping. The sample is not a real example, but is fabricated for better understanding. It envisages four different relative positions of activity B (successor) to activity A (predecessor) in the form of bar charts. In the first position, activity B has no overlapping with activity A, but in the second, third and fourth positions, the degree of overlapping has been increased to 25%, 50% and 75% respectively. Right under the bar charts and proportional to their position, a diagram shows loss, benefit and net benefit values of different degrees of overlapping versus timesaving.

Although the time unit really does not matter in figure 4, let's assume it is presented in terms of *days*. Therefore, activity A has 40 days duration, activity B has 60 days duration and their total duration is 100 days when no overlapping exists. Naturally, the total duration of both A and B is reduced as the overlapping is increased, e.g. 70 days (which is the same as 30 days timesaving) when the degree of overlapping is 75%. In addition, there is an important assumption in this figure: any change in the

total duration of A and B will be directly transferred to the finish time of the project (in that case both A and B must be on the critical path of the project).

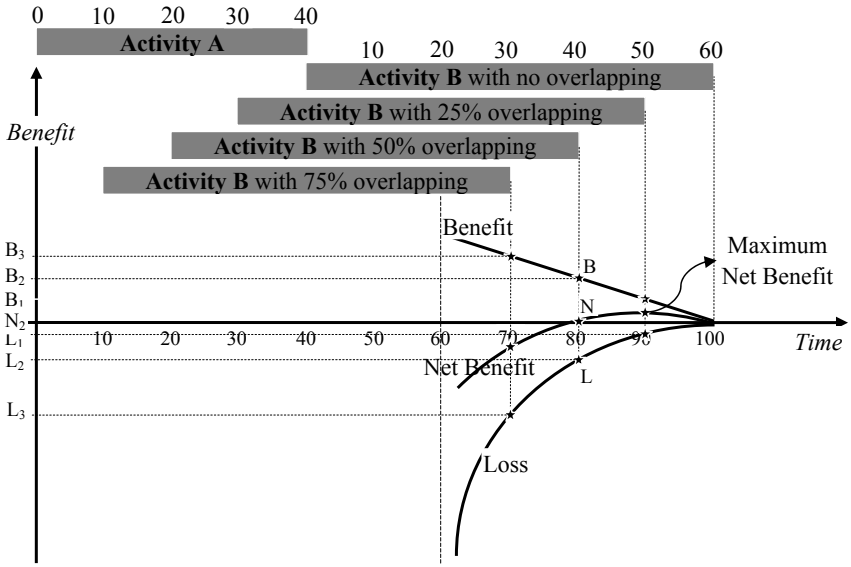


Figure 4- Loss-benefit tradeoff for different degrees of overlapping

When activities A and B are performed sequentially, they generate an added value to the project resulting from the benefits they bring to the project minus the costs of implementation. Such costs and benefits (or losses and benefits) are attributed to the sequential or normal execution of A and B, i.e. when no overlapping exists between them. But as soon as overlapping starts, both extra loss and extra benefit are generated on top of the normal execution cost and benefit. For example in figure 4, when the degree of overlapping is increased to 25%, an additional B_1 benefit and an additional L_1 loss are generated. B_1 is the timesaving benefit because of finishing the project sooner than expected; it reflects gaining any additional financial benefit and tackling any additional business advantage because of reducing project finish time (according to the right hand side of the influence diagram of figure 3). L_1, on the other side, reflects all negative impacts imposed on the project because of the overlapping (refer to left hand side of the influence diagram of figure 3). Examples are losing time and money because of rework, infringement of quality requirements because of work based on incomplete activities, jeopardizing safety because of parallel work, etc. Likewise, when overlapping is increased to 50%, B_2 and L_2 represent the related benefit and loss, and the same is true for 75% overlapping, B_3, and L_3. Normally, with further overlapping, further loss and benefit are generated. In other words, it is expected that $B_3 > B_2 > B_1$ and $L_1 > L_2 > L_3$ (or $|L_1| < |L_2| < |L_3|$).

It is important to note neither B_1, B_2, B_3 nor L_1, L_2, L_3 in figure 4 are necessarily in terms of a monetary unit such as dollars. In fact, they are only virtual values representing all types of benefits and losses resulting from overlapping, including cost, time, quality, safety, prestige, etc. Theoretically it is possible to convert all losses and benefits to a unique unit such as dollars, or days; however, practically it is very difficult.

If a sufficient number of different degrees of overlapping are evaluated the same way as above, then it is possible to plot two curves, one showing the benefits of overlapping versus timesaving and the other showing the losses of overlapping versus timesaving. Such curves have been shown in figure 4 as *benefit* and *loss*. Both curves pass the zero loss/benefit point on day 100. Moreover, the *benefit* curve can never touch the vertical line passing day 60, because it seems like A and B have 100% overlapping, and this is theoretically almost impossible (it is like considering no sequence for performing two activities that are inherently sequential). Then, the net benefit of overlapping is the algebraic summation of its benefit and loss graphically shown as the *net benefit* curve plotted between *benefit* and *loss* curves. This curve determines if a degree of overlapping between two activities is beneficial to the project. For example, in the area between 80 days and 100 days (which represents 50% overlapping to zero overlapping), various degrees of overlapping are beneficial to the project, because the net benefit is higher than the default case, i.e. the time no overlapping exists. On the other hand, if the overall timesaving goes beyond 20 days (more than 50% overlapping) the net benefit becomes negative, which means that any degree of overlapping more than 50% is actually a loss to the project. The net benefit curve has a maximum point as well on day 90 (reflecting 25% overlapping or 10 days timesaving), which reflects the maximum possible net benefit the project can gain from overlapping activity A with activity B. In other words, in this example 25% overlapping is the optimum degree of overlapping, because it generates the maximum net benefit. Likewise, each overlapping has its own characteristics, losses and benefits, which means that each overlapping has its own optimum degree.

In this light, the optimum degree of overlapping between two activities is highly dependent on the maximum net benefit they bring to the project. As a result, a method is required to evaluate the net benefit of different degrees of overlapping, to identify the maximum net benefit, and consequently to determine the optimum degree of overlapping.

5- Framework

In the industry's current practice, activity dependencies and overlapping between activities are defined by project planners and schedulers and other project team members based on their experience and established practices. The problem with the current practice is its weakness in identifying the best and optimized degree of overlapping. In other words, overlapping based on the current practice does not necessarily generate the maximum benefit, and sometimes generates loss as admitted

by both industry practitioners and academics (Eastham 2002). Considering the hypothesis explained earlier, this paper explain the current research work to develop a new method, *overlapping assessment*, for identifying the optimum degree of overlapping.

To illustrate the sample example of solution, 3 points are considered on the curves shown in figure 4, i.e. B on *benefit* curve, L on *loss* curve and N on *net benefit* curve. These points are attributed to 50% overlapping between activities A and B and their values have been shown on the *loss/benefit* axis as B_2, L_2 and N_2. As stated earlier, $N_2 = B_2 + L_2$ (or $N_2 = |B_2| - |L_2|$), therefore B_2 and L_2 must be found to evaluate N_2. As noted earlier, B_2 reflects the big picture of the project including the business, market, and financial objectives of the project plus reputation of the company. Therefore, it is reasonably expected that the senior management of any company has a reliable idea of the real value of any timesaving in their projects, and this value is convertible to a unique quantity, such as dollars. In other words, the senior management can convert every monetary and non-monetary added value because of timesaving to a *time to money ratio*. As a result, it is assumed that B_2 is available to the project manager as well. The remaining step, and the hard one, is to assess L_2.

Since L_2 reflects all negative impacts (resulting from various risks or issues), it is suggested a risk assessment be performed on the designated overlapping, i.e. on 50% overlapping between activity A and activity B. On this basis and like typical risk analysis procedures, the risks should be identified, their probabilities of occurrence should be estimated, and their impacts on various project objectives such as cost, time, quality, environment and safety should be evaluated. The main and important difference is that here the focus is merely on the risks originated from the overlapping, and not on all types of risks. However, it is obvious that the risks adversely impacting the overlapping are different in nature. For example, the negative impact of extra costs can be presented in monetary values, while the negative impact of a safety risk can be a human life, which hardly can be expressed in monetary values. Therefore, a challenging part of such a risk assessment lies in converting the negative impacts into a common basis, so that their superposition results in a unique value. A possible solution is to take a veto process for risks impacting safety, quality and environment, and to convert the risks impacting cost and time to their dollar values. The following procedure simplifies the process of evaluating negative impacts of overlapping (50% in our example) as follows:

1- Risks impacting safety: If 50% overlapping between A and B generates notable safety risks that can not be mitigated, it must be avoided and no further assessment is required. Otherwise, proceed to the next step.
2- Risks impacting quality: If 50% overlapping between A and B infringes on any quality standards, it must be avoided (this means that loss of quality is accepted to some extent) and no further assessment is required. Otherwise, proceed to the next step.

3- Risks impacting environment: If 50% overlapping between A and B violates any environmental standards, it must be avoided and no further assessment is required. Otherwise, proceed to the next step.
4- Risks impacting cost: Any negative impact on cost (after taking all mitigation actions into account) should be calculated in terms of dollars.
5- Risks impacting time: The dollar value of any negative impact on time (after taking all mitigation actions into account) should be calculated. For this purpose, any time loss should be converted to its dollar value using the time to money ratio explained before.

The summation of cost and time impact (items 4 and 5 above) gives the dollar value of the overlapping loss, which is the same as L_2 in figure 4. Such a summation may be evaluated in different ways, for example by multiplying the probability of occurrence of each risk in its impact value in dollar, and then add up the results for all identified risks. With both B_2 and L_2 at hand, N_2 can be evaluated easily.

Now there is a discussion: If $N_2 \leq 0$, then 50% overlapping is too much and should be reduced. If $N_2 > 0$, then 50% overlapping is acceptable, but other degrees of overlapping should be checked to find if higher net profit is achievable. For example, 25% or 75% overlapping is checked and it is concluded that 75% overlapping is not advised, but 25% overlapping is more profitable than 50% overlapping. Other degrees of overlapping may be checked as well to find the optimum overlap with the maximum net benefit. However, such a search can be a time-consuming process, and probably is best to be performed through a heuristic approach that relies on gut feelings, experience, and the facts and figures resulting from the risk analysis process. Such an approach has been developed (Dehghan 2009) and may be presented in a separate paper.

In real world practice, an individual inside the project management team, such as a project planner or project engineer, can take responsibility for *overlapping assessment*. For each overlapping assessment, he/she should form a team of 3 to 4 experts including the specialists for both predecessor and successor activities plus any other individual who may have remarkable knowledge or experience regarding the designated overlapping (e.g. project engineering manager). As such, for different overlaps, he/she may approach different individuals.

Overlapping assessment is a time-consuming teamwork task, which requires input from several project key members. In other words, it consumes man-hours from the project and therefore there should be significant potential gains made by completing it. Furthermore, there might be thousands of instances of overlapping in a project schedule, and it is neither worthy nor possible to assess them all.

Based on the above, only the most important overlaps, those with the highest influence on the finish time of the project, should be assessed. This requires a separate algorithm to identify and rank overlaps. Such an algorithm, *activity*

overlapping algorithm, has been developed (Dehghan 2009) and will be presented in a separate paper.

6- Conclusion

In this paper a new framework to assess activity overlapping in construction, oil and gas projects was introduced and the hypothesis behind it was explained. The framework has been developed based on an analytical study on activity overlapping and its effect on the project duration. The framework utilizes a risk analysis process to perform a loss-benefit tradeoff on the activity overlapping, and thus it determines what degree of overlapping brings the maximum benefit to the project. Currently, the test and validation stage is under progress. It involves real world case studies from the construction and oil and gas industries. If the above framework is successfully tested and validated, it will be an innovative method for reliably adjusting overlapping between activities in the project schedule and will further results in more realistic schedules and more effective schedule reduction. The novelty of this framework is its ability to relate activity overlapping to the overall business objectives of the project. It is noteworthy that the framework can be applied to stochastic schedules as well, but the mechanism will be discussed in a separate paper.

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Optimizing Labor Utilization in Multiple Shifts for Construction Projects

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ABSTRACT

Multiple shifts are often utilized in construction projects to accelerate schedules. Despite its advantages, the utilization of multiple shifts in construction often suffers from a number of limitations including additional acceleration costs and productivity losses. This paper presents the development of a multi-objective optimization model for scheduling multiple shifts that is capable of generating optimal tradeoffs among (1) minimizing the project duration; (2) minimizing the project cost; and (3) minimizing the utilization of evening and night shifts. An application example is analyzed to illustrate the use of the model and demonstrate its capabilities in generating optimal schedules and labor utilization plans for the day, evening, and night shifts.

INTRODUCTION

The utilization of multiple shifts is reported to provide a number of advantages, including (1) doubling or tripling weekly work-hours; (2) lowering the required premium costs for evening and/or night shifts compared to those of overtime hours; and (3) reducing productivity losses during evening and night shifts compared to those encountered during overtime hours due to workers fatigue and site congestion (Hanna et al. 2008). Despite these advantages, the utilization of multiple shifts still has a number of limitations including its negative impacts on construction, cost, productivity, and safety. Nighttime construction often disrupts the circadian rhythm of shift workers, and thereby they often struggle with adapting to new sleep cycles. Accordingly, the utilization of evening and night shifts is reported to cause productivity losses due to workers fatigue, health disorder, and lower morale (Helander 1981; Kogi 1985). Moreover, working during evening and night shifts are reported to increase the risk of injuries and accident rate. Folkard and Tucker (2003) found that (a) the risk of injuries and accidents on evening shifts is higher than day shifts; and (b) night shifts have the highest risk of injuries and accidents among the

three shifts. Staffing evening and night shifts is another problem, because most workers prefer to work on day shifts (Czeisler et al. 1982; Guerin and DelPo 2007). The utilization of evening and night shifts also causes higher rates of labor turnover and absenteeism which lead to project delays and cost overruns (Gomar et al. 2002; Guerin and DelPo 2007; Knauth 2001). In order to minimize these negative impacts of utilizing multiple shifts, the number of utilized labor hours during the evening and/or night shifts should be minimize whenever possible.

A number of research studies have developed models to optimize the utilization of construction resources in order to accelerate the delivery of construction projects (El-Rayes and Moselhi 2001; Feng et al. 1997; Hegazy and Ersahin 2001; Leu and Hwang 2001; Li et al. 1999; Maxwell et al. 1998; Moussourakis and Haksever 2004). Despite the contributions of these studies, there has been little or no reported research that focused on optimizing the utilization of multiple labor shifts in construction projects. This paper presents the development of a robust multi-objective optimization model that supports construction planners in searching for optimum shift work plans and schedules that simultaneously (1) minimize project duration; (2) minimize project cost; and (3) minimize the negative impacts of shift work on productivity and safety. To accomplish this, the present model is developed in two main phases: (1) formulating the decision variables and optimization objectives; and (2) implementing the model as a multi-objective genetic algorithm.

DECISION VARIABLES AND OPTIMIZATION OBJECTIVES

The present model is formulated to support construction planners in identifying optimum/near optimum shift work plans and schedules that maximize project performance and minimize the negative impacts of shift work. As such, the considered decision variables in the present model are the shift-option (S_n) for each activity (n), as shown in Figure 1. Shift-option (S_n) represents the feasible options of utilizing multiple shifts for each activity (n), and the number of feasible shift options varies according to whether the activity can be constructed using one, two, and three shifts per day, as shown in Table 1. For example, the utilization of three shifts per day can be assumed to be divided among the three shifts as follows: (1) the day shift includes 8 work hours and one half hour break (8:00 AM to 4:30 PM); (2) the evening shift includes 7.5 work hours and one half hour break (from 4:30 PM to 12:30 AM); and (3) the night shift includes 7 work hours and one half hour break (from 12:30 AM to 8:00 AM), as shown in Table 1 (Popescu et al. 2003). Accordingly, each shift utilization option has different work hours per day, production rate, and cost rate, and accordingly it leads to unique duration and cost for each activity (n). Construction planners can specify the number of feasible shift options (S_n) for each activity (n) based on the type of shift system used for the project (e.g. two shifts, or three shifts).

Minimize Project Duration

The first optimization objective in this model is to minimize the project duration, as shown in Equation (1). In order to provide construction planners with more reliable estimates of activity durations for multiple shifts schedule, the present model is designed to consider the impact of productivity losses that will be encountered during evening shifts and night shifts when calculating the duration (D_{Sn}) of activity (n)

based on the selected shift-option (S_n). The duration (D_{Sn}) of activity (n) can be adjusted based on the historical data or the recommendation provided by the Mechanical Contractors Association of America (MCAA) Labor Estimating Manual. The manual recommends increasing man-hours for evening shifts by 20% and night shifts by 30% (Kitchens 1996).

$$Mininimize\ T = \underset{n \in All}{Max}\{\ EF_n\} \tag{1}$$

$$ES_n = \underset{n' \in PRE_n}{Max}\{\ EF_{n'}\} + 1 \tag{2}$$

$$EF_n = ES_n + D_{S_n} - 1 \tag{3}$$

Where, T = project duration; EF_n = early finish time of activity (n); ES_n = early start time of activity (n); PRE_n = set of immediate predecessors of activity (n); D_{Sn}= duration of activity (n) under Shift-option (S_n), which is rounded up to the nearest integer number.

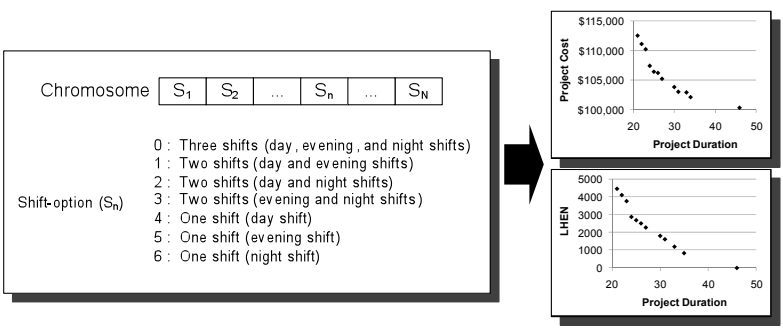


Figure 1. Decision variables and optimization objectives

Minimize Project Cost

The second major optimization objective in the present mode is to minimize the total project direct cost, as shown in Equation (4). The present model is designed to consider shift premium costs in the labor cost rate based on the selected shift-option (S_n) when estimating the direct cost (DC_{Sn}) for each activity (n).

$$Minimize\ C = \sum_{n=1}^{N} DC_{S_n} \tag{4}$$

Where, C = total project direct cost; N = total number of activities in the project; and DC_{Sn}= direct cost of activity (n) using Shift-option (S_n). The direct cost can be calculated based on the duration (d_{Sn}) of activity (n) under the shift-option (S_n). This second optimization objectives enables the model to generate optimal tradeoffs

between the project duration (T) and cost (C) which can used to identify the optimal project duration that minimize total project cost including its indirect cost.

Table 1. Multiple shift options

Shift-option (S_n)	Two shifts system	Work hours/day	Three shifts system	Work hours/day
0	Two shifts (Day & Evening Shifts)	15.5 hrs	Three shifts (Day, Evening, & Night shifts)	22.5 hrs
1	One shift (Day shift)	8 hrs	Two shifts (Day & Evening shifts)	15.5 hrs
2	One shift (Evening shift)	7.5 hrs	Two shifts (Day & Night shifts)	15 hrs
3	-		Two shifts (Evening & Night shifts)	14.5 hrs
4	-		One shift (Day shift)	8 hrs
5	-		One shift (Evening shift)	7.5 hrs
6	-		One shift (Night shift)	7 hrs

0.5 hours of meal break is not included in total work hours per day

Minimize Labor Utilization in Evening and Night Shifts

The third optimization objective in the present model focuses on minimizing labor utilization in evening and night shifts so as to minimize their negative impacts on construction productivity, cost, and safety, as shown in Equation (5). As stated earlier, the utilization of more labor hours during the evening or night shifts exposes more workers to the aforementioned risks of nighttime work including the risk of accidents, injuries, health disorders, and social life disruption which often leads to additional costs and schedule delays. In order to minimize these negative impacts of evening and night shifts, the third optimization function is designed to focus on minimizing the utilization of labor in night and evening shifts.

Minimize LHEN = LHE + LHN × (1+W) if three shifts system (5a)

Minimize LHEN = LHE if two shifts system (5b)

$$LHE = \sum_{n=1}^{N} (D_{S_n} \times RE_{S_n}) \times HE \quad (6)$$

$$LHN = \sum_{n=1}^{N} (D_{S_n} \times RN_{S_n}) \times HN \quad (7)$$

Where, LHEN = total labor hours in evening and night shifts; W = planner defined weight to represent the relative importance of minimizing the total number of labor hours on night shift (e.g. W = 0% to 100%); LHE = total number of labor hours in evening shifts; LHN = total number of labor hours in night shifts; D_{Sn}= duration of activity (n) based on Shift-option (Sn); RE_{Sn}= daily labor demand of activity (n) on evening shift under Shift-option (S_n); RN_{Sn}= daily labor demand of activity (n) on night shift under Shift-option (S_n); HE = daily work hours for evening shift (e.g. 7.5 hours per day); and HN = daily work hours for night shift (e.g. 7 hours per day).

MODEL IMPLEMENTATION

The present model is implemented as a multi-objective genetic algorithm (Deb et al. 2001) in order to generate optimal multiple shift plans and schedules that minimize project duration, minimize project cost, and minimize labor utilization in evening and night shifts simultaneously. This algorithm adopts the concept of Pareto optimality to enable multi-objective optimization and the survival of the fittest criteria to evolve solutions over a number of specified generations until it reaches optimal/near optimal solutions. The model is implemented using this algorithm in four main phases: (1) initialization phase that generates a random population, where each solution represents a combination of feasible shift options for each activity; (2) fitness evaluation phase that evaluates each solution based on the calculated objective functions of project duration, project cost, and labor utilization in evening and night shifts; (3) reproduction phase that selects the most fit solutions in the parent population based on the fitness criteria, Pareto optimal rank, and crowding distance for each solution and reproduces a new child population using genetic operators of crossover and mutation; and (4) elitism phase that evaluates the fitness of new child population and generates the improved parent population by selecting the best 50% of members from the combined population (i.e. child population + parent population) to preserve the best solutions of the parent population over generations (Deb et al. 2001). Phases (2) to (4) are then repeated over a number of predetermined generations to generate a Pareto optimal set of non-dominated solutions (See Figure 2).

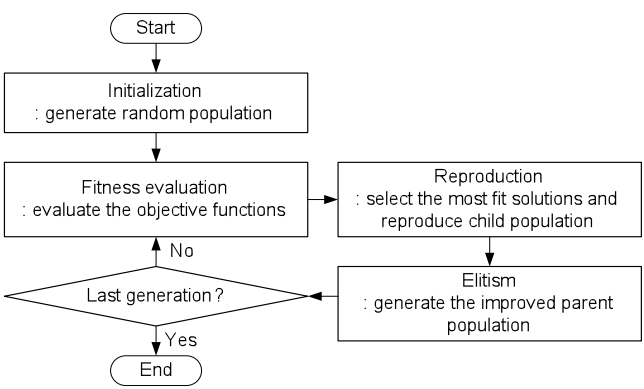


Figure 2. Main phases of optimization model.

APPLICATION EXAMPLE

An application example is analyzed to illustrate the use of the present model and demonstrate its capabilities. The example includes 10 activities that have finish to start relationships among them, as shown in Figure 3. Table 2 illustrates the activity data including the feasible shift options for each activity, its direct cost, and duration. It is assumed that every shift requires the same crew formation to perform the activities in the project and the daily work hours for the day, evening, and night shifts are 8 hours, 7.5 hours, and 7 hours, respectively. The early schedule of this example based on the single day shift operation (i.e. $S_n = 4$) requires a project duration of 46 days and a total direct cost of $100,300. If all activities operate two shifts (i.e. $S_n = 1$), the project can be completed in 27 days with a total direct cost of $106,600 and a total of 2820 labor hours in the evening shift (Simple solution 1). On the other hand, if all activities operate three shifts to accelerate the schedule, the project can be completed in 21 days with a total direct cost of $118,200 and a total of 2212.5 and 2065 labor hours in the evening and night shifts respectively (Simple solution 2). In order to simultaneously minimize project duration and cost while minimizing labor utilization in evening and night shifts, this example was analyzed using the developed multi-objective optimization model.

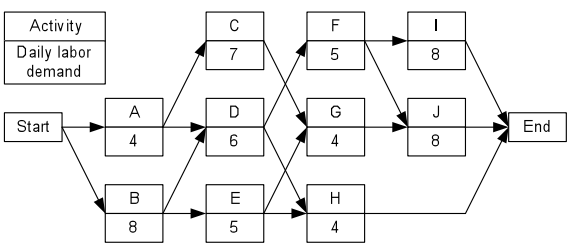


Figure 3. Activity network.

Two experiments were conducted to analyze the impact of utilizing two and three shifts system. In the first experiment, a three shifts system was utilized in the example. As shown in Table 2, each activity has 7 possible types of shift options for this three shift system. In order to minimize the labor utilization in evening and night shifts, the weight for night shift in Equation (5a) was set as W=80%. This represents that reducing the number of labor hours in night shifts is 80% more critical than the evening shift because evening shifts typically have less negative impacts on project performance compared to night shifts. In the second experiment, a two shifts system was utilized in the example. Only the types of shift options belonging to the two shifts system (i.e. S_n=1, 4, and 5) were selected from the activity data shown in Table 2 and analyzed by setting them as S_n=0, 1, and 2 respectively. The results of these two experiments are summarized in Figure 4 that illustrates the generated optimal tradeoffs among three optimization objectives. It should be noted that the generated optimal solutions outperform the simple solutions by providing the same project

duration while providing significant reduction in the project direct cost and labor utilization in evening and night shifts, as shown in Figure 4.

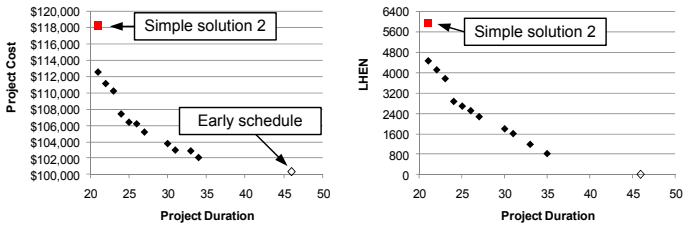
Table 2. Activity data

Activity	Duration (D) & Cost (DC)	Shift-option (S_n)						
		0	1	2	3	4	5	6
A	D (days)	6	8	8	10	14	18	20
	DC ($)	$12,600	$11,400	$12,700	$15,000	$11,100	$14,800	$18,600
B	D	4	5	6	7	9	12	13
	DC	$8,400	$7,400	$8,200	$9,700	$6,400	$8,700	$10,900
C	D	7	9	9	11	15	20	23
	DC	$13,700	$12,400	$13,800	$16,200	$11,600	$15,600	$19,600
D	D	3	4	4	5	7	9	10
	DC	$11,800	$10,800	$12,000	$14,100	$10,700	$14,300	$17,900
E	D	5	6	6	7	10	13	15
	DC	$18,100	$16,400	$18,200	$21,500	$15,700	$21,100	$26,400
F	D	3	3	3	4	5	7	8
	DC	$8,600	$7,800	$8,700	$10,200	$7,500	$10,000	$12,600
G	D	3	4	4	5	7	8	10
	DC	$6,800	$6,000	$6,600	$7,800	$5,200	$7,000	$8,800
H	D	4	5	5	6	9	11	13
	DC	$5,600	$5,000	$5,500	$6,500	$4,300	$5,800	$7,300
I	D	9	12	12	14	20	26	30
	DC	$25,100	$22,800	$25,400	$29,900	$22,100	$29,700	$37,300
J	D	4	5	5	6	8	10	12
	DC	$7,500	$6,600	$7,300	$8,700	$5,700	$7,800	$9,700

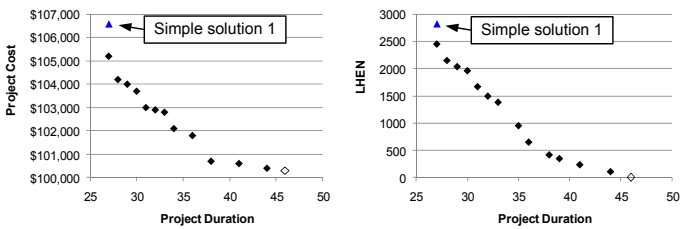
SUMMARY

A robust multi-objective optimization model was developed for scheduling multiple shifts in construction projects. The model was designed to search for and generate optimal shift work plans and schedules that simultaneously minimize project duration, cost, and the negative impacts of utilizing evening and night shifts. A multi-objective genetic algorithm was implemented in the model to generate optimal tradeoffs among these three objectives. An application example was analyzed to illustrate the use of present model and demonstrate its capabilities. Two experiments were conducted to illustrate the impact of two and three shifts systems on project performance. The results of the analysis highlight the new and unique capabilities of the present model in generating optimal tradeoffs among minimizing project duration, cost, and labor utilization in evening and night shifts. This should prove useful to construction planners and can lead to significant improvements in the optimization of scheduling multiple shifts in construction projects. Future research will study the performance of the present model in optimizing large-scale construction projects to analyze its

effectiveness and efficiency in optimizing the scheduling of multiple shifts for real-life construction projects.



(A) Three shifts system (Experiment 1)



(B) Two shifts system (Experiment 2)

Figure 4. Non-dominated optimal solutions

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OPTIMIZING MATERIAL LOGISTICS PLANNING IN CONSTRUCTION PROJECTS

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ABSTRACT: Construction logistics can be used by contractors to plan and control the efficient and effective flow of materials from the suppliers to their incorporation into the finished structure. This paper presents the development of a construction logistics planning model that simultaneously optimizes the decisions of material supply and site layout in order to minimize logistics costs that include ordering, carrying, shortage, and layout costs. New methodologies are incorporated in the developed model to represent the interdependencies between material supply and layout decisions as well as to measure the impact of these decisions on project delays. An application example is analyzed to highlight the capabilities and performance of the proposed model.

INTRODUCTION

Construction logistics involves the planning of efficient transfer of material and equipments from the suppliers to the construction site in a cost-effective way and timely manner (Rushton et al. 2000). Construction materials need to be supplied and stored on construction sites using timely plans that are dependent on the activities schedule, site space availability, and suppliers' constraints. Construction logistics planning provides an integration framework to coordinate between material supply and storage decisions in order to consider their mutual impacts and interdependencies. Ignoring this coordination between material supply and storage may result in serious project problems, including material shortages, unsafe site layout, and productivity losses (Thomas et al. 1989).

A number of research studies were conducted to investigate best practices and develop decision support systems for material supply and site storage. Existing studies on construction material supply focused on: (1) analyzing the impact of

material management practices on construction labor productivity (Thomas et al 1989); (2) investigating the implementation of Just-In-Time strategies in construction projects (Polat and Arditi 2005); (3) developing 4D visualization systems to help contractors visualize material supply progress and onsite storage (Subsomboon and Christodoulou 2004); (4) establishing data exchange standards for construction supply chains (Danso-Amoako et al. 2004); and (5) formulating optimization models for economical material supply decisions (Tserng et al 2006; Polat et al 2007). Other research studies focused on various aspects of site layout planning for material storage, including: (1) investigating construction practices for material site storage (Thomas et al 2005); (2) developing static site layout planning models (Tommelein et al. 1999; El-Rayes and Khalafallah 2005); and (3) developing dynamic site layout planning models (Zouein and Tommelein 1999; El-Rayes and Said 2009). Despite the significant contributions of these research studies, they did not study and model the mutual interactions and interdependencies between the decisions of material supply and site storage.

To address this research gap, the objective of this paper is to present the development of a new Construction Logistics Planning (CLP) model that is capable of integrating and optimizing the critical planning decisions of material supply and material storage on construction sites. As shown in Figure 1, the proposed model is composed of two main modules: (1) *Supply Logistics* module that focuses on the planning of material supply, and (2) *Site Logistics* module that models site layout planning of material storage areas as well as construction temporary facilities. The decisions in these modules have a direct impact on the construction logistics cost that is comprised of ordering, carrying, shortage, and layout costs, as shown in Figure 1. The following sections describe in more details the development and implementation of these two modules.

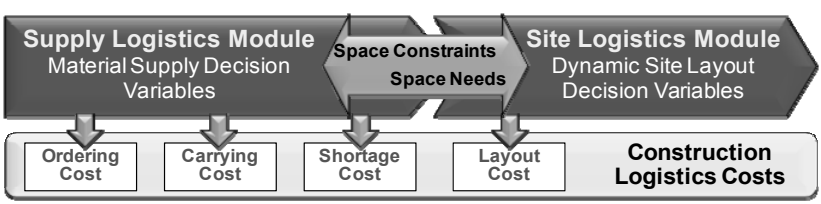


FIGURE 1. Proposed Construction Logistics Planning Model

SUPPLY LOGISTICS MODULE

This module is designed to represent and optimize the decisions of material supply from suppliers to constructions sites. As shown in Figure 2, the supply logistics module requires planners to provide all relevant data of suppliers and construction sites. The suppliers' data include: (1) supply capacities that would limit the size of material orders; (2) purchase costs for different order sizes that reflects possible discounts for large orders; and (3) delivery costs for different order sizes that are calculated based on truck capacities. The construction site data include: (a) the

cumulative demand of each material that represents its consumption overtime by the construction activities; (b) a detailed construction schedule that provides the early times, late times and floats of the construction activities; and (c) construction stages that are identified by the planner to represent the start and finish of major site activities such as substructure, superstructures, and finishes.

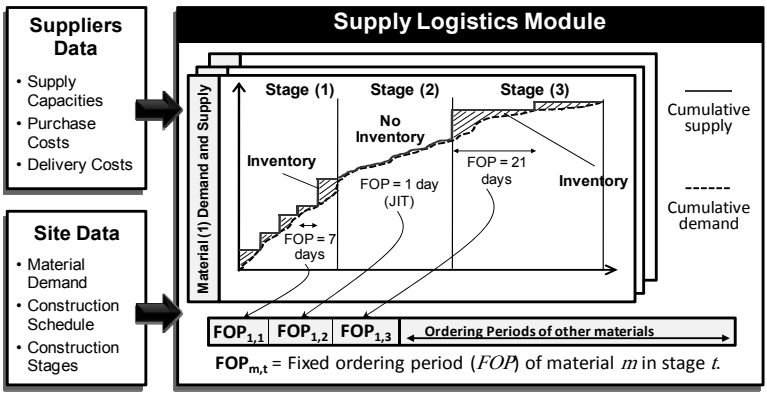


FIGURE 2. Input Data and Decision Variables of the Supply Logistics Module

The material supply in the present CLP model is represented as a fixed ordering period (FOP) system that replenishes the onsite inventory using ordering cycles of fixed intervals (Waller 2003). Construction material is delivered to the site in the beginning of these cycles with sufficient quantity to fulfill the demand in the corresponding periods. In the present supply logistics module, each construction stage is represented using different FOP system to account for the change of material demand rates, prices, and availability over these stages. Accordingly, material supply decision variables represent the fixed ordering period ($FOP_{m,t}$) of each material (m) in every construction stage (t). The values for these FOP variables can range from 1 day interval, which is the case of Just in Time (JIT) system, to longer intervals, which represent traditional inventory systems. As shown in Figure 2, the demand of material 1 in stage 2 is fulfilled by a JIT daily material supply ($FOP_{1,2}$ = 1 day), which eliminates the need for onsite inventory. On the other hand, the supply of the same material in the other stages is planned using longer ordering periods that generates onsite inventory and storage space needs. The present CLP model is designed to generate the optimal ordering periods for every material in all construction stages ($FOP_{m,t}$) that minimize the supply logistics costs (i.e. ordering, carrying, and shortage) while considering site space constraints, as described in the following subsections.

Ordering Cost

The ordering cost (OC) is formulated as the cost of purchasing and delivering the material from the suppliers to the construction site (Magad and Amos 1995). First, the purchase cost represents the direct cost of material acquisition to the contractor that

involves material bare costs, supplier administration cost, and supplier profit. As shown in Figure 3, the purchase cost rate decreases with the increase of order quantities because of the savings of supplier administration cost and the provision of discount rates. Second, the delivery cost is the expenses of transporting the material from the supplier to the construction site, which decreases as larger quantities of materials are ordered because of the greater utilization of the available trucks' capacity, as shown in Figure 3. Accordingly, the purchase and delivery costs can be minimized by supplying the material demand quantity (TQ_m^t) using fewer deliveries (ND_m^t) with larger sizes (Q) than more deliveries with smaller sizes. As shown in Figure 3, the supply decision variables ($FOP_{m,t}$) have a significant impact on ordering costs, where longer ordering periods result in fewer number of deliveries with lower purchase and delivery costs.

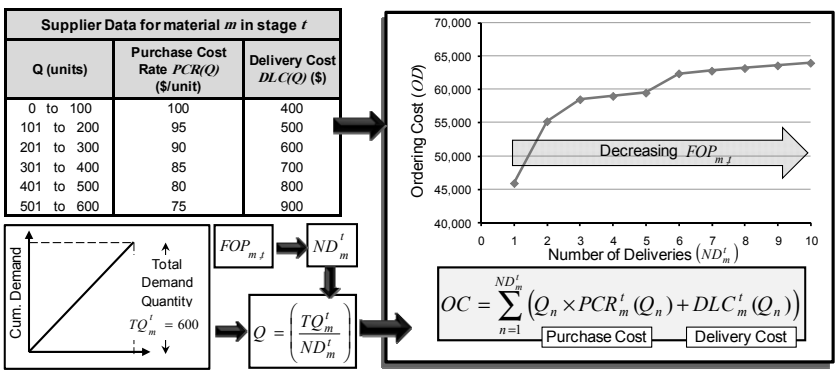


FIGURE 3. Input Data and Decision Variables of the Supply Logistics Module

Carrying Cost

Contractors encounter carrying costs to maintain the material inventory onsite between supply and consumption times (Pooler and Pooler 1997). Carrying cost includes the expenses tied up in material inventories such as interest on investment, insurance, taxes, obsolescence, depreciation, and deterioration, which can be represented using a carrying cost rate (*CCR*) as a percentage of one dollar's worth of material inventory in one day. As shown in Figure 4, the carrying cost (CC) depends on the total material inventory *A* (i.e. the difference between cumulative demand and supply), its average purchase cost (PCR_{avg}), and carrying cost rate *CCR* ($/$/time). Accordingly, the carrying cost can be minimized by utilizing frequent material deliveries with short ordering periods especially for expensive and valuable materials.

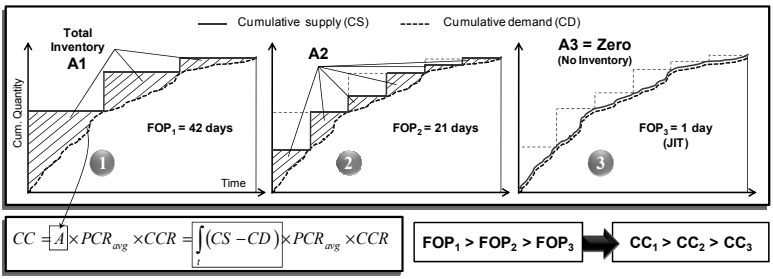


FIGURE 4. Impact of Ordering Period on Carrying Cost

Shortage Cost

The shortage cost includes any expenses to the contractor that occurs due to belated material deliveries and the shortage of material when needed (Magad and Amos 1995). The present model calculates material shortage cost (*SC*) using Equation 1 based on the project liquidated damage for schedule delays (*LQD*), time-dependent indirect cost (*TDIC*), and material-related project delay (*MRPD*). A newly developed algorithm was incorporated in the present CLP model to compute *MRPD* using the following input data: (1) construction activities and schedule; (2) material demand for each activity; (3) material average delay (*DAD*) that is estimated based on historical delivery records and/or suppliers input; and (4) material delivery times that are identified based on supply decision variables (*FOP*). The example shown in Figure 5 illustrates the computation of *MRPD* caused by the belated supply of a material for two activities (A and B) considering two possible options for ordering periods.

The first material supply option in Figure 5 represents supplying the material in 5-day fixed period ordering cycles, which results in two deliveries in the start of days 1 and 6. The expected delay of these deliveries does not result in a project delay (MRPD = 0) because: (1) the first delivery is scheduled on the start of a non-critical activity that has a total float of 2 days that is more than the delivery average delay (DAD); and (2) the second delivery is scheduled one day ahead of the start of the critical activity B that absorbs the expected delay of this delivery. On the other hand, the second option considers a shorter ordering period of 3 days that results in 3 deliveries in the start of days 1, 4, and 7. This option caused the project to delay 1 day because the third delivery was scheduled in the first day of the critical activity B that doesn't have any float to accommodate the expected delays of material delivery ($TF_B < DAD$). It should be noted that the delays of the first two deliveries do not contribute to the project delay because they are scheduled during activity A, which has sufficient float for these delays ($TF_A = 2*DAD$). Accordingly, the example in Figure 5 illustrates that construction projects with frequent material deliveries (i.e. short ordering periods) are more vulnerable to delays than those with longer ordering periods.

$$SC = MRPD \times (LQD + TDIC) \quad (1)$$

Where *MRPD* = materials-related project delay; *LQD* = liquidated damage cost; and *TDIC* = time-dependent indirect cost.

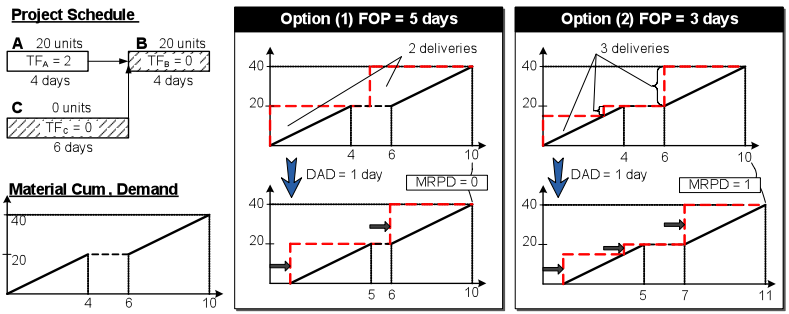


FIGURE 5. Example of Calculating Material-Related Project Delay (MRPD)

SITE LOGISTICS MODULE

The purpose of this module is to represent and optimize the decisions of dynamic site layout planning considering site space needs for material storage areas and temporary facilities. First, the site space needed for the storage area of material 2 in stage 1 is calculated considering: (1) the maximum level of site inventory; and (2) material storage footprint, as shown in Figure 6. The maximum inventory level is the largest quantity of the material stored onsite during the corresponding stage, which is determined in the present model based on the largest order quantity in the supply plan generated from the supply logistics module. Accordingly, this maximum inventory level is used to identify the dimensions (Lx and Ly) of the required storage area based on the material footprint schedule that is specified by the contractor site personnel. It should be noted that the generated values of the fixed ordering period (FOP) from the supply logistics module controls the required onsite storage spaces, where longer ordering periods results in higher inventory levels and larger storage areas. Second, the layout planning decisions are generated considering the required space of construction temporary facilities that include moveable and stationary facilities (Zouein and Tommelein 1999), as shown in Figure 6. Moveable facilities, such as site offices and fabrication areas, can be relocated between the construction stages to account for the dynamic demand and release of site space for other facilities. Stationary facilities, such as tower cranes and batch plants, cannot be relocated because of their excessive and infeasible relocation cost, time, and/or effort.

Dynamic layout planning is performed in the present site logistics module by identifying the locations and orientations of material storage areas and temporary facilities in each construction stage. The construction site space is represented using a grid of locations that is identified by the planner, where storage areas and temporary facilities can be positioned using two possible orientations (0° or 90°). Accordingly, dynamic site layout planning of the example, shown in Figure 6, involves 20 decision variables: (1) four decision variables for the layout of the storage area of material 1 in stages 2 and 3; (2) six decision variables for the layout of the storage area of material

2 in stages 1 through 3; (3) two decision variables for the first temporary facility (stationary) for its fixed location over the project duration; (4) four decision variables for the layout of the second facility (moveable) in stages 1 and 2; and (5) four decision variables for the layout of the third facility (moveable) in stages 2 and 3. Material storage areas and temporary facilities are positioned considering possible safety or operational requirements that are represented using a set of distance and/or zone constraints (El-Rayes and Said 2009). The present site logistics module optimizes these layout decision variables in order to minimize layout cost, as described in the following subsection.

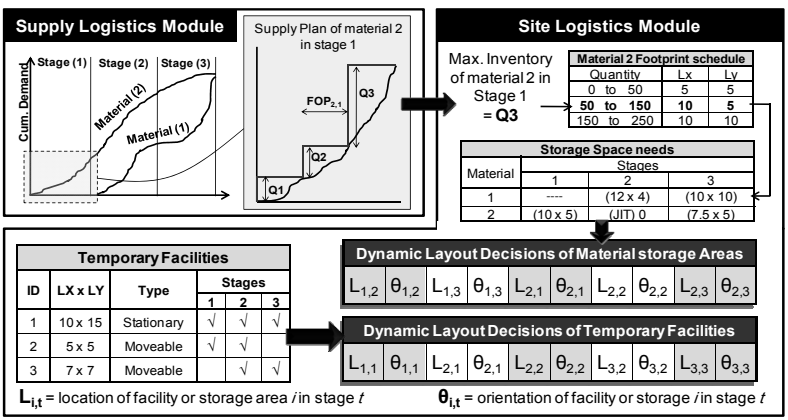


FIGURE 6. Site Logistics Module

Layout Cost

Layout cost includes material handling costs, the travel cost of the construction resources, and relocation costs of moveable facilities. First, the material handling cost is calculated between each storage area and site facilities (buildings under construction and/or the temporary facilities) considering: (1) rectilinear distances between these storage areas and facilities; (2) the handling quantities of the materials; and (3) the hourly cost, speed, and capacity of the handling crew. Second, the travel costs are calculated for other construction resources (i.e. supervision personnel, equipments, labors) moving between the temporary facilities using a set of travel cost rates ($/m) that depend on their travel frequency, travel distance, and hourly costs. Third, the relocation cost is calculated for each moveable facility in every stage as the summation of: (1) a fixed cost that occurs if the facility's location and/or orientation are changed; and (2) a variable cost that depends on the relocation distance. It should be noted that the present model eliminates the negative impacts of material relocation by changing the storage layout between stages before the arrival of new deliveries.

MODEL IMPLEMENTATION

The implementation of the present CLP model is supported by the input and the optimization components. The input component is a relational database that facilitates

the storage and retrieval of all input data relevant to project schedule, material-activities assignments, total cumulative demand, suppliers' data, temporary facilities, layout constraints, and onsite handling crews. The optimization component utilizes Genetic Algorithms (GA) (Deb et al. 2000) to facilitate the automated modeling and simultaneous optimization of supply and layout decision variables in order to minimize total construction logistics cost. The optimization results are extracted in textual and worksheet formats that represent material supply plans and the layout of material storage areas as well as temporary facilities.

APPLICATION EXAMPLE

The present model is evaluated using an application example to illustrate its performance and capabilities in optimizing material logistics planning. The example represents the planning of material supply and site layout of three materials (reinforcing rebar, masonry blocks, and curtain wall panels) for the construction of two multi-story buildings, as shown Figure 7. All relevant data are identified, such as: (1) suppliers' data that include their delivering capacity, purchase and delivery costs; (2) project master plan that describes construction stages, activities scheduling times, activities demand for material, indirect costs and delay liquidated damage; and (3) site data that include material footprint schedules, handling crews, the dimensions of the construction site, buildings and temporary facilities.

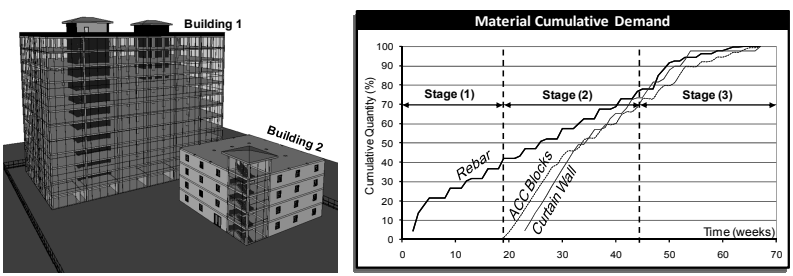
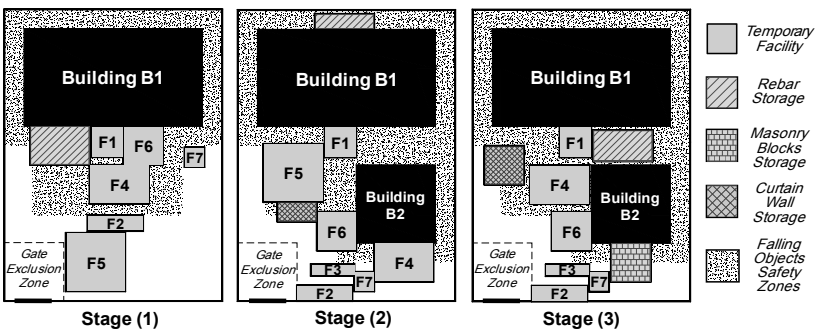


FIGURE 7. Material Demand and Construction Site of the Application Example

As shown in Figure 8, the present CLP model generated optimal decisions for material supply and site layout planning that minimize the total construction logistics costs. Optimal material supply decisions were generated considering site space availability and the criticality of the construction activities that consume the supplied material. First, the congested construction site in the second stage resulted in the generation of shorter ordering periods for masonry and curtain walls (1 and 7 days, respectively) in order to reduce storage space needs. The supply of these materials was supplied in the third stage using longer ordering periods (21 days) because of the removal of the dump area (F5) and the increase in site space availability. Second, the criticality of the concrete skeleton construction activities required the supply of the rebar in long ordering periods (21 days) for all project stages in order to minimize the potential impacts of material delivery delays on the project completion date. On the other hand, optimal dynamic layout decisions were generated considering site space

needs and layout constraints. First, facilities F2 and F7 were relocated in the second stage due to the start of building B2 construction and to provide sufficient spaces for material storage areas. Second, operational and safety constraints were considered in the generated site layout plans by: (a) positioning personnel-related facilities (F2, F3, and F7) out of the falling objects hazard zones around the buildings and the tower crane; and (b) positioning material storage areas within the reach of the tower crane jib.



Fixed Ordering Periods ($FOP_{m,t}$)

Material	Stage 1	Stage 2	Stage 3
Rebar	21	21	21
Masonry	---	1 (JIT)	21
Curtain Wall	---	7	21

Temporary Facilities

ID	Description	ID	Description
F1	Tower Crane	F5	Dump Area
F2	Site office trailer (1)	F6	Lay-Down Area
F3	Site office trailer (2)	F7	Labor Rest Area
F4	Fabrication Area		

FIGURE 8. Generated Optimal Plan of Material Supply and Site Storage Layout

CONCLUSIONS

This paper presented the development of a new construction logistics planning model that is capable of integrating and optimizing the critical decisions of material supply and site storage layout. These decisions are optimized simultaneously using Genetic Algorithms to minimize construction logistics cost that include ordering, carrying, shortage, and layout costs. Future research efforts are planned to expand the present model by: (1) including other critical layout decisions such as equipment routing planning; (2) considering indoor spaces for material storage areas; (3) developing visualization systems to help construction planners in optimizing material logistics planning; and (4) considering and minimizing the joint costs for vendors and buyers.

ACKNOWLEDGEMENTS

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Progress Monitoring of Construction Projects Using Statistical Pattern Recognition

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Abstract

The traditional monitoring practice involves collecting actual quantity data, and comparing against a benchmark which represents the relevant planned data. The encountered well-known problem in monitoring is that the quality of the collected data is often subjected to great variation due to the variation in the reporting skills as well as the willingness to record data accurately. A potential technique to circumvent this problem is to conduct the comparison against multiple possible outcomes rather than a single-valued benchmark. The main objective of this research is to utilize the Statistical Pattern Recognition (SPR) technique to classify the work planned at specified cut-off dates during the planning stage and use the classification to monitor and evaluate the progress during the construction stage. The SPR technique generalizes a virtual benchmark to represent the whole project based on multiple possible outcomes generated at a given cut-off date. The generalization feature offers a potential tool to overcome the problem of variation in the quality of data collected. Patterns are constructed to encode work of the project at different cut-off dates. Finally, the SPR concept and technique proved its robustness to monitor and evaluate progress of construction projects based on the technique of Critical Path Method (CPM).

Introduction

Time management is a basic function of the system of construction project management. Time management constitutes project planning and project control. A project plan is devised to provide time guidance for the expeditious accomplishment of the project. During the construction phase of the project, project management controls site operations by establishing a progress monitoring and information feedback procedures. Current practices of progress monitoring and evaluation involve the use of the superintendent's daily site reports and the project manager's monthly progress reports to describe the quantities of completed activities. Project monitoring involves the determination of work quantities put into place and the feedback of this information in a format suitable for direct comparison with the plan. Project monitoring is performed at regular intervals and at a predetermined cut-off dates. Based on the fed back data, the

whole situation of the project is analyzed and consequently corrective actions are suggested to expedite lagging activities.

One objective of this research is to design and construct patterns that are being mapped to CPM schedules to describe the work planned during the planning stage as well as the work accomplished during construction stage. Patterns lend themselves well for manipulation by computer programs. The second objective is to employ the SPR technique to; classify the work planned at the predetermined cut-off dates during the planning stage using multiple possible patterns; and recognize the week that corresponds to the input patterns which represents the actual work accomplishments at a given cut-off dates during the construction stage.

Previous research

Several studies were reported in the literature related to computer-aided techniques that can be used for viewing site conditions and progress monitoring of construction projects. Hiroshi and Nobuoh (1993) described a filing system of construction pictures and its integration with a database. Abeid et. al. (2003) described the development and implementation of an automated real-time monitoring system for construction project programmed in a Delphi Environment. Riley and Whitesides (1999) conducted a study that assessed the feasibility, potentialities and best application for the implementation of digital image photography in the building design and construction process. Kubicki et al. (2004) focused on the use of building construction digital imagery as a computer-aided communication tool for improving coordination between the different actors involved in progress monitoring. Abd Majid et. al. (2004) discussed the development of a conceptual integrated model that acts as a tool to monitor and evaluate the physical progress of a construction project at periodic intervals. The model integrates the 2D digital images captured from small-detail concrete structural elements at construction sites, the as-built AutoCAD drawings of these elements, and the standard scheduling tools such as Microsoft Project. Memon et. al. (2005) discussed a Digitalizing Construction Monitoring (DCM) model which integrates 3D CAD drawings and digital images to document as-built construction schedules.

Other studies were recently reported in the literature related to techniques that could be used for progress monitoring and evaluating performance of construction projects. Barraza et. al. (2000) used a stochastic S-curve as an alternative to using the deterministic S-curve technique. Stochastic S-curves provide probability distributions for expected cost and duration for a given percentage of work completed. Monitoring project performance is performed by comparing the most likely budget and duration values, obtained from respective probability distributions for actual progress, with the project's actual data and cumulative cost. Cheng and Chen (2002) reported a study that focuses on developing an automated schedule monitoring system for precast building construction. The system, which is called ArcSched, is composed of a Geographic Information System (GIS) integrated with a database management system. Through systematic monitoring of the construction process and representation of the erection progress in graphics and colors, the scheduled components for erection are repetitively tracked. Construction progress is monitored through identifying the differences between the planned schedule and the real-time schedule. Nassar et. al. (2005) presented a statistical approach, namely Weibull

analysis, which can be used in conjunction with the Earned Value Method to evaluate stochastically the schedule performance of construction projects. Poku and Arditi (2006) developed a system called PMS-GIS (Progress Monitoring System with Geographical Information System) to represent construction progress not only in terms of a CPM schedule but also in terms of a graphical representation of the construction that is synchronized with the work schedule.

It became obvious by surveying the previous research that, utilizing pattern recognition concept and techniques in monitoring and evaluating the progress of construction projects is a novel approach in project management. Recently, Elazouni and Abdel-Wahhab (2009) developed a Neural Network (NN) pattern recognition model to monitor and evaluate progress of construction projects based on the technique of Critical Path Method (CPM) achieving the same above-mentioned objectives. The model classifies the work accomplishments achieved at predetermined cut-off dates. During planning stage, a number of patterns are prepared at the cut-off dates and used to train the NN. Thus, the evaluation of the completed work at a certain cut-off date is performed by benchmarking against multiple possible outcomes which is more meaningful than benchmarking against only a single outcome. During construction stage, a pattern is prepared to describe the work accomplishment at a given cut-off date and entered to the trained NN. The trained NN declares a date for the input pattern. Comparing the declared date to the actual cut-off date of the input pattern will indicate the status of progress. The results were such that the developed NN could recognize patterns with no recognition error. The study proved that the concept and technique of PR offers a very effective and robust approach to monitor and evaluate the progress of construction projects.

Naïve Bayes classifier

A naive Bayes classifier is a simple probabilistic classifier based on applying Bayes theorem with strong (naive) independence assumptions. Naive Bayes classifier is particularly suited when the dimensionality of the inputs is high. Despite its simplicity, Naive Bayes can often outperform more sophisticated classification methods. An advantage of the Naive Bayes classifier is that it requires a small amount of training data to estimate the parameters (means and variances of the variables) necessary for classification. Because independent variables are assumed, only the variances of the variables for each class need to be determined and not the entire covariance matrix.

From a Bayesian viewpoint, a classification problem can be written as the problem of finding the class with maximum probability given a set of observed attribute values. Such probability is seen as the posterior probability of the class given the data, and is usually computed using the Bayes theorem, as $P(C|X) = P(X|C)\ P(C)/P(X)$, where C is any of the possible class values, X is a vector of N feature attribute values, while P(C) and P(X|C) are the prior probability of the class and the conditional probability of the attribute values given the class, respectively. Usually Bayesian classifiers maximize $P(X|C)P(C)$, which is proportional to P(C|X), being P(X) constant given a dataset.

Bayesian classifiers are known to be the optimal classifiers, since they minimize the risk of misclassification. However, they require defining P(X|C), i.e. the joint probability of the attributes given the class. Estimating this probability distribution from a training dataset is a difficult problem, because it may require a very large dataset even for a moderate number of attributes in order to significantly explore all the possible combinations.

Conversely, in the framework of Naïve Bayes classifiers, the attributes are assumed to be independent from each other given the class. This allows write the following Bayes theorem, the posterior probability of the class C as: The Naïve Bayes classifier is therefore fully defined by the conditional probabilities of each attribute given the class. The conditional independence property largely simplifies the learning process of the model from data. In presence of discrete and Gaussian data this process turns out to be straightforward. Despite its simplicity, the Naïve Bayes classifier is known to be a robust method, which shows on average good performance in terms of classification accuracy, also when the independence assumption does not hold.

Methodology

During the planning phase of the project, cut-off dates separating periods at which the project will be regularly monitored during construction are specified. Normally, a monitoring period, typically a week, is determined when there is a need to describe a new stage of the project marked by the addition of an appreciable amount of work relative to the previous monitoring period. Patterns are designed and used to describe the work accomplishments of the particular project. A pattern is basically a matrix with appropriate numbers of rows and columns which can be used conveniently to map the CPM schedule of the project. The project work accomplishments at any time can be represented by filling in the appropriate cells of the schemes with 0-1 entries.

During the planning stage of the project, a number of patterns are generated for the project by assigning different start times of the project activities. The start times are selected randomly within the range of the early and late start times taking activities' sequence in consideration. Then, the completed patterns are curtailed at the cut-off dates to produce as many patterns as the number of the cut-off dates. The cells of the curtailed patterns to the right of the respective cut-off dates are filled with zero entries to produce patterns with identical dimensions. The variation between the generated patterns at a given cut-off date is basically due to the selected values of the start times. The set of patterns at a given cut-off date represent possible outcomes of the actual accomplishment at this particular cut-off date. The sets of patterns at all the cut-off dates along with the corresponding weeks constitute the input patterns to the SPR model. Some of the generated patterns are used for training the model and the remaining patterns are kept for testing.

During the construction stage of the project, the project monitoring is pursued regularly at the same cut-off dates specified during the planning stage. At any desired cut-off date, a pattern is prepared to describe the actual work accomplishments. This involves determining the actual start times of activities and the number of working days the activities have been in progress up to the cut-off date. Similarly, the cells of the pattern to the right of the cut-off date are filled with zero entries to produce patterns with identical dimensions. This pattern which represents the status of the project at the given cut-off date is introduced as an input pattern to the trained model. The trained model will declare the week that this input pattern tends to converge to its patterns. Comparing the date of the declared week to the cut-off date of the input pattern will indicate whether the actual progress is ahead or behind. Thus, the pattern recognition technique automatically implements the task of project monitoring and evaluation. A

detailed implementation of the outlined methodology is demonstrated in the application section below.

Application

Figures 1 and 2 show the CPM network and the corresponding pattern respectively of an example project of 25 activities. The pattern in figure 2 is basically a matrix of 25 rows and 27 columns to indicate the numbers of activities and working days respectively. The appropriate cells of the matrix are filled in with "one" entries knowing the start times and durations of the activities. The remaining cells of the matrix are filled in with "zero" entries. Thus, the matrix filled with 0-1 entries in figure 2 constitutes a pattern that represents the CPM schedule of the whole project and can be manipulated by computer programs. The cut-off dates of 5-day interval are indicated in heavy vertical lines in Figure 2. A patterns at the given cut-off date can be easily produced of the pattern in Figure 2 by maintaining the left-hand part and filling in the cells of the right-hand part with zero entries.

A total of twenty patterns were generated for the CPM network shown in Figure 1 at each cut-off date. The patterns are generated by randomly assigning values to the activities' start times within the range of the early start and late start values maintaining the sequence of activities. Figure 3 shows ten out of the twenty patterns of the CPM network at 27 days with shaded areas indicating cells with entries of "ones". Confining the start times of activities to a value between the early and late start times ensures that these patterns represent multiple possible patterns which will lead to the same project duration. Thus, the variation between the generated patterns at a given cut-off date is basically due to the variation of the start times of the activities. Twenty patterns at a given cut-off date can be generated by maintaining the left-hand side of the complete patterns and filling in the cells of the right-hand side with zero entries. The sets of random patterns at all the specified cut-off dates along with the corresponding weeks constitute the input to the SPR model.

It is more appropriate to divide each working day to 100 adjacent horizontal cells so any percentage of actual work accomplishment can be precisely indicated. In this case the number of columns of a pattern is increased hundred times. Thus, the actual work put in place of a given activity can be expressed as an even number of cells determined as a percentage of the total number of the cells reserved for that activity.

Implementation

The set of data for training and testing the model constitutes 6 cut-off dates each has 20 random patterns with a total of 120 patterns representing the input patterns. Associated with each input pattern there exits an output pattern of a vector of 6 entries indicating entry of "one" for the cut-off date of the pattern and "zero" for the entries of the other 5 weeks. The input pattern to the model is a vector 675 elements representing entries of 27 columns and 25 rows and the output represents a vector of six elements of the project cut-off date.

The model was trained on 3 patterns out of the 20 random patterns representing 18 input/output pairs. The trained SPR model was tested using the remaining 17 patterns representing 102 input/output pairs. When a particular test pattern is entered to the trained model, the recognized week is the week exhibiting the highest output among the twenty weeks. The results indicate that the 102 patterns were all recognized correctly. Ten different runs were done using 3

different patterns for training in each run and testing with the remaining 17 patterns. The results were such that there were no erroneous results in all runs.

Benefits of using PR technique

The collection of actual data in construction sites is prone to high degree of imprecision. Russell and Fayek (1994) noted that the issue of detection in the field contains a large extent of uncertainty and inconsistency. They imputed this problem to the considerable variance in levels of education and experience as well as attitudes toward recording daily site information by field personnel. Personnel responsible for recording daily site information range from experienced and educated engineers who are willing to accurately document work progress and productivity to inexperienced and uneducated personnel who struggle hard to document daily site information. Russell and Fayek (1994) noted that the attitude of personnel is either to align themselves with the field or the office. Those who are pro-field personnel tend to avoid paperwork. In addition, the detection of work progress by general contractor's personnel can be biased against the subcontractors.

Another problematic attitude of field personnel is to conceal the slow progress of some activities to appear in good shape. Knowing that the actual data will be compared directly against planned data on an activity-by-activity basis, the personnel reporting actual progress tends to covert the bad performance of stumbling activities by generously reporting the actual progress. They speculate that the problems are not really serious and some remedial actions upon putting in action will definitely speed up progress and produce better results by the subsequent cut-off date. Another reason to conceal slow progress is that being evaluated on an activity-by-activity basis and not on the holistic project performance, the bad performance of stumbling activities will camouflage the outstanding performance they accomplished in some other activities. All these problems result in a great deal of variation in the quality of information collected in the field.

The process of traditional monitoring which compares the actual collected data of individual activities against single-valued benchmarks often results in great variation in the quality of data collected due to reporting skills as well as willingness to record accurately. The generalization feature that the SPR brings about offers a potential environment to overcome this problem. The SPR technique generalizes a virtual benchmark to represent the whole project based on multiple possible outcomes generated at each cut-off date. The merits that the generalized benchmark offers include: The effect of the imprecision in data collection, which happens due to either the lack of experience or the nature of the work which makes it difficult to figure out the accurate amount of completed work, on the evaluation of the status of activities and the whole project is significantly diminished; The impetus for personnel to inaccurately report data on-purpose is entirely negated as actual progress is being evaluated against a virtual benchmark; A fair overall evaluation of the project considering both slow-progressed and well-progressed activities is presented to the field personnel while keeping the single-valued benchmarks of the individual activities exclusively to project managers to analyze situations and make decisions. The limitation of the SPR technique is that huge patterns need to be constructed for projects of long durations in case of representing a working day with 100 cells.

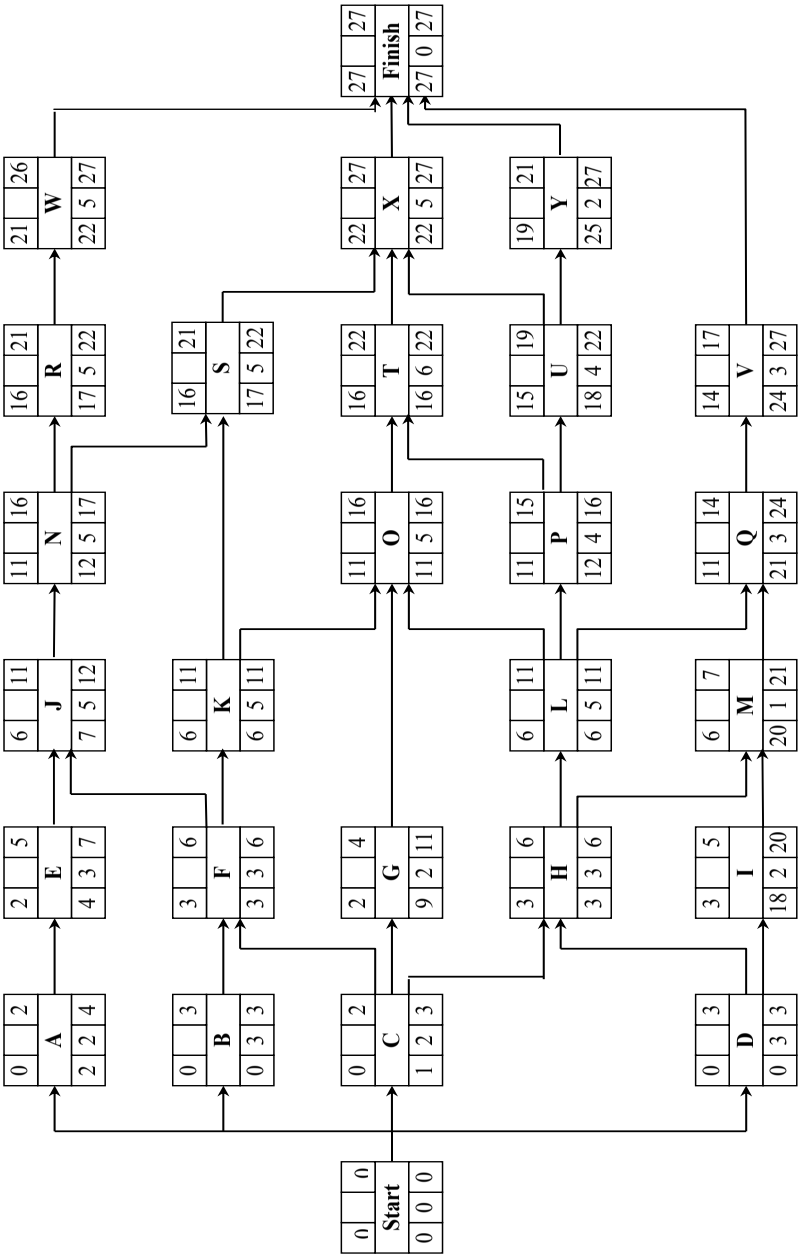


Figure 1: CPM network of an example project of 25 activities.

Days►	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Activity▼	Week 1					Week 2					Week 3					Week 4					Week 5					Week 6	
A	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C		1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
J	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
O	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Q	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
U	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
W	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Y	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0

Figure 2: Pattern of the example project of 25 activities.

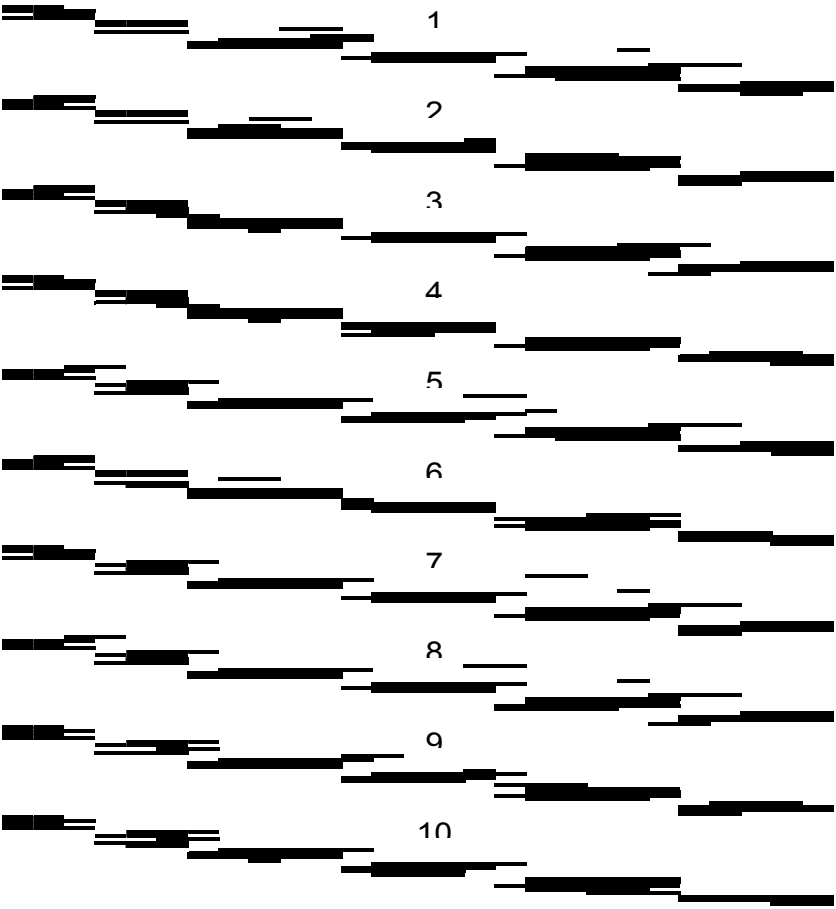


Figure 3: Ten random patterns of the example project at 27 days.

Conclusion

The objective of this study was to investigate the utilization of the concept and technique of pattern recognition to monitor and evaluate progress of the CPM schedules. The results were such that the SPR technique could correctly recognize 102 members out of 102 with no recognition error. This result indicates that the concept and technique of pattern recognition proved effectiveness and robustness to monitor and evaluate the progress of construction projects.

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SIGNIFICANT FACTORS AFFECTING RIGHT-OF-WAY ACQUISITION TIME IN HIGHWAY PROJECTS

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ABSTRACT

Right-of-Way (R/W) acquisition for highway projects is a complicated process that involves many parties. It is critical for project participants to know the main factors that determine the R/W acquisition schedule. This paper reports on a research project that studies the impact of inherent factors on R/W acquisition durations. The research uses ANOVA and correlation techniques to analyze the impact of 15 inherent factors on 14 different durations in R/W acquisition. Data from 13 projects in Texas with 172 parcels were collected. Among the 15 factors, Transitional Area, Acquisition Method, Ownership Type, Title Issue, Mapping/Survey Issue, and Exchange were found to have significant impact on at least 4 durations, including the Total Duration. Using results from the post-hoc tests, this paper presents quantitatively how R/W Acquisition Total Duration is different among levels of each of the significant factors. This research is believed to place an important stepping-stone in improving R/W acquisition and project development for highway projects through the better understanding of the critical factors and better forecast for R/W acquisition durations.

INTRODUCTION

R/W acquisition is a complex and complicated process, which might take years to complete and has many stakeholders, including the public. The acquisition process is critical in project development of many infrastructure projects because it determines when the project is ready for letting and construction. It is important for the project development team to know how long it takes to acquire necessary R/W and what factors may have significant impact on the acquisition time. While there have been scores of studies on Right-of-Way (R/W) and the project development process, overall understanding of these factors and their impacts remains limited.

Using historical data, this paper shows how factors inherent to the R/W project and parcel can be identified and their impact statically determined. Six out of 15 identified factors were determined to be important in R/W acquisition time because they have highly significant impact on the Total Duration (from R/W Release to Possession) and at least three other sub-durations. If a parcel is acquired by negotiation (deed), "Possession" is the "Closing" date; if it is acquired by eminent domain (condemnation), "Possession" is the "Deposit to the Registry of Court" date.

This paper reports this research process and provides a discussion on the research analysis results, including how the presence of a factor might make a difference in acquisition time. This exploratory research shows that investigating the inherent factors is valuable to project development estimating and planning and that further research is needed for better understanding and improvement of the R/W acquisition process. The inherent factors are defined as factors of the project and parcel that are relatively independent of the project team's direct influence and control. More detail on the research process and results can be found in Le (2009).

BACKGROUND

Current research on Right-of-Way acquisition tends to be more qualitative than quantitative. Three widely cited publications in R/W are those by the American Association of State and Highway Transportation Officials (AASHTO 2004), the Federal Highway Administration (FHWA 2002), and the National Cooperative Highway Research Program (NCHRP 2000). In the "Right of Way and Utilities Guidelines and Best Practices" publication, the AASHTO (2004) provides guidelines and best practices for eight major functional areas in the R/W and utilities processes. This document serves as an excellent method to disseminate best practices in the R/W and utilities professional community. Similarly, NCHRP (2000) reports on the state of practices in R/W and innovative project management models from several states. The FHWA went another step further by bringing the best practices in R/W acquisition and utility adjustment from select European countries (FHWA 2002). The FHWA's publication is the culmination of the findings and observations from visits to the European countries by the FHWA research team. These publications altogether provide an important snapshot of the best practices in R/W acquisition and utility adjustment in the US and Europe.

At the state level, the Center for Transportation Research (CTR) at The University of Texas at Austin conducted a research project on durations and delays in highway project R/W acquisition (Gibson et al. 2006). The research results included the categorization of delay factors into nine groups, each with specific challenges and

management strategies. The research also statistically identified four major factors affecting R/W acquisition time, namely "Total number of parcels," "Location type," "District R/W staff size," and "District annual R/W budget" (Gibson et al. 2006).

Current research in R/W acquisition is instrumental in helping improve the R/W acquisition process by reducing time and cost. The research, however, leaves a considerable gap in our understanding of how factors of different types and natures affect actual R/W acquisition time. A better understanding of these factors and their impacts will be valuable for the project development team in estimating acquisition time and devising proper action plan. This paper reports a part of the authors' research on the inherent factors of R/W project and parcels and the impact of these factors on the R/W acquisition durations. The paper sheds light on statistically significant factors and how they impact the R/W acquisition time.

RESEARCH PROCESS AND RESULTS

The first task of this research was to identify main R/W acquisition milestones and parcel and project inherent factors. The milestones and inherent factors identified are used for data collection and checking, which is the second research task. The data checking is to maximize the reliability of the data. The last task is data analysis, which is to analyze the impact of inherent factors on the R/W durations using the ANOVA and correlation techniques. In the following sections, details on the research tasks will be presented along with corresponding research results.

R/W Acquisition Milestones and Inherent Factors

The research team adopted TxDOT's then current R/W acquisition flowchart. A series of seven combined research team meetings were held from January to March 2008 to investigate and revise the acquisition flowchart. As a result, an updated R/W Parcel Acquisition Flowchart was created. It includes 85 milestones for the entire process, ranging from early planning (e.g., Early Coordination with Local Agencies, Preliminary ROW/Utility Data Collection) to the end of relocation (Parcel Cleared for Utilities). For further investigation of the acquisition process, the research team decided to select only the most critical milestones. As a result, 26 milestones were selected.

To start with identifying inherent factors, closely related literature was reviewed (e.g., Gibson et. al., 2006 and Heiner and Kockelman, 2005), and a preliminary list of factors was generated. This list of factors was updated based on the input from five interviews with seven R/W experts and project managers. This updated list was then used as a starting point for discussions among the researchers and R/W experts in the Austin district. Given their combined expertise in practice and research, the team was able to create a list of inherent factors with corresponding levels and units. This list of milestones was later shortened for data analysis; the shortened list is mentioned and presented later in this paper. Table 1 provides the final list of the factors and their levels and units.

Data Collection and Checking

With the critical R/W milestones and inherent factors identified, data collection started with selecting R/W projects. Only those projects that were under the management of TxDOT's Austin district and started within five years from the data

collection start date were considered. The TxDOT's Austin district expert team was asked to identify and recommend projects that met these criteria. As a result, 15 projects were selected for data collection.

Table 1. Inherent Factors with Levels and Unit

ID	Factor (Levels and/or Unit)	ID	Factor (Levels and/or Unit)
1	Total Duration	9	Title Issues (Yes; No)
2	Transitional Area (Rural; Urban; Suburban)	10	Mapping/Survey Issues (Yes; No)
3	Acquisition Method (Deed; Eminent Domain; ED then Deed)	11	Exchange Involved (Yes; No)
4	Ownership Type (Individual; Multiple; Business)	12	Relocation (Yes; No)
5	Use of Property (Residential; Business; Personal Property; Vacant)	13	Demolition of Improvements (Yes; No)
6	Improvements (Yes; No)	14	Project's Number of Parcels (Each)
7	Bisection of Property (Yes; No)	15	Parcel Size
8	Improvements Affected Not in Acquired Area (Yes; No)	16	Remainder Area (Percentage taken, i.e. parcel size compared to the entire land area)

Data Collection for R/W Acquisition Milestones

The data collection started with R/W acquisition milestones. The research team utilized both electronic and physical sources to collect data. First, the R/W data information management system (Tracker) used by the Austin district was the starting point for the data collection efforts. The team was able to retrieve about 30 percent of the needed data from it. Second, more data were collected from some of the project managers' individual computer files. The most important data source is the physical files of each project. The physical files store all documents, including correspondence among project participants and project R/W maps related to the projects. From April to November 2008, about 90 percent of the needed data was collected. The last major source of data was the TxDOT's Right-of-Way Information System (ROWIS). ROWIS was a helpful additional source of data that was employed when data could not be obtained from the other three sources and when data needed to be checked for accuracy.

At the end of the data collection process, one project was eliminated due to a significant lack of data for its two parcels. Another project was eliminated due to its special administrative arrangement. This project had been originally outsourced to another entity, which was to perform the entire R/W acquisition process. It was later changed to a semi-traditional project, whereby a consulting company would perform R/W acquisition while all the approval and payment related activities would be performed by TxDOT. This special arrangement disqualified the project from the research, and the research team decided to exclude it. As a result, 13 projects, with 172 parcels, were valid for further data collection and analysis.

Data Collection for Inherent Factors

After the data collection for R/W acquisition milestones was substantially completed, data collection for the inherent factors of 13 projects was carried out from November to December 2008. Similar to those of the milestones, data for the inherent factors were collected using various methods and sources, including the projects' physical files and the TxDOT's Right-of-Way Information System. The data collected for inherent factors would then be checked and finalized.

Data Checking and Finalizing

The processes of entering data into the information systems and collecting data from the physical files left much room for data inaccuracy, especially since the research required such extensive data collection efforts. The research team, therefore, strived to maximize the data reliability by carefully recording and checking data. Among others, the most formal strategy used for checking the data collected was preliminary data analysis. Data for the R/W acquisition milestones were used to calculate durations among the major milestones. Basic descriptive statistics such as minimum, maximum, mean, and standard deviation were calculated. The data checking strategies taken together helped the team identify and correct a considerable number of errors in the data collected.

Data Analysis

Analysis of variance (ANOVA) and correlation are the techniques that were used to perform the analysis of the inherent factors' impact on the R/W acquisition total duration and its sub-durations. A preliminary examination of the data collected showed that the sample size was not sufficient to perform analysis on all sub-durations between all pairs of successive milestones. The main reason was that the majority of the parcels did not have data on many of the milestones because the parcels were acquired by negotiation and did not go through the condemnation process. There were only 35 parcels (out of 172) that were acquired by condemnation. Therefore, the list of 26 milestones that was selected for data collection was again shortened to contain only 14 major milestones for further analysis. These milestones are presented in Table 2.

Table 2. Selected Milestones for Impact Analysis

ID	Milestone	ID	Milestone
1	R/W release	8	Parcel sent to condemnation
2	Appraisal ordered	9	Minute order issued
3	Approved by TxDOT	10	Law suit (petition) filed
4	Offer presented to owner	11	Hearing
5	Offer accepted	12	Warrant requested
6	Closing	13	Date of deposit into registry of court
7	TxDOT approval of final offer/presented	14	Actual vacate date

The fifth and sixth milestones ("Offer Accepted" and "Closing") are applicable to negotiation parcels only. Negotiation parcels have only five sub-periods between five pairs of successive milestones. Condemnation parcels, on the other hand, have 12 milestones (all but the fifth and sixth). Condemnation parcels therefore have 11 sub-

periods from 11 successive pairs of milestones. All parcels, negotiation or condemnation, share the same first three sub-periods because all parcels share the same path from the beginning to "Offer Presented to Owner." All 13 (11 + 5 - 3 = 13) sub-durations of the sub-periods were calculated and used for data analysis. Table 3 presents definitions of the durations. ANOVA was used to analyze the effects of the first 12 inherent factors in Table 2 (represented by 12 categorical variables) on the 14 durations (13 sub-durations and Total Duration). "Duration" is used as a generic term to designate either a sub-duration or "Total Duration." Correlation was used to analyze the relationships between each of the last three inherent factors (represented by three continuous variables) with the durations. The last variable, the remainder area, was presented as "Percentage Taken," which equals the quotient of the parcel size divided by the total area. Correlation was also used to analyze the relationship among the durations.

Table 3. R/W Acquisition Durations

Period	Duration	Period	Duration
R/W Release *to* Possession	Total Duration	Final Offer Approval *to* Condemnation Start	Sub-duration 5b
Release *to* Appraisal Ordered	Sub-duration 1	Condemnation Start *to* Minute Order	Sub-duration 6
Appraisal Ordered *to* Approved	Sub-duration 2	Minute Ordered *to* Law Suit	Sub-duration 7
Approved *to* Offered	Sub-duration 3	Law Suit *to* Hearing	Sub-duration 8
Offered *to* Accepted	Sub-duration 4a	Hearing *to* Warrant	Sub-duration 9
Accepted *to* Closing	Sub-duration 5a	Warrant *to* Deposit	Sub-duration 10
Offered *to* Approval of Final Offer	Sub-duration 4b	Possession *to* Actual Vacate	Sub-duration 11

Table 4 summarizes the analysis results using the analysis of variance and correlation techniques. Post-hoc tests (Tukey) were also performed when significance was found for a qualitative factor that had more than two groups.

Table 5 summarizes the averages of levels of factors that have significant impact on the Total Duration. For example, Acquisition Method is a significant factor; the table shows the averages of Deed, eminent domain (ED), and ED then Deed parcels. Pairs of levels that were found significantly different are denoted by the same lower letter. For example, Deed parcels and ED parcels are statistically different; they are denoted by the same letter "c."

Table 4. Summary of ANOVA and Correlation Analyses

	Total	Sub1	Sub2	Sub3	Sub4a	Sub5a	Sub4b	Sub5b	Sub8	Sub10	Sub11
Transitional Area	<.001	.024		.006	<.001	.001			<.001		
Acquisition Method	<.001				.002	.004	.018				.003
Ownership Type	.002		.002		<.001					.016	
Use of Property											
Improvements									.041		
Bisection of Property			.010								
Improvements Affected Not in Acquired Area			.001			.046					
Title Issues	.006		.023			<.001		.001			
Mapping/Survey Issues	.001	.003	.009		.017						
Exchange Involved	<.001			.001	<.001	.005					
Relocation			.011								
Demolition of Improvements											
Project's Number of Parcels	.042	.003	.005								
Parcel Size			.018					.014			
Percentage Taken											.021

Table 5. Averages of Levels of Significant Factors

Transitional Area			**Title Issue**	
Rural[a]	Suburban[b]	Urban[ab]	Title Issue	No Title Issue
407	457	952	690	459
Acquisition Method			**Mapping/Survey Issue**	
Deed[c]	ED-Deed	ED[c]	Mapping/Survey Issue	No Mapping/Survey Issue
411	514	606	653	447
Ownership Type			**Exchange**	
Business[d]	Business[d]	Business[d]	Exchange	No Exchange
544	544	544	1059	435

DISCUSSION OF RESEARCH ANALYSIS RESULTS

This section discusses the research analysis results. Six factors that have significant impact on the Total Duration are discussed.

Transitional Area

Transitional Area is the area that the parcel is located. Table 4 shows that Transitional Area has significant impact on five sub-durations and the Total Duration, with five of the six *p* values lower than 0.01. Take sub-duration 8 for example, Transitional Area has a extremely significant impact on the duration, from Law Suit to Hearing. Observations during data collection suggest that there is a great difference in terms of court's availability in different areas. This different availability may explain in part the significant difference in terms of time. A closer look at Table 5 reveals that there are significant differences between urban area and each of the other areas. Acquisition of an average urban parcel takes twice as much as that of a rural or sub-urban parcel (952 days vs. 407 or 457 days). However, there is no statistically significant difference between rural and sub-urban parcels in acquisition time. While this finding might not be very surprising, it provides statistically proved evidence that urban areas pose unique challenges to R/W acquisition in terms of time. The project team and the planning agencies should take the finding into account in planning for project development.

Acquisition Method

Acquisition Method describes the basis on which the parcel is acquired, whether by negotiation (Deed), by condemnation (Eminent Domain), or by negotiation but the eminent domain was initiated prior to reaching agreement (Eminent Domain then Deed). Table 4 shows highly significant impact of the acquisition method on the Total Duration ($p < 0.001$). Four other sub-durations are also significantly affected by the acquisition method. As Table 5 indicates, there is statistical evidence for the difference between acquisition by negotiation and by condemnation. While this finding is expected, the gap in terms of time needed to acquire parcels is a warning sign for planning. On average, a condemnation parcel is 47% longer than a negotiation one (606 days vs. 411 days, or a 6.5 month difference). There could be many reasons for the condemnation process to be initiated; one important reason is the value evaluated by the appraiser. The ability and willingness to compensate the landowner in a more flexible manner would give the state highway agency the flexibility in time.

Even though there is not yet a statistically significant acquisition time difference between Deed and ED-then-Deed parcels, Table 5 shows a difference of more than 100 days. Loosely speaking, when letting a parcel have the Eminent Domain process initiated, the state highway agency would need, on average, 100 days more than the time needed to acquire by Deed.

Ownership Type

Ownership Type is used to describe how the property of interest is owned, by a business, by an individual, or by more than one person. The research results show that Ownership Type significantly affects the Total Duration and three other sub-durations. The post-hoc test revealed that time to acquire a business-owned property

is significantly longer than that to acquire a multiple-owner one. Business property tends to be more difficult to evaluate due to the complex nature of the property itself and the business opportunities to be lost in association with the relocation of the business. On average, the acquisition time for a business property is more than 3 months longer than that for a single-owner property (544 days vs. 441 days) and more than 5 months longer than that for a multiple-owner property (544 days vs. 380 days). Because it is quick and easy to identify which property is a business, this finding is valuable to the project development team in estimating and planning for acquisition of properties of this ownership type.

Title Issue

There are a wide range of title issues in R/W acquisition, for example, a lien on the property of interest or the passing away of the property owner. Title Issue is a significant factor affecting the Total Duration and three other sub-durations of which the *p* values are all smaller than 0.05. On average, it takes 231 days (almost 8 months) longer to acquire a parcel if it has a title issue. Most of the time, the presence of a title issue is out of control of the project team. However, in order to minimize the impact of title issues on the acquisition time, the project team can streamline the process so that such issues can be identified earlier. For example, communication with the property owner and the title company should be initiated as soon as possible, after the R/W Release.

Mapping/Survey Issue

Mapping/Survey Issue includes all types of issues directly related to the mapping and survey work. Mapping/Survey Issue was found to have significant impact on the Total Duration and three other sub-durations. Mapping/survey issue is quite prevalent in R/W acquisition; twenty-one out of 172 parcels (12%) in this study involved at least one mapping/survey issue. Oftentimes, this type of issues involves discrepancies between the R/W map and the reality. For example, it was later discovered that a substantial part of one of the studied parcels was a roadway easement therefore the TxDOT did not have to pay for this easement part; the R/W map had to be revised.

When a parcel has a mapping/survey issue, it takes, on average, more than 200 days (653 vs. 447) to acquire. Many of the issues of this type are related to survey work. Good coordination and cooperation among the offices in the project development process would likely improve the acquisition time since the issues could then be prevented or, if present, identified earlier.

Exchange

It is not unusual for the property being acquired to be exchanged for a state-owned property (eleven of the 172 parcels studied were exchanged). Most of the time, these two properties are close to each other and have similar characteristics. When an exchange is involved, appraisals need to be done for both properties. The state-owned property must be made ready for the owner to take over before the state can possess the property of interest. These reasons, among others, explain why Exchange was found to be a highly significant factor determining the R/W acquisition time. The statistical analyses revealed that Exchange has significant impact on the Total Duration ($p < 0.001$) and three other sub-durations. On average, the time it takes to acquire an exchange parcel is about 2.5 times (1059 days vs. 435 days) as much as

that to acquire a non-exchange one. Exchange is necessary in some cases, e.g. there is a road running through the land to be acquired. In other cases, exchange is voluntary for the state highway agency. Due to the significantly longer time needed for an exchange parcel, it is crucial for the project team to plan accordingly when exchange is unavoidable or is selected.

CONCLUSIONS

This paper presented a part of an exploratory study on the impact of inherent factors on R/W acquisition schedule. The study showed that "Transitional Area," "Acquisition Method," "Ownership Type," "Title Issue," "Mapping/Survey Issues," and "Exchange" are statistically significant to the Total Duration. Taking these factors into consideration in estimating and planning for R/W acquisition would be helpful for the project team. The discussion section provided further insight on how each of the significant factors affected the R/W acquisition time. This study considered a large number of milestones and inherent factors while the sample size was relatively small. Further data collection and analysis are, therefore, expected to provide a further insight into the impact of inherent factors on R/W acquisition time. Importantly, this study shows that the better understanding of the impact of the inherent factors is beneficial to the project development process and further research in this direction is needed.

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USING KEY DATE MATRIX (KDM) TO MINIMIZE RISK IN SEMICONDUCTOR FACILITY PROJECTS

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ABSTRACT

A new semiconductor facility project can take four years to build, install production tools and start manufacturing. With the current market competition, companies target facility completion within 18 months. Projects are typically planned using a traditional scheduling methodology where successor activities start when the predecessors are finished, resulting in zero float in the schedule. Any delay can have a domino impact on the completion date. Often during the 18 months facility schedule, the owner will continue to adjust their end date and facility scope due to market demand. These changes can modify the contract scope and schedule causing the project team to lose sight of the project priories and lower their efficiency, passing accountability to the owner. In order to increase accountability and focus on the correct priorities a Key Date Matrix (KDM) was developed. The KDM improves the communication between different project teams, identifying and re-sequencing scope, quickly defining risk between the execution schedule versus need date for the activities. This was demonstrated to increase contractor accountability as 98% of the planned schedule was completed on time.

KEYWORDS: Semiconductor Facility, Scheduling, Project Delays, Project Communication,

INTRODUCTION:

The semi-conductor industry is more competitive than ever. Every company tries to release its latest technology once it is developed. The profit margin can be significant for the first company that can bring the latest technology to the market. While the

high initial investment can bring a wafer manufacturer a high return, any delay in construction of the manufacturing facility can cause the loss of millions of dollars in opportunity cost and market share. According to research from In-Stat (2007) worldwide semiconductor revenue was $267.3 billion in 2006 and is forecast to surpass $300 billion in 2010. As a result, the semiconductor industry is trying to construct its manufacturing facilities and install its process equipment as fast as possible for production requirements. Due to the rapid pace with which the semiconductor industry is growing, cost and time of a semiconductor manufacturing become the key factors to the success of the semiconductor manufacturer. Knowledge of the time required for construction of a facility, the speed of construction, and its impact on cost are significant factors that determine the marketability of the product in terms of the time frame associated with the product (Patel and Chasey, 2005).

A typical semi-conductor manufacturing facility can take three to four years from ground breaking to start of production, but many companies are now targeting to finish construction and tool installation within 18 months. He et al (2002) discussed the competitive nature of the semiconductor industry, "Under the existing volatile economic environment and with the shortened cycle of technology, wafer manufacturers are facing increasingly intense competition either at the domestic or international market level" (He, Chasey, Patel 2002). Since each owner wants to maximize the return on their multi-billion dollar facility investment, they pressure the project team to complete the facility as soon as possible. With this pressure, schedule stability is important to the supplier as well as the contractor (Chester and Hendrickson, 2005). For tool install construction, construction is dependent upon the tools sent by the supplier. If the schedule is not stable, the supplier may send the tools to other manufacturers or the tool may show up too early and require storage space. The more time and effort spent on the pre-project planning process will result in more gains for the owner, including increased predictability of costs and the schedule, a reduced probability of project failures, and improved operational performance (Chasey and Guo 2000).

The semi-conductor industry is such a dynamic industry, the semiconductor manufacturer will adjust production output each quarter based on market demand. This required output statistic will drive the number of wafers to be produced in the near future. This adjustment will change the number of production tools that are required in a factory. When a project is under construction, this fluctuating demand can impact the construction schedule and cause re-prioritizing of tool installation and facility construction sequencing. According to Chester and Hendrickson (2005), "Construction mismanagement often results from changing plans at the last minute. A change of plan is felt not just by the project manager but can be felt by all of the contractors on the job whose tasks are interconnected" (Chester and Hendrickson, 2005). Ibbs (2008) research demonstrated that if there is continuous change during the [construction] execution labor productivity will decrease. It is important to understand that if the schedule of a semiconductor facility is changing, it will decrease contractor productivity and affect the final completion of the facility and tool installation.

BACKGROUND

A semiconductor facility project contains three distinct phases: cleanroom construction, process support system (PSSS) construction, and tool installation and qualification (IQ). During the project cycle each phase has activities that can follow one another or be performed in parallel. In order for activities to be done on time, pre-planning and integration among the three phases are key to the success of the project. Figure 1 outlines the overall project timeline.

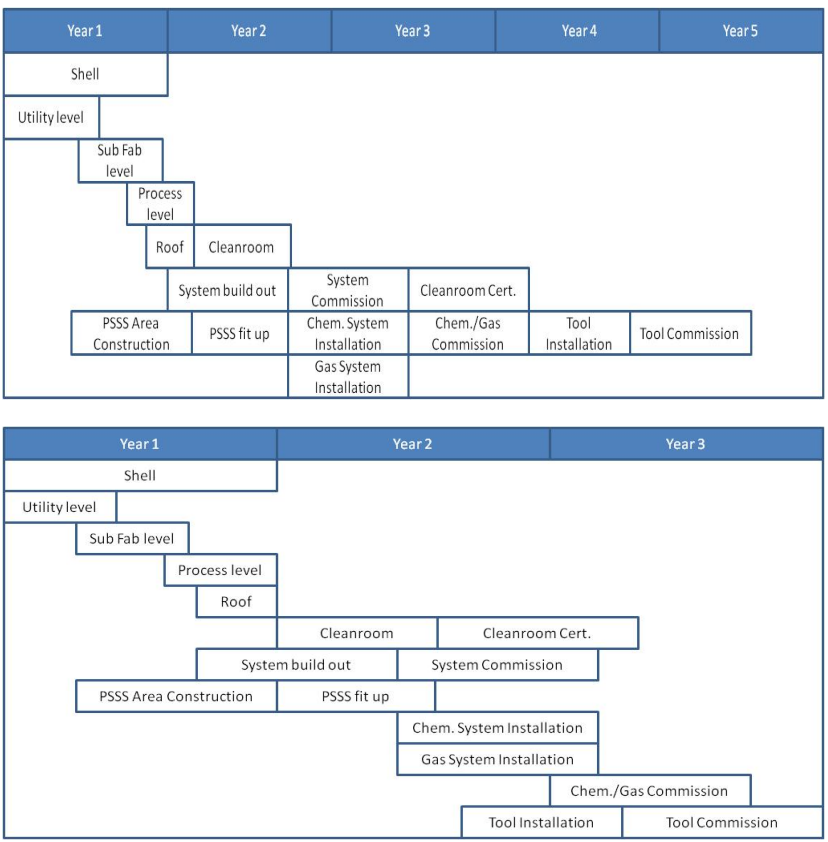


Figure 1: Typical vs. current overall Program Timeline

In order to better manage the multiple scopes of work, each phase is divided amongst different management teams. The cleanroom construction team handles the overall cleanroom build out and the systems that support the cleanroom functionality. The process specific support system (PSSS) construction project team installs process specific systems to support the variety of chemicals and gases that are used during the

manufacturing process. The manufacturing tool installation and qualification (IQ) team is responsible for installation of the production tools and delivery system (piping) between the cleanroom and the process specific chemical/gas systems. Both the cleanroom construction and PSSS are generally contracted to a CM firm to manage the subcontractors. For IQ construction, the owner typically acts as the construction manager responsible for managing the subcontractors because IQ construction is involved with manufacturing information that is considered intellectual property. Owners want to manage this portion of work. The construction team structure is show graphically in Figure 2.

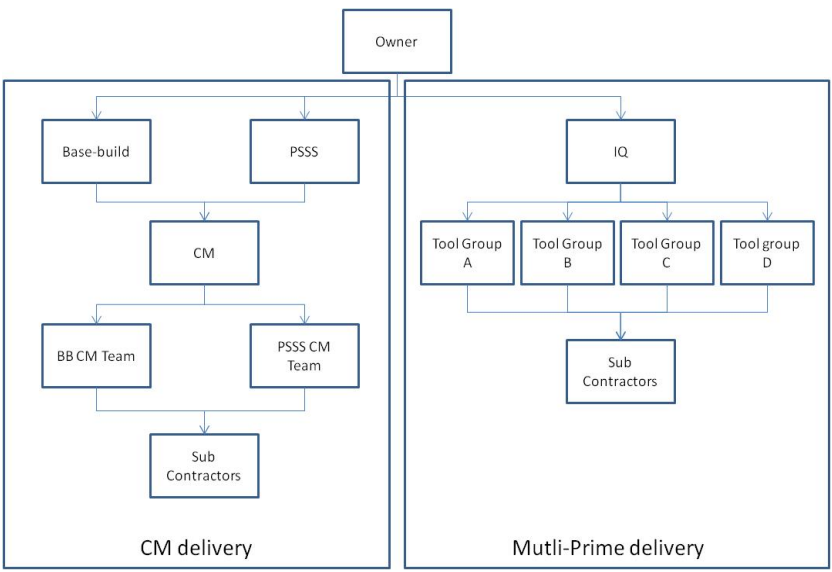


Figure 2: Semiconductor Construction Project Team Structure

SEMICONDUCTOR PROJECT CONSTRUCTION ISSUES

The semiconductor project can be divided into two different delivery methods: CM at risk and Multi-prime. The cleanroom and PSSS construction are delivered using CM at risk where the CM firm is responsible to manage and complete the project. For the tool installation phase, a multi-prime delivery approach is used where the owner acts as CM and manages the subcontractors directly to complete the defined scope of work. This approach can lead to conflicts during execution. Three main issues arise with this delivery approach:

- Changes: The project schedule is generally planned using a backward pass calculation. The need date for each activity is planned to start and finish on the date needed with no schedule buffer. If a successor activity completion date changes, the predecessor activity will be impacted. For a semiconductor facility

project, IQ construction and tool commissioning is the driver. Changes made during IQ construction often are mishandled by the owner project team. For example, re-prioritizing the tool installation sequence will impact the cleanroom and PSSS construction schedules.

- Mixed direction and priorities: The current project execution method provides mixed direction and priorities to the construction teams. The IQ team is divided into tool groups to manage the different tool installation requirements. A typical semiconductor fabrication facility will have over 230 different types of tools in a manufacturing line, each tool requiring different utilities and chemicals for production. Before installation of a particular tool, the cleanroom area needs to be certified and the chemical/gas systems need to be commissioned and available for tool start up. Since each tool group has their own priorities, each thinks their priorities are more important than the others; therefore, they will request their area and systems be completed first. This creates mixed directions for the contractors, because each tool group usually shares resources and subcontractors within IQ. Allocating resources to other activities without proper planning will impact schedules and confuse contractors regarding installation priorities.
- Limited communication with other stakeholders: Beside construction and tool installation, other groups, such as purchasing, logistics, and equipment vendors, also support the project. For IQ construction to start on time, the production tool must be on site. This requires clear communication between purchasing, logistics, and IQ construction because the date the tool installation process is to begin must be identified. Purchasing and logistics needs to ensure the tools are purchased with sufficient lead time to be available for installation start. All other manufacturing support groups also need to be part of the communication to ensure vendor support, spare parts and production materials are available for tool commissioning activities. Since some of these activities can be overlooked, they can also cause delay to the schedule and invite possible claims from subcontractors and suppliers.

Change can impact the critical path of the project and re-sequencing scope can have a domino effect on successor activities. Consequently, a project team is unable to foresee future activities as being as important as current execution. If the schedule does not predict and foresee potential impacts, the project will have uncertainty, which becomes risk. To minimize the impact of missed communication and loss of priorities, a Key Date Matrix (KDM) was developed to maximize communication regarding changes and prioritization of scope, while increasing the accountability of project completion for the contractor. The KDM minimized the number of change orders and reduced the impact on the project timeline.

KEY DATE MATRIX

The fast pace of a semiconductor facility project can lead each project team to focus on their individual scope and lose sight of the project goal: to complete the installation of the process tools and start wafer production. With each of the three project teams (cleanroom, PSSS and IQ) managing their own scope of work, they

could work on the wrong or conflicting priorities. By simplifying the integration process between the teams and establishing a communication tool, confusion over priorities and completion dates can be minimized.

Since each project team may have their own schedule of 10,000+ line items, it is difficult to identify and prioritize needs between the various schedules. The KDM was developed to clearly communicate when the cleanroom space is required and when each of the utilities are needed to support commissioning of the process tools. The benefit of the KDM is to simplify the integration process among the three project teams. Figure 3 below illustrates the KDM integration.

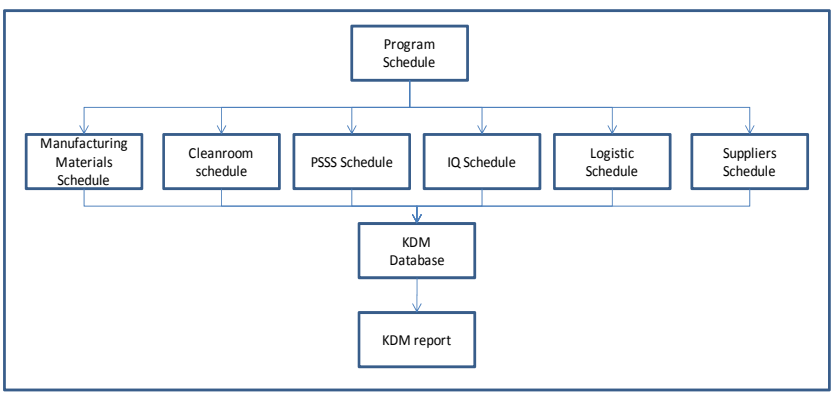


Figure 3: Key Date Matrix Integration

- Program schedule – contains the overall project milestones including the project start date, funds available date, mobilization, cleanroom finish date, cleanroom certification, and IQ start date.
- Manufacturing materials schedule – provides information when manufacturing materials will be available to start tool commissioning activities. These materials are production materials provided to the tool vendor to test the functionality of the tools.
- Cleanroom schedule – provides the date the cleanroom space will be certified for tool installation. This is one of the critical activities for the semi-conductor facility project. If the cleanroom cannot meet the cleanliness requirements, the tool installation cannot start.
- PSSS schedule – provides the installation timing for supporting distribution piping for the chemical and specialty gases. This construction provides the distribution system required to supply the gases and chemicals to the production equipment. Tool commissioning cannot start until the system is installed, tested, and accepted.
- IQ Schedule – provided tool installation and qualification dates. All schedules revolve around the IQ schedule. The cleanroom schedule needs to plan area

certification according to the IQ priorities. The manufacturing materials and PSSS schedule are to ensure materials availability and chemical and gas delivery system commissioning according to the IQ activities. The logistic and supplier teams schedule production tool installation per the IQ need date. Any change in the IQ schedule impacts everyone's schedule.

- Logistic Schedule – provides the estimated arrival date of the production equipment to the factory. If the tool is not available for installation, subcontractors will not be productive and installation schedules will slip.
- Suppliers Schedule – provides the vendor arrival date to support commissioning activities. Specialized installation teams from tool vendors install and commission the process tools for process qualification.

The ultimate users of the KDM are the subcontractors. The matrix provides information on priorities and changes when they happen, eliminating confusion or faulty direction. Using an integrated schedule helps forecast potential risk and helps project teams focus on problem areas. The schedules described require dates to be at a system and area completion level. If the schedule is at a micro level it will contain too much detail to effectively manage integration. Conversely, if the schedule is at too high a level, integration and priorities cannot be set. To understand the level differences, the schedules are broken down as follows:

- Level A – program milestones – Pre-programming, planning, execution start
- Level B – project milestones – funding, design start, tool move in
- Level C – scope milestones – area specific system completion, cleanroom area ready date, safety system completion date, vendor availability, material availability. This is the level for KDM integration.
- Level D – activities milestones – panel finish, valve installation, gas/chemical lateral complete

The level C schedule indicates which systems, what areas, when needed, and in what order. If level A or B schedules are used for integration, it will not be successful because they are at a programming or milestone level. Similarly, if a Level D schedule is used, it will be too detailed to manage and integrate the project teams. Using a Level C schedule, a project manager can focus on the priority systems in the different areas required by IQ. The KDM should be published weekly by the scheduling team allowing changes to be reflected and then reviewed by the project team.

Combining the cleanroom and IQ schedules into one matrix provides a clear priority list of cleanroom area, chemical/gas materials needed and tool delivery date. This allows identification of potential risk to the IQ schedule, i.e. which tools will not be available on the requested need date or which vendor will not be able to support commissioning activities due to lack of resources. In addition to the data required to develop the KDM, a few additional criteria are needed for the matrix to function properly. These criteria are as follows:

1) The entire schedule needs to speak the same language, that is, each schedule must have a link to connect to each other schedule. For example, the location naming

convention should be identical, agreed upon, and reconciled between groups with the established schedule.
2) A strong leader is needed to facilitate the integration meetings and understand the communication process between groups.
3) Programming changes need to be reported and the scope re-prioritized due to the changes brought to the meeting.
4) Each project team leader needs to be ready and prepared for the integration meeting. Follow-up is assigned to the responsible group and the due date is documented. Each action item is reviewed during the meeting and project teams are held accountable for the follow-up action.
5) Integration meetings should be discontinued when they are no longer required.

The KDM is developed using the IQ schedule as the basis since the IQ schedule contains the tool's location and the installation start date. These two elements will assist the cleanroom construction team in developing the priority for certification of the cleanroom area needed. The tool type and commissioning start date in the IQ schedule help the PSSS team determine which gas and/or chemical systems are needed to support tool commissioning. Table 1 is an example of a KDM for the cleanroom. It compares the cleanroom schedule with the tool installation schedule and identifies which cleanroom space is at risk for a tool to be installed as scheduled to meet the tool need date. Table 2 below is the KDM for the utilities that compares the PSSS schedule to the tool installation schedule. This table assists the project team in prioritizing the PSSS construction and identifies risk to the completion date.

Table 1: Example of Cleanroom Key Date Matrix

Zone	Fab Certification (Complete)		First Tool	
Fab Level	**Certed**	**Float**	**ID**	**Set Date**
BD Zone #1	11/29/06	**-1**	601	11/29/06
BD Zone #2	11/27/06	**-29**	501	10/30/06
BD Zone #3	12/11/06	**-8**	505	12/04/06
BD Zone #4	11/28/06	**-9**	504	11/20/06
BD Zone #5	01/12/07	**-8**	611	01/05/07
BD Zone #6	12/13/06	**-10**	536	12/04/06

Location | Clean-room schedule | Tool-install schedule

The KDM simplifies the integration between each construction team and helps identify gaps between the finish date and the need date. For example, Table 2 shows that the oil free air (OFA) system completion date is six days after the IQ need date for tool 501 at location 304. This provides a clear direction for the project team to focus on this area, thus prioritizing risk in the schedule. At the same time the KDM defines which utilities or systems are needed. This KDM can be generated weekly so the scheduling team can host a schedule review meeting to analyze potential risk

(negative float) and document any work-arounds or solutions to the identified problems.

Table 2: Example of Utilities Key Date Matrix

Base-build / PSSS Completion date					IQ need date			
Scope	System	Facility System	First Need	FLOAT	Tool ID	Bay Location	Start	Finish
PSSS	AW	09-Nov-06	21-Dec-06	42	509	IM PC F2B41	04-Dec-06	21-Dec-06
BB	EXGF	09-Nov-06	30-Nov-06	21	504	309	21-Nov-06	30-Nov-06
BB	EXSC	09-Nov-06	26-Dec-06	47	536	312	05-Dec-06	26-Dec-06
BB	ICW / IW	09-Nov-06	22-Dec-06	43	504	IM PC Subfab	07-Dec-06	22-Dec-06
PSSS	NH4W	09-Nov-06	19-Dec-06	40	602	402	08-Dec-06	19-Dec-06
BB	OFA	09-Nov-06	03-Nov-06	-6	501	304	31-Oct-06	03-Nov-06
BB	SW	09-Nov-06	21-Dec-06	42	509	IM PC F2B41	04-Dec-06	21-Dec-06
BB	UPW	09-Nov-06	26-Dec-06	47	504	311S	05-Dec-06	26-Dec-06

Type of utilities | Clean-room /PSSS Schedule | Tool install schedule

IMPLICATION FOR SEMICONDUCTOR FACILITY PROJECTS

Although having a consistent and reliable KDM will reduce confusion over priorities, a dynamic updating process and a stable schedule is required to keep the KDM accurate. If the schedule is unstable, the priorities in the KDM will constantly change thereby compromising the KDM credibility. If the KDM loses credibility, the project teams may lose direction and revert to setting their own priorities. This KDM methodology could be used on any construction project that needs to integrate multiple project teams. It will also improve the ability of project managers to foresee risk, increasing the potential for project success.

CONCLUSION

To simplify the integration process among the various project teams, the Key Date Matrix (KDM) was developed. The KDM improved the communication process, defined priorities, and provided a methodology to identify areas at risk. In the semiconductor industry, communication between project team is critical for the project to be successful. Semiconductor facility projects are challenged by constant owner changes, overlapping of work between the project management teams, and tight schedules. Because of these challenges, contractors may not be held accountable for project slippage and the efficiency of the entire project team is lowered. The

creation of the KDM developed a communication bridge between the owner, project teams, and sub-contractors. The KDM reduced the communication gap between the project teams and increased the accountability of the subcontractors, keeping their focus on correct priorities and assisting them in properly sequencing their work.

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A Decision Model for Technology Selection in Renovation Project Planning

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Abstract

As infrastructure ages, a significant portion of US capital expenditure is incurred for the renovation and retrofit of existing facilities. Renovation projects are complex, high risk, and involve extensive coordination and planning, primarily due to uncertain site conditions and continuing operation requirements of existing facilities. Early studies have identified innovative and emerging technologies that facilitate site investigation and align renovation and maintenance activities with business production and operation schedules. However, the selection of appropriate technologies in specific project and business environments remains a challenge. Particularly, there is no guidance for project teams who must incorporate the selected new technologies into scope management and project planning. This paper establishes a framework to guide project teams towards appropriate technology selection in renovation project planning. A decision model is developed to integrate the technology selection process into a widely used scope management tool, Project Definition Rating Index (PDRI). The model is specially designed and flexible enough to allow project teams to decide appropriate technologies according to various criteria, including cost, application area, and risk mitigation.

Keywords: Renovation, Project Planning, Project Definition Rating Index, Technology Selection, Decision Model

1. Introduction

A large volume of construction work has been carried out during the past decade in renovation projects in the United States. According to a survey conducted by the Construction Industry Institute (CII), approximately 30% of project funds spent by CII member companies were allocated for renovation and maintenance of existing facilities (CII 2009a). Nationwide, the U.S. Department of Commerce estimated that nonresidential renovation projects account for hundreds of billions of dollars annually (USDOC 2009). Consequently, a large volume of contractor work is in the renovation arena as well. As the US is taking steps to improve energy efficiency and combat global warming, the renovation construction market is widely anticipated to grow rapidly to meet the constantly increasing demand for energy efficient facilities.

Renovation projects, also named retrofit, revamp, rehabilitation, maintenance, turnover, upgrade, overhaul, reconstruction, or brownfield projects, tend to be smaller in size than typical greenfield projects. However, individual renovation projects can be quite large. In renovation projects, unique or increased risks associated with cost,

schedule, or quality appearance are not generally present in greenfield projects. The initiation of a renovation project usually involves a long process of contemplation under conditions of high uncertainty. The conditions of the existing site and in-place equipment are typically unknown. Older facilities often have unusual safety hazards, uncertain spatial characteristics such as unseen interferences, outdated or inaccurate existing condition information, legacy environmental conditions, architectural or historical concerns, or issues with dismantling or demolition.

It is arguable that these risks involved in renovation projects could be reduced in the Front End Planning. Front End Planning is defined as "the process of developing sufficient strategic information with which owners can address risk and decide to commit resources to maximize the chance for a successful project" (Gibson and Pappas 2003). CII research indicates that well-performed front end planning can reduce costs, lead to less project variability in terms of cost, schedule and operating characteristics, and increase the chance of meeting project's environmental and operational goals. This previous research has lead to tools such as the Project Definition Rating Indexes (PDRI), and the Alignment Thermometer to help teams more effectively plan projects. Additional research also has identified a few new technologies such as Penetrating Radar, 3D Laser Scanning, and Rapid Prototyping etc., that can improve the accuracy of condition investigation. However, it is still a challenge for project teams to select appropriate technologies and apply them on a renovation project because of the lack of effective tools for decision making.

This paper aims to develop a decision model to facilitate the selection process on site condition investigation technologies in renovation projects. The paper starts with a review on the scope definition rating tool PDRI and Project Condition Investigation (PCI) Technologies. Then, the paper defines the characteristics of PCI technologies and their relationships with the PDRI elements. Furthermore, a decision model is presented that combines the PDRI sheet with site condition investigation technologies. Finally, a case study is discussed to illustrate the application of the model.

2. Project Definition Rating Index

A poorly defined project can undergo considerable changes that may result in cost overruns and a greater potential for disputes (Gibson and Kaczmarowski 1995, Dumont et al 1997). The PDRI for construction projects is developed by CII as a powerful and easy-to-use tool that provides a method to measure project scope definition for completeness. It identifies and precisely describes each critical element in a scope definition package and allows a project team to quickly predict factors impacting project risk (Dumont et al 1997). The PDRI allows a project planning team to quantify, rate, and assess the level of scope definition on industrial construction projects prior to authorization for detailed design or construction. It is intended to evaluate the completeness of scope definition at any point prior to detailed design and construction.

The PDRI offers a comprehensive checklist of 70 scope definition elements in an easy-to-use score sheet format. Each element is weighted based on its relative importance to the other elements. Since the PDRI score relates to risk, those areas

that need further work can be easily isolated. Applicable industrial-type projects may include the following: Oil / Gas production facilities, Textile mills, Chemical plants, Pharmaceutical plants, Paper mills, Steel/Aluminum mills, Power plants, Manufacturing facilities, Food processing plants, Refineries, Civil/Industrial Infrastructure, and Plant upgrade/retrofit (CII 2009b).

There are three main sections of PDRI; each of them is broken down into a series of categories, which, in turn, are further broken down into elements. Adding the individual element evaluations and their corresponding weights leads to a single PDRI score for the project, which can range from zero to 1000. The lower the total score, the better definition of a project. The PDRI target score is 200 points. In other words, the project scope could be considered to be well defined if the PDRI score is below this benchmark. Nevertheless, it should be noted that the PDRI alone does not ensure project success but should be coupled with sound business planning, alignment, and good project execution to greatly improve the probability of meeting or exceeding project objectives (CII 2009b).

3. Emerging Technologies for Project Condition Investigation

New and emerging technologies and tools have great potential to help project teams mitigate risks associated with unknown existing site and equipment conditions or other factors (Rosenfeld and Shohet 1999). A number of PCI cards, which have been developed, document some of the tools currently in use. For each of the tools, the PCI cards cover the following topics: Tool Name, Alias, Description, Service Fee, Benefits/Features, Application Areas, Service Providers, Equipment Suppliers, and Other Issues.

Existing facility conditions pose a unique risk issue for renovation projects. Unknown subsurface conditions, facility configuration, and degraded equipment or systems can threaten the successful completion of a renovation project. Effective front end planning requires the project team to perform a comprehensive assessment of existing site and equipment conditions (CII 2009a). The assessment must be based on a detailed investigation of six categories of project conditions, which are shown below in Table 1.

4. Model Development

As the PCI technologies provide potential to improve project planning, research effort is needed to integrate the PCI technologies into the successful front end planning process. Especially, the integration process must consider that fact that project teams may have very different demands. For instance, some teams may identify their problems well and need a tool to help them to select appropriate PCI technologies, while others may not fully understand the site condition, or they are willing to try new technologies in their projects. Therefore, this model is specially designed to satisfy project teams' needs and defines three levels of technology selection processes, namely problem-oriented, risk-oriented and technology-oriented. Accordingly, decision criteria for technology selection are identified as application area, risk mitigation, cost effectiveness measured by performance over cost ratio, and technology match. The framework of the Decision Model for Technology Selection (DMTS) is shown in figure 1. The following sections will describe how

the proposed model facilitates project teams with PCI technology selection on renovation project planning.

Table 1: Application Areas of PCI technologies (CII 2009a)

Application Areas	Scope of Areas	Example Technologies
1. Underground Conditions	Underground or embedded utilities, structures, and other unknowns are potentially dangerous and expensive to address if found during construction.	Ground Penetrating Radar, Electromagnetic Conductivity.
2. Integrity	The current condition of existing mechanical and electrical systems, structures, and their components must be assessed in terms of their fitness for further use.	Ultrasonic Testing, Hydrostatic Isolation Technologies.
3. Restricted Access	Renovation projects many times involve tasks that must be performed in restricted or difficult areas due to safety hazards (e.g. elevation, temperature, radiation, hazardous chemicals etc.), and/or inherent security issues.	3D Laser Scanning, Photogrammetry, Rapid Prototyping.
4. Spatial Relationships	Existing facilities and equipment may have incomplete or inaccurate design or as-built documentation, or dimensions may have changed since original installation.	3D Wind Tunnel Modeling, Real-Time GPS Monitoring System.
5. Risk Identification	Unique and increased risk issues for renovation projects require detailed analysis and recognition of various uncertainties during Front End Planning.	Infrared Scanning, Liquid Penetrant Inspection.
6. Environmental Constraints	Renovation projects may require additional environmental considerations due to existing conditions such as soil conditions, endangered species, noise, dust etc.	Mass Spectrometers, Site Characterization and Analysis Penetrometer System.

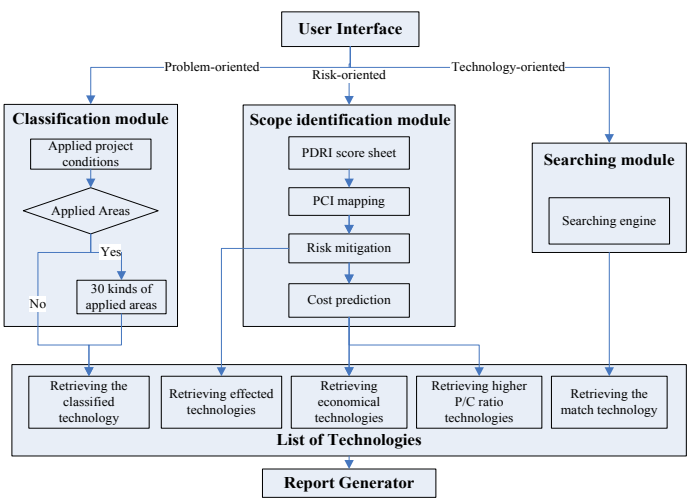


Figure 1: The framework of DMTS

4.1 Problem-Oriented Decision Structure

Twenty-four (24) PCI technologies identified from previous studies (CII 2009a) have been integrated into the DMTS model. The model also allows project teams to add more emerging PCI technologies. Two decision criteria are formed at this level to classify PCI technologies, namely applied project condition and application area. Applied project conditions consist of six categories as described in section 3. Application areas, on the other hand, document 30 types of project areas where the PCI technologies could apply. When a project team is aware of project condition and has already identified risky areas, the model allows them to follow a logic procedure to locate one or several matching PCI technologies.

At this level, a project team must have conducted detailed frond end planning and identified a specific condition (problem, situation, need). For example, Ground Penetrating Radar will be shortlisted when the project team identifies underground or integrity as an applied condition on the project. The results can be improved if project teams are able to define the application areas of the project condition. Application areas could be subsurface survey, structural mapping, forensic investigation or infrastructure characterization, etc. Otherwise, a shortlist of potential PCI technologies that match the applied condition is generated based on the input from previous step. Figure 2 illustrates the decision process for a PCI technology Ground Penetrating Radar. This process can be easily coded into Microsoft Excel as follows.

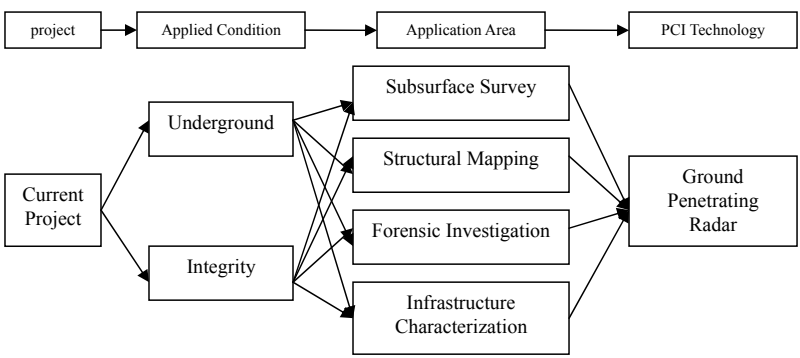


Figure 2: Classification process of Ground Penetrating Radar

=IF(AND(APC=a, OR(AA=1,AA=2,AA=3,AA=4,AA=5)),"Ground Penetrating Radar", IF(AND(APC=b, OR(AA=1,AA=2,AA=3,AA=4,AA=5)),"Ground Penetrating Radar","")) (1)

APC = Applied Project Conditions
AA = Application Areas
a = Underground
b = Integrity

1 = Users don't know the application area
2 = Subsurface Survey
3 = Structural Mapping
4 = Forensic Investigation
5 = Infrastructure Characterization

4.2 Risk Oriented Decision Structure

4.2.1 PDRI rating calculation

At this level, the DMTS model helps project teams mitigate project risks by incorporating technology selection with front end planning process. The team must conduct a PDRI analysis on the renovation project before the technology selection process. After the PDRI analysis is complete, the team will get a series of definition levels that cover all PDRI elements. The series can be defined as π^A, which is a 70x6 matrix for industrial renovation projects. We can define the PRDI scores matrix π^B, a 70x6 matrix, where rows of the matrix represent PDRI elements, and columns representing the scores of definition levels. A project rating matrix π^C, therefore, can be calculated by an element-by-element multiplication between matrix π^A and matrix π^B, also called dot multiplication or Hadamard Product. See equation 2 below.

$$\pi^A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix}, \quad \pi^B = \begin{bmatrix} 0 & 1 & 12 & 23 & 33 & 44 \\ 0 & 1 & 8 & 14 & 24 & 27 \\ 0 & 2 & 8 & 14 & 20 & 26 \\ \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix} \quad \pi^C = \pi^A \square \pi^B = \begin{bmatrix} 0 & 0 & 0 & 23 & 0 & 0 \\ 0 & 0 & 0 & 14 & 0 & 0 \\ 0 & 0 & 8 & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix} \tag{2}$$

A final PDRI rating score for a project can be generated. If p is the PDRI total score for a given project at a certain stage, it is equal to the multiplication of the project rating matrix π^C with two unit matrix (vectors), $\mathbf{J^1}$ and $\mathbf{J^2}$. A unit matrix is an integer matrix consisting of all 1s. The dimensions of $\mathbf{J^1}$ depend on the level of π or the dimension of π^C and π^B. For a industry project, $\mathbf{J^1}$ is a 1x70 vector and $\mathbf{J^2} = [1,1,1,1,1,1]^T$

$$p = \mathbf{J^1} * \pi^C * \mathbf{J^2} \tag{3}$$

4.2.2 Mapping PCI technologies with PDRI

One of the key features of the DMTC model is to integrate technology selection into the scope management process. Especially, each PCI technology is evaluated in terms of the effectiveness of reducing risks associated with site condition and continuous operation requirements. The evaluation addresses all elements in PDRI worksheet and their scales that the PCI technology could make an improvement.

Three levels of improvement are considered in the evaluation to map project's definition level, namely no improvement, minor improvement, and major improvement. If the PCI technology is not applicable to the PDRI element or has no significant impact on improving project scope definition, no improvement with a value of 0 will be assigned. If a PCI technology significantly improves the definition level for a element, major improvement level with a value of 3 will be assigned to that element. If minor improvement is expected, a value of 1 is assigned to indicate a minor improvement on scope definition level. Then, a vector is defined to describe the values of improvement level. For example, 3D Laser Scanning technology significantly improves the definition level on some PDRI elements A3, D4, and E2. A value of 3 will be assigned (Table 2). The definition level of other elements, e.g. A1, D3, E3, are somewhat improved, therefore, a value of 1 is assigned. A mapping

vector v_k is defined as

Table 2 Mapping PCI Technologies with PDRI: 3D Laser Scanning Example

Value	Improvement Level	Elements
3	Major	A3. Operating Philosophy Available vs. Required, D4. Dismantling and Demolition Requirements, E2. Design & Material Alternatives Considered/Rejected, F2. Surveys & Soil Tests, G3. Piping & Instrumentation Diagrams
1	Minor	A1. Reliability Philosophy, D3. Site Characteristics, E3. Design for Constructability Analysis, I1. Civil/Structural Requirements, I2. Architectural Requirements, M1. CADD/Model Requirements, P2. Engineering/Construction Plan & Approach
0	No	All other PDRI elements

$v_k = [1,0,3,0,0,0, \ldots\ldots]^T$,

Where, k indicates the PCI technology, and the values of the vector indicate the improvement level of the PCI technology on the PDRI elements has 1 or 3 if it corresponds to a PDRI element listed above, otherwise it is 0. Given a PDRI rating matrix π^C before the application of any PCI technology, the maximum scope definition improvement level (or PDRI score reduction) could be obtained. The calculation is coded in an Excel spreadsheet as follows.

a. If A1<B1, the score will show A1

b. If A1=0, B1≠0, the score will show A1

c. If A1≠0, B1=0, the score will show A1

=IF(A1=0,0,IF(B1=0,A1,IF(OFFSET(element,0,B1)>A1,A1,OFFSET(element,0,B1)))) (4)

*A1= The definition level in PDRI rating matrix π^C

*B1= Improvement level of PCI technology in the mapping vector v_k

The improved project scope definition level after the use of 3D Laser Scanning is calculated as

$$P^* = \mathbf{J^1} * \pi^C * v_k * \mathbf{J^2} \quad (5)$$

4.2.3 Decision on Applying New Tech

When there are several new technologies available, we can define a PDRI score improvement matrix $\Psi = [v_1, v_2, v_3, \ldots v_n]$, where each column vector is a PDRI score improvement vector for a certain new technology, e.g. v_1 is the PDRI score improvement vector for 3D Laser Scanning, and v_n indicates number of new technologies used in FEP. We can define the improved PDRI score as

$$S = [\ p\text{-}v_1,\ p\text{-}v_2,\ p\text{-}\ v_3, \ldots\ldots..p\text{-}\ v_n\ ] \quad (6)$$

Where, **S** is PDRI score improvement vector for all new technologies. And **S** = $[\ s_1, s_2, s_3, \ldots s_n\ ]$. Given a threshold value for PDRI score improvement, say p, any new technology with s larger than p, will be feasible based on the criteria of reducing risks. The larger reduced score the better result for reducing risk in PDRI. A feasible new technology is any technology **i** with $s_i > p$,

$$s_m = \text{Max } \mathbf{S} = \mathbf{Max} (s_1, s_2, s_3, \ldots\ldots s_n) \quad (7)$$

4.2.4 Cost calculating and P/C ratio

In addition to the decision structure discussed previously, the model also incorporates technology application costs into the decision process. This feature is specially designed to meet project teams' needs for the most cost effective selection of PCI technologies. The DMTS model defines a performance-cost (P/C) ratio to measure the cost effectiveness. The higher the ratio, the more efficient the PCI technology is.

$$\text{Performance-Cost (P/C) Ratio} = (p\text{-}v_k)/ c_k \quad (8)$$

Where, p is the PDRI rating score before applying any PCI technology. v_k represents the improved PDRI rating score after the use of PCI technology k. And c_k depicts the application cost of PCI technology k. While, a user can follow the calculation method discussed before to obtain p and v_k, there are more complicated to accurately estimate technology application costs. The DMTS model offers two methods to integrate cost data into the decision process. The estimating methods are either based on unit price per square foot, or unit price per labor hours. Project complexity is also considered as a parameter for this decision process. The user is required to input project data into the worksheet. Then the model automatically generates a list of proper PCI technologies that are ranked from high to low performance-cost ratio.

4.3 Technology Oriented Decision Structure

This model also provides a technology searching function for users who are willing to apply innovative technologies in the project. At this level, the model identifies key terms and words of each PCI technology and indexed context. A user is able to locate specific technologies through a topic search.

5. Application of DMTS Model

The previous sections discuss the framework of the decision model. An Excel based DMTS package has also been developed (Figure 3). This section presents an example to illustrate how the package can help project teams strengthen renovation project planning process model can be used. First, we assumed that the user knew that his project condition was underground conditions, but he/she did not know the type of applied area for the project. Therefore, the answer was 1 for the first question, and 0 for the second question in the Problem Oriented Classification Tool that was shown in figure 3. The list of technologies shows that three PCI technologies match the query. Additionally, PCI technology report will be generated through the link "Click for Report".

Users can follow the steps of questions to get three kinds of matched technologies through Risk Oriented Decision Structure. The first step is to fill out the PDRI score sheet, and the questions that follow in the next step have been described above. The assumed answers and list of matched technologies were shown with number priority which means that the first one matched technology may prove better than the second, also the second may be better than the third in figure 3. The final tool

can provide technology searching function. Users can type any keywords of PCI technology details which they would like to use and get a list of appropriate PCI technologies. The example illustrates the technology selection results when a user is

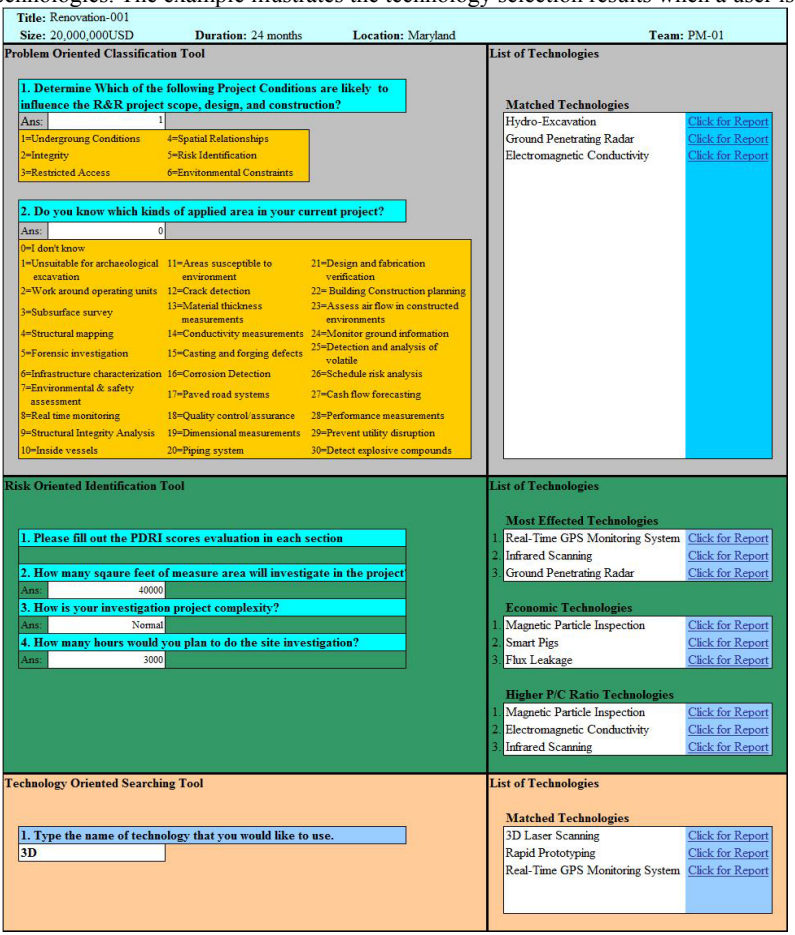


Figure 3 Decision Model for PCI Technology Selection Worksheet

willing to test any PCI technologies indexed with 3D. As shown in Figure 3, a list of three PCI technologies namely 3D Laser Scanning, Rapid Prototyping, and Real-time GPS Monitoring System is identified as matching technologies that have been indexed with 3D.

6. Conclusions

Renovation projects account for an increasing proportion of construction expenditure

in the US and require special attention to ensure successful delivery. As compared to Greenfield projects, renovation projects present unique risks in areas such as security, existing conditions, coordination, compatibility, environmental issues etc. Better Front End Planning, along with the application of Project Condition Investigation technologies, help project teams identify therefore mitigate special risks in renovation projects. This paper presents a decision model DMTS to integrate PCI technology selection into the renovation project planning process. The model is a flexible and user friendly Excel based decision tool. It provides three decision structures and allows project teams to select appropriate PCI technologies according their special needs. One must note that many parameters, e.g. cost, and definition level, in the DMTS model need to be regularly review to reflect the advance of new technologies. The model is specially designed to allow project teams to update the parameters and add emerging technologies for team's special needs. Finally, the next step of the research is to apply a real case to prove the practicability of the model.

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A Valuation Model for Choosing the Optimal Minimum Revenue Guarantee (MRG) in a Highway Project: A Real-Option Approach

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Abstract

Using Public-Private Partnership (PPP) model, the governments can utilize the resources of the private sector for financing and development of the capital-intensive infrastructure projects such as highways. PPP Highway projects are subject to revenue risks due to the uncertainty inherent in future traffic projections. Hence, the private sector is often reluctant to engage in these high-risk investments unless the government shares a portion of revenue risk by providing support instruments such as Minimum Revenue Guarantee (MRG). Incorrect modeling of traffic uncertainty and poor choices of MRG and Toll Revenue Cap (TRC) thresholds leads to inappropriate risk-sharing between public and private partners. This may inhibit the government from utilizing the capabilities of private sector and reduce the government's flexibility in investing on infrastructures in the future. A model for finding the optimal MRG and TRC thresholds based on Real Options methodology is presented. It incorporates the concepts of risk-neutrality and computes the investors' risk profile under MRG and TRC. It can help private sector better analyze the financial risks of BOT projects and make proper entry decisions based on the support instrument provided. It can be used by government to avoid undervaluing PPP initiatives or granting unnecessary subsidies to investors.

Keywords: Public-Private Partnership, Transportation Infrastructure, Toll Roads, Government Guarantees, Real Options.

1. Introduction

According to the Report Card for America's Infrastructure (ASCE, 2009), 33% of major U.S. roads are in poor or mediocre condition and 36% of major urban highways are congested. As a result, annually more than 4.2 billion hours are wasted in traffic at the cost of $78.2 billion. The roadways condition cost the U.S. motorists $67 billion a

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year in repairs. Nevertheless, due to capital limitations, the amount of investment for the development and improvement of highway systems has often been significantly lower than the level required for effectively responding to the rising demand. These challenges are not unique to the U.S.; worldwide there is a growing urge for using novel strategies in order to respond to rising demand for transportation infrastructure.

The Public-Private Partnership (PPP) model seems capable of satisfying such expectations. The PPPs are long-term alliances between public and private partners with the aim of benefiting from the private sectors' resources and expertise for the delivery of public services. Typically, the private investor finances, develops and operates the facility with the intention to recover its investment by raising a reasonable return from the collection of tolls and tariffs while the public partner is mainly concerned with the economical and social benefits that the expansion of the infrastructure services can provide. A common form of implementing PPP is the Build-Operate-Transfer (BOT) method, through which a private entity finances, designs, constructs a facility and operates it for a specified period based on a concession contract. At the end of the concession period, the public partner assumes operating responsibility of the facility. According to the World Bank, from 2001 to 2006, BOTs made two-thirds ($18 billion) of the private investment in highways in developing countries. Nevertheless, implementation of BOT projects has not been without trouble. There are evidences showing the failure of many BOT initiatives around the world. Based on such evidences, private investors tend to consider BOT initiatives as risky and hesitate to invest in them. It can be a contributing factor to the downward trend in private involvement in infrastructure projects that started in the late 1990s. Besides major global economic crisis, most failures were partly resulted from unrealistic revenue and cost estimations driven by poor data or incorrect assumptions in models as well as inappropriate risk sharing which exposed public and private partners to financial risks. Some of these issues are related to the weaknesses of models conventionally used for financial evaluation of BOT projects.

Traditionally, Discounted Cash Flow (DCF) techniques, such as deterministic Net Present Value (NPV) models, have been used to evaluate the economic feasibility of highway projects. In order to apply the NPV method, two key parameters, namely the discount rate and the series of future cash-flows, are required as the inputs. Theoretically, the discount rate is the expected rate of return for a non-traded asset and is complicated to measure (Cheah & Garvin, 2009). Moreover, there are uncertainties about the events which may affect the future cashflows and, ultimately, the profitability of the project. In fact a significant financial risk in a BOT highway project is the traffic revenue risk, which is the risk that the project may not earn sufficient revenue to service its operating costs and debt and leave an adequate return (Chiara et al, 2007). The traditional NPV models are unable to capture such uncertainty about the future traffic revenue. If used as a basis for decision making, the financial solvency of both the project and the concessionaire might become jeopardized. Thus, it will be better if, instead of making impossible predictions of future outcomes, the financial analysis of a BOT project is developed "on a non-deterministic basis so the events will need to be considered in terms of their probability of occurrence" (Kaka & AlSharif, 2009).

The private investors recognize their vulnerability to the financial risks inherent in BOT highway projects and are reluctant to assume them entirely. Failing to address

the concerns of the private sector about the project financial risks would likely reduce the participation of the private investors and result in a loss of value to the private sector and public. This has created growing pressure on governments to offer, as incentives to the private investors, support instruments that guarantee the financial viability of the projects. There are a variety of public support instruments applicable to PPP projects including: (a) Output-based cash subsidies (b) In-kind grants (c) Tax breaks (d) Capital contributions (e) Guarantees of risks under government's control (I) Guarantees of risks not under government's control (Irwin, 2003). The intention is to enhance the concessionaire's ability to develop, operate and maintain the facility to the desired standard while maintaining the tolls at levels affordable to users.

The Minimum [Toll] Revenue Guarantee (MRG) is a common form of support instrument offered by the governments in the BOT projects. By offering a MRG, for a specific period, the government partially assumes the risk of fluctuations in the future toll revenue levels, over which it does not have much control. The MRG reduces the concessionaire's exposure to the demand risk, by compensating the concessionaire if toll revenue falls below a specified minimum. A similar measure might be considered for the cases in which the toll revenue passes certain threshold by considering a Toll Revenue Cap (TRC). In such cases the concessionaire and the government agree to share surplus revenue. Poor choice of the MRG and TRC thresholds may lead to inappropriate risk-sharing between the partners, which can damage their credit rating and significantly reduce their flexibility of for investing in the future projects. Thus, to avoid failure, the reasonable thresholds for MRG and TRC should be calculated prior to consideration of such provisions in BOT contracts.

The notion of acknowledging the impact of the future uncertainties on the profitability of a project and considering some measures for protecting the investments against them is not captured by the traditional NPV method. Such limitations can be overcome by using the Real Options (RO) method. The real options approach is concerned with the strategic behaviors of decision makers under dynamic uncertainty. In the context of BOT projects, it provides a single analytical framework for enhancing decision maker's flexibility regarding whether or how to proceed with the development of a project considering the uncertainty of the underlying factors such as the future demand. In this paper, a novel real options framework to evaluate the financial performance of BOT projects under the traffic uncertainty is presented.

2. Research Objectives

One of the main objectives of this research endeavor is to illustrate and emphasize the gap between the results of the commonly used deterministic NPV method and a more sophisticated valuation method which considers revenue risk for the BOT highway projects. A model is constructed, which integrates the merits of the two frequently used techniques for studying the values under uncertainty; namely the binomial lattice and the Monte Carlo simulation. It primarily simulates the future traffic volume as the main source of uncertainty affecting the NPV of a BOT highway project and helps conducting Life Cycle Cost and Revenue Analysis for the project. The model provides the distribution of the NPV, which could be interpreted as the risk profile for the project and enables an analysis of the concessionaire's investment risk. This illustration emphasizes the need for the applications of more novel managerial approaches that provide the flexibilities for dealing with the uncertainties

regarding the future events. Finally, using the RO methods, the changes in the concessionaire's risk profile under different MRG and TRC configurations is analyzed and the fair premium of the MRG and TRC provisions is calculated. Figure (1) is graphical summary of model. The application of this model is illustrated by the case study on the International Airport Highway (IIAH) project in South Korea.

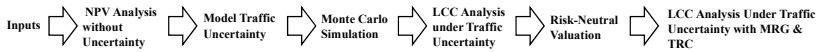


Figure 1. Graphical Presentation of Model

3. Research Background

The body of knowledge related to the application of real option methodologies in the infrastructure investments is still growing. Prior research endeavors have focused on the definition and analysis of a variety of options including the option to expand, option to abandon and MRG as an option. Ho and Liu (2002) defined the revenue guarantee on in a BOT project as an option, which helps hedging the revenue risk. Zhao and Tseng (2003) studied the designed capacity of an infrastructure with uncertain demands in the presence of an option to expand. Garvin and Cheah (2004) studied the options applicable to toll road projects. Cheah and Liu (2006) proposed a model developed based on RO methodology in order to value a MRG using a Monte Carlo simulation approach. Huang and Chou (2006) applied the RO approach to value a MRG in conjunction with the option to abandon. Chiara et al. (2007) developed a model where the MRG is in the form of Bermudan and Australian options and used the least squares simulation approach to value them. Brandao and Saraiva (2008) presented a Minimum Traffic Guarantee real options model that used the market data to determine stochastic project parameters.

4. Model Construction

4.1. Analysis of NPV without Uncertainty

In order to construct a deterministic NPV model, two parameters are required as the inputs. These two parameters are the series of cashflows during the construction and operating period and the discount rate. For a BOT highway project, the series of cash flows is comprised of the construction cost, the operations and maintenance cost, the operating revenue and the cash flow from the financing activities, which includes the cash inflow from raising equity and debt and the cash outflows related to the recovery of them (Table 1).

Table 1.Sample cashflow table for the construction and concession periods of a BOT project ($ Million)

Year	1995	1996	1997	1998	1999	2000	2001	2002	….	2030
Financing Activities Inflows	34.9	209.7	385.4	351.7	240.1	279.8			….	
Equity	34.9	209.7	131.9						….	
Debt			253.6	351.7	240.1	279.8			….	
Financing Activities Outflows							-1.9	-56.1		
Construction Cost	-34.9	-209.7	-385.4	-351.7	-240.1	-277.8			….	
Operations Revenue						45.3	208.3	240.6	….	882.5
Operations & Maintenance						-47.2	-185.7	-186.3	….	-373.7

The choice of the discount rate is challenging. The NPV of a BOT highway project is very sensitive to even small changes in discount rate. Inappropriate choice of discount rate makes such capital intensive projects unfavorable. Considering the uncertainty inherent to BOT highway projects, the discount rate should be adjusted for the risks using appropriate methods such as Capital Asset Pricing Model (CAPM). For discussion on the choice of discount rate, please refer to de Neufville (1990).

Following the determination of the discount rate and the subsequent cash lows, the project NPV (no uncertainty) will be calculated using the following equation:

$$NPV = \sum_{i=n+1}^{N} \frac{(OR_i - OC_i)}{(1+r)^i} - \sum_{i=0}^{n} \frac{CC_i}{(1+r)^i} \quad (1)$$

CC is the construction cost while OR and OC refer to the operation revenue and operation cost respectively. N is the total project time, n is the length of construction period and r represents the cost of equity.

Despite the relative simplicity and frequent use, the NPV method and CAPM based discounting cannot appropriately address the uncertainties and risks inherent to the BOT projects as well as the effect of the government support instruments.

4.2. Modeling the Uncertainty

The two major risk categories a PPP highway project are the economic risks and the construction risks. The construction or completion risks can be characterized by the construction cost uncertainty, include the risks of cost overrun, schedule delay, and technical difficulties. The economic or operating risks are the major risks that can affect the future cash flows generated in the operation period (Ho and Liu, 2002). This study is merely focused on modeling the uncertainty about the future traffic demand, which the researchers have consensus to be the most significant source of financial risk in the BOT projects. However, the proposed model has the flexibility to incorporate the uncertainties in construction cost, interest rate or exchange once the appropriate process for modeling their dynamic nature is identified.

The two primary models that can be used to represent the investment dynamics are the binomial lattices and the Ito processes. Binomial lattices, used as the foundation for analysis in this study, are analytically simpler than the Ito process and provide an excellent basis for computational work associated with the investment problems (Luenberger, 1998). In a binomial model, the value of parameter under study at the beginning of a period is defined to be a multiple of its value from the previous period; a multiple u (if value goes up) and a multiple d (of value goes down). Hence, if the value at a given period is S, at the following period, it will be either uS (for the top node) or dS (for the bottom node). This model could expand for several periods (Figure 2a). For the period length of Δt and expected volatility of σ the parameters u, d and the probability of an upward movement (p) are calculated as:

$$\begin{aligned} u &= e^{\sigma\sqrt{\Delta t}} \\ d &= e^{-\sigma\sqrt{\Delta t}} \\ p &= \frac{e^{\mu\Delta t} - d}{u - d} \end{aligned} \quad (2)$$

Here, μ is the expected growth of traffic demand (volume). Thus, using the expected initial traffic volume (S_0) and σ, a model for forecasting the future traffic volume can be created in the form of a lattice. A limit should be placed on the upward expansion of the lattice as there is a maximum traffic capacity for each highway.

For NPV analysis under the uncertainty of future traffic demands, a Monte Carlo simulation must be performed. Each round of simulation selects randomly one possible path on the binomial lattice(Figure 2b) which presents a potential series of annual traffic volume and, consequently, annual toll revenues, which can be used for

the NPV calculation by means of equation (1). There will be thousands of iterations of this process so, contrary to traditional NPV calculation, the result of the NPV analysis with uncertainty will be a range of NPV values, not a single NPV value, along with their probability of occurrence.

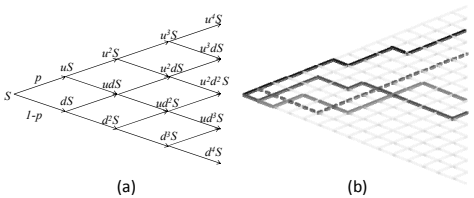


Figure 2. (a) A Hypothetical Binomial Lattice (b) Sample Simulated Paths on the Lattice

4.3. NPV Analysis with Minimum Revenue Guarantee and Toll Revenue Cap

Since the consideration is that the revenue represents the only source of project uncertainty, it can be argued that the value of the project depends on traffic demand. Assuming that μ and σ are the expected growth rate and volatility of the traffic, λ which is defined as the market price of the risk of the traffic can be calculated from:

$$\lambda = \frac{\rho}{\sigma}(\mu - r_f) \tag{3}$$

Here, ρ is the correlation between the project returns and the market and r_f is the risk-free rate of return. Now, the concept of risk-neutral valuation, an important notion used in the options pricing, can be extended to show the value of the project is established by changing the expected growth rate of the traffic from μ to $\mu - \lambda\sigma$, and later, discounting the cash-flows at the risk-free rate (Hull, 2008). Using this approach, the risk-neutral probability for an upward movement *(q)* from any given is:

$$q = \frac{e^{(\mu - \lambda\sigma)\Delta t} - d}{u - d} \tag{4}$$

Using these parameters, a risk-neutral binomial lattice is developed that enables the calculation of NPV under demand uncertainty as well as the option premium. For details on risk-neutral evaluation please refer to Hull (2008) and Luenberger (1990).

An option gives the option holder the right but not the obligation to take a measure, within a predefined time frame. The option holder would logically exercise the right provided by the option if the circumstances are favorable. These characteristics justify the proposal of using Real Options (RO) methods in the valuation of the BOT projects with MRG and TRC provisions. A toll revenue guarantee is a discrete-exercise "real" option, (Chiara et al, 2007). The MRG holder has the right but not the obligation to use the guarantee at specified discrete points of concession period. The MRG could take the form of a European option, exercised only at the expiry date of the option. In such case, the MRG is a contract by which the government pledges that, at the end of period Δt, it will pay the concessionaire an amount equivalent to difference of the guaranteed toll revenue and the toll revenue collected in that period. Thus, if *X* is the minimum guaranteed toll revenue, and $S(\Delta t)$ is the toll revenue at Δt, the concessionaire's end-of–period toll revenue will be:

$$R = \max (X, S(\Delta t)) \tag{5}$$

Moreover, the payoff (P) by the guarantor, to the guaranteed party will be:

$$P=\max\ (X\text{-}S(\Delta t),0) \tag{6}$$

The model considers that N minimum revenue guarantees (one per year) are stipulated in the contract. Accordingly, the premium for MRG provision (P_c) to the concessionaire can be defined as the expected payoff by governments resulted from exercising the MRG provision discounted back using the risk-free rate of return.

$$P_c = \sum_{t=1}^{N} e^{-r_f(t)} E\left[\max(0, X - S(t)\right] \tag{7}$$

When government protects the investors against low traffic demand by a MRG, there may be a consideration of Toll Revenue Cap (TRC) for splitting the surplus revenue resulted from the excessive growth of the demand beyond the projections. The joint modeling of a MRG and TRC should be addressed as a case of compound options, "where distinct options can be exercised over the same underlying asset. Even though they are mutually exclusive, they exist simultaneously and must be modeled as such" (Brandao & Saraiva, 2008). The TRC is typically defined as the maximum percentage of surplus allowed over the projected toll revenue. For instance, in the case that TRC threshold is 110% of projected traffic; if annual toll revenue goes beyond this threshold, the concessionaire should split the surplus revenue with government. Thus, if at the end of period Δt, the toll revenue S (Δt) is above the defined revenue cap (C) the concessionaire will earn R_C as calculated below:

$$R_c=C+ (S(\Delta t)\text{-}C)* k \tag{8}$$

k is the percentage of surplus that will be shared by concessionaire. In presence of MRG and TRC, the end-of-year toll revenue received by the concessionaire will be:

$$R=\min\ (\max(X, S(\Delta t)), R_c) \tag{9}$$

Therefore, the analysis, the step following the simulation of various traffic volume paths is to apply of the MRG and TRC to the toll revenue realized at the end of each period on the path using equation (9). This will be followed with discounting the values back to period t_0 using rate of rate of return on the equity(r).

$$NPV = \sum_{i=n+1}^{N} \frac{((\min(\max(X, S(i)), R_c) + R_m - OC_i)}{(1+r_f)^i} - \sum_{i=0}^{n} \frac{CC_i}{(1+r_f)^i} \tag{10}$$

Here, X is the MRG; $S(i)$ is the actual toll revenue realized from the operation of asset at the end of year i; R_m is the miscellaneous revenue from other sources(i.e. shopping and rest areas), OC_i is the operations cost during year i; CC_i is the construction cost during year i; N is the total project time, n is the length of construction period and r represents the risk-free rate of return.

5. The Case Study

The IIAH is a 36.6 km long highway between Incheon International Airport and Seoul. The project was financed and developed by the private sector according to a BOT contract. The construction began in 1995 and by 2000 the highway was open to traffic. Before opening, the highway was transferred to the government and the concessionaire received the right to operate it until 2030. The total financing amount needed for the project was $1.7 billion; almost 25% of it, $434 million, was from equity of the investors and the remaining $1.3 billion was acquired through syndicated loans. The concessionaire's cost of equity was 13.06%, while the risk-free

rate was 12.65%. Table (2) presents the MRG and TRC structure of the project. The projections of the future cashflows of the project are partially presented in table (1).

6. The Results

By deterministic discounted cash flow analysis the NPV was calculated to be $77.5 million. For modeling the NPV under uncertainty, the traffic volatility was assumed to be 10% per year. The expected growth rate of traffic demand was extracted from traffic projection by the Korean government. The initial level of annual average daily traffic (AADT) was assumed to be 100,720. It was assumed that this initial traffic volume is subject to uncertainty and follows a triangular distribution around this value with the minimum of 80,576 and a maximum of 120,864.

The risk analysis of the project shows that the expected project NPV is $36.26 Million while the standard deviation is $ 189 Million. There is a 40.6% probability that NPV will be negative, which shows the level of exposure of concessionaire to the traffic demand risk. Table (3) underlines the extreme sensitivity of the NPV to the volatility of the future demands. By using the CAPM model, the risk premium of project cash flows was determined to be 0.5%. Also, Monte Carlo simulation showed significant project volatility of 97.63%. Using the Equation (3) the value for the risk premium of traffic $\sigma_R\lambda_R$ was calculated to be 0.1024%. At this point, following the risk-neutral process, the expected growth rates of traffic were revised and a risk-neutral binomial lattice for NPV analysis under MRG and TRC was developed. To analyze the impact of MRG on concessionaire's risk profile, three scenarios were considered; the currently applied scenario (Scenario 1) and two other scenarios with different support levels (Table 4). For each scenario, the NPV of project under MRG was determined. The effect of MRG provision on the NPV distribution is significant; table (4) and figure (3) illustrate the changes in project value for each level of MRG. The MRG reduces the probability of having very low NPVs, and increases the expected NPV. Higher guarantee levels will reduce the vulnerability of private sector to traffic risk by reducing the probability of having low NPVs which shift the CDF diagram to right. Table (4) illustrates the affect of different MRG levels on the expected project value and emphasizes that MRG is an effective mechanisms for reducing the effect of demand risk on concessionaire's expected value. As the MRG level increases, so does the expected payoff by the government to the concessionaire as a result of exercising the MRG option (Table 3). It not only increases the value of MRG for concessionaire but also increases potential liability of government in future. Introduction of TRC provisions means that the government could potentially benefit in cases that the traffic demand grows extremely beyond the projections. The TRC, hence, will reduce concessionaire's expected NPV by reducing its share of the revenue surplus beyond the designated cap while increasing the expected payoff to the government. Table (5) represents the impact of adding TRC and MRG to the contract. Scenario (1) present the TRC option similar to what is currently enforced on the IIAH while Scenario 2 presents a more relax TRC in which the cap is set at higher level. Figure (4) shows that higher TRC level increases concessionaire's expected NPV as it allows concessionaire have a bigger share of the revenue surplus.

Table (6) and Figure (5) compare three scenarios: 1.No MRG and TRC 2. Only MRG offered, 3. Both MRG and TRC are offered. The expected NPV increases from $36.26 to $72.53 Million when MRG is included as concessionaire gets compensated

for revenue shortfalls. Adding TRC will reduce expected project value to $56.11 Million and the standard deviation to $170.55 Million. However, with MRG and TRC offered, private investor's incentive for entering into BOT project will remain strong as there would be a balance in the distribution of consequences of demand risk.

Operation Period	MRG	TRC
0 To 5	90%	110%
5 To 10	80%	110%
10 To 15	70%	110%
After 15	0	110%

Table 2. MRG and TRC options for IIAH Project

σt	Mean	σ
5%	93.16	112.88
7%	71.68	147.49
10%	36.28	188.52
15%	-29.6	248.08
20%	-96.78	292.71
25%	-164.3	321.43
30%	-230.26	349.45

Table 3. Analysis of NPV Sensitivity to Volatility ($ Million)

	MRG		
Operation Period	Scenario 1	Scenario2	Scenario 3
0 To 5	90%	70%	50%
5 To 10	80%	60%	40%
10 To 15	70%	50%	30%
After 15	0	0%	0%
Expected NPV	72.53	59.27	58.57
Std. Dev.	187.83	206.03	207.52
MRG Value	14.36	0.71	0.00

Table 4. Three MRG scenarios, their impact on NPV and their value for the concessionaire ($ Million)

	TRC	
	Scenario 1	Scenario 2
TRC Level	110%	120%
Expected NPV	56.11	67.21
Std. Dev.	170.55	181.38
TRC Value for Government	16.86	5.43

Table 5. Two TRC scenarios, their impact on NPV and their value for the government ($ Million)

7. Conclusion

A financial model for evaluating BOT highway projects under uncertainty is presented here. The model incorporates toll revenue uncertainty as the major source of financial risk in BOT projects. It is shown that, as the demand volatility increases, the concessionaire's exposure will increase due to higher risk of having low NPVs. The private sector is often reluctant to participate in such risky investments, and this justifies the offering of support instruments as incentives by the government.

The MRG is a common type of support instrument through which the government reduces private investors' financial exposure by compensating the concessionaire if traffic or revenue falls below a specified minimum. Offering MRG brings option-like features to contract, hence, the model was enhanced with real options valuation capabilities. Various levels of MRG were examined to illustrate its impact on the project value and the risk profile of investors. Also, analysis showed that offering MRG without appropriate cost-benefit analysis may increase the government's future commitments and limit its flexibility in future spending. Some PPP highway projects have Toll Revenue Cap (TRC) provisions that make the government entitled to a share of the toll revenue if it grows beyond a stipulated value. Different levels of TRC in mixture with MRG were examined to evaluate its impact on partners' risk profile.

Using this model the public and private sectors can analyze the financial risk of PPP projects. The private sector can use this innovative model to make better entry decisions to PPP highway projects considering the level of support provided by the government. The government can use this model to identify the optimal thresholds and levels of MRG and TRC that encourage private investments but do not comprise government's future budgetary strength. This model can be developed to incorporate other sources of uncertainty including the interest rate or exchange rate. It can also be extended so that it can be applicable to the analysis of the efficiency and effectiveness of other government fiscal support instruments such as the exchange rate guarantees.

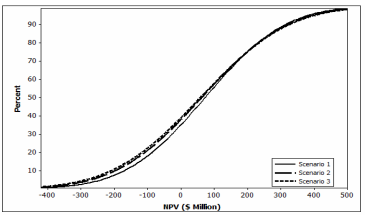


Figure 3. CDF of NPV under three different MRG scenarios

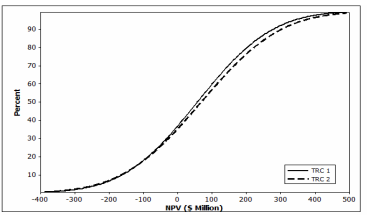


Figure 4. CDF of NPV under two different TRC scenarios

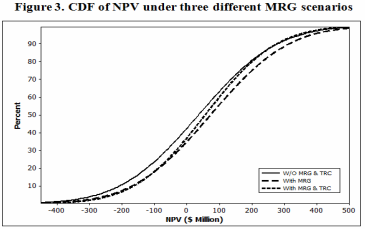


Figure 5. CDF of NPV under three different scenarios: Without MRG and TRC; With MRG and With MRG and TRC

	Without MRG or TRC	With MRG	With MRG&TCP
Expected NPV	$36.26	$72.53	$56.11
Std. Dev.	$189	$187.83	$170.55

Table 6. NPV distribution parameters under three scenarios: Without MRG and TRC; With MRG and With MRG and TRC

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CLASSIFICATION OF RISKS FOR INTERNATIONAL CONSTRUCTION JOINT VENTURES (ICJV) PROJECTS

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ABSTRACT

Several (ICJVs) have failed achieving time, cost and quality targets because of lack of an appropriate risk assessment methodology. This paper focuses on the analysis of the different ICJV risk environments. The related risks are analyzed into country, operating, sociopolitical and financial risks and then identified and grouped into internal, project specific, schedules, and major contract clauses risks. A simplified decision support system (RAMSCO) is proposed that breaks down project risks into discrete phases systematically. At each completion phase, there is a decision point where the up-date risk assessment can be reviewed and forth-coming actions can be identified giving the user a decision milestone whether to proceed or not. RAMSCO directs users through indices to minimize ICJV failure chances and evaluates the project's overall risk based on factor weighted ratings obtained from published researches. Two case studies are used to demonstrate RAMSCO's potential value.

INTRODUCTION

JVs are considered a convenient and a flexible vehicle for executing many national and international projects (Becker and Cushman, 1992). Several studies reported that the majority of international construction projects fail to achieve their objectives regarding schedules (Cooper, 1994). In developing countries for example, the number of JVs that failed is significantly high and is estimated to be more than fifty percent

(Beamish, 1993). Setting a high contingency without proper justification is not the answer to achieve profit or success for such joint ventures. Identifying and classifying the risk factors associated with projects have proven to be a valuable and a more productive approach (Mulholland and Christian, 1999). These factors, when evaluated and assessed, would lead to an overall project risk. When compared against an established criterion, the overall project risk helps the decision-maker in his decisions regarding contingency. The main objectives of this study are to classify risks for ICJVs projects and to establish a simplified, systematic, easy-to-use risk assessment decision support system for ICJVs. Such a system would first compile the risk factors affecting JVs and then assess the overall project risk. When comparing the resulting overall project risk against established criteria, the user would then be able to make better decisions regarding the project.

The following methodology has been adopted to achieve the objectives of this study:

1. Conduct a literature review for studies on risk factors associated with ICJVs Projects performance.
2. Based on these studies, perform classification, grouping, and categorization of the risk factors.
3. Establish evaluation criteria for each category of risk.
4. Develop an easy-to-use decision support system that contains the pre-determined risk factors.
5. Demonstrate through case studies the application of the proposed decision support system.

LITERATURE REVIEW

The process of risk management can be broken into four stages (Jones, 2000); 1) Identification of risk sources: This includes determining which risks are likely to offset the project and documenting the characteristics of each risk; 2) Quantification of risk sources: This covers the extent to which a certain risk can affect a project and its interactions with other risk factors; 3) Risk response system development: It defines enhancement steps for opportunities and responses to threats. It also covers, the response to changes in risk over the course of the project.; and 4) Project residual risk estimate: This should reflect the residual risk that accumulated through the process. Two techniques are commonly used: the experience-based and the brainstorming-based risk assessment techniques. Seven risk categories seem to be accepted in the field (Royer, 2000); 1) scope/change management risk 2) operational risk 3) financial risk 4) project management risk 5) strategic risk 6) technology risk and 7) failed assumption. It would seem logical to calculate the average risk from the individual risks and assign such average to the project as a whole. As long as low-risk items are not included, this is probably a "safe" estimate. However, high-risk items contribute more heavily to the overall project risk and should be weighted more heavily. Equation 1 may be used instead of just the average risk to evaluate the overall severity project risk (SPR) from individual environments SPR's, Where SPR_K , are the individual SPR risk for risk k. Table 1 shows an example of overall project risk calculations (Royer, 2000).

$$\sqrt{\sum_{1}^{n}\left(\frac{(SPR)_k{}^2}{n}\right)} \qquad \text{Eq.1}$$

Table 1. Example of Overall Project Risk Calculations (Royer, 2000).

Risk #	1	2	3	4	5	6	7	8	9	10	Simple Average	Overall Project Risk Formula
SPR	3	3	3	3	2	2	2	1	1	1	2.1	2.3

RAMSCO A DECISION SUPPORT SYSTEM FOR ANALYZING RISKS IN JOINT VENTURES

A Risk Assessment Management System for Construction Operations (RAMSCO) is developed for JV projects as a Decision Support System (DSS) designed to assess the different risk factors in the different activities involved in a JV construction project (Abdelghany, 2003). After reviewing, analyzing several literatures in the risk management of ICJVs environment, the authors studied, grouped, and categorized a total of 126 risks as the most important and inclusive risk factors. These 126 risk factors are compiled in RAMSCO under four major risk environment groups as shown in Table 2. The country risks are divided into operating, sociopolitical, and financial. The schedule risks are divided into engineering deign, procurement, site construction and project management risk factors.

Table 2. Decision Support System Risks

Risk Environments	Number of Risk Factors
Country risks	34
Internal, project specific risks	14
Schedule risks	61
Major contract clauses risks	17

As a decision support system for risk management of ICJV, RAMSCO is designed to assist users achieve the following:

- Breaking down the risks in a systematic way for an effective risk management process;
- Giving indices to help the decision maker minimize the chances of failure or under-performance of ICJV thus leading to better chances of meeting the construction project objectives;
- Increasing the effectiveness of ICJV project scheduling;
- Decreasing the amount of uncertainty in the internal, project specific, country, and major contract clauses risk environments of a project.

To assess the risks in a JV project, the following procedure, proposed by Smith, N. et al, (1999) is implemented in RAMSCO's Logic:

- The project is divided into a number of discrete phases, each of which has a predetermined purpose and therefore an identifiable scope of work.
- At the completion of each phase there is a decision point at which progress to date can be reviewed and forth-coming actions identified.
- It is recognized that the foremost amongst the information generated during each phase is an assessment of the project's risks.
- At each decision point, a risk assessment is made and is a key factor in the decision whether to proceed or not to the next phase.
- Risks which impact equally on all the options are critical in assessing the variability of the project.

RAMSCO is designed and works as a spread sheet written in MICROSOFT EXCEL to facilitate its use by project managers and engineers. It consists of 5 main columns as follows:

- The first column lists the risks factors to permit the user to systematically assess and rate each factor as they appear in the list.
- The second column includes the assessment of the risk factor on a scale of 0 to 5 based on experience and risk according to the criteria presented by Table 3.
- The third column permits the user to register, if necessary, the reason for his assessment of a given rating to a factor.
- The fourth Column includes the relative weight, in percentage of the different risk factors and is based on published literaure. In order not to burden the user, this column is not displayed to the user and is only used for calculations.
- The last column is the output of RAMSCO and gives the estimate, in percent, for every risk.

Table 3. RAMSCO Input Scale

Risk Assessment	Rating
Extremely Critical/Effective	5
Very Critical/Effective	4
Critical/Effective	3
Fairly Critical/Effective	2
Not Critical/Effective	1
Irrelevant or Not Applicable	0

The following section describes the process of RAMSCO's Data Entry and Analysis.

- The user would read the list factor, assess the situation of the project based on experience and available information, then enters a rating of 0 to 5 for the factor in column 2. The user would also enter justifying comments in column 3 if necessary.

- Based on the risk factor weight in column 4, RAMSCO then calculates and record the risk percentage contribution of this factor.
- Once the entries for a risk environment group are completed, RAMSCO calculates the subtotal for the group.
- After evaluating all the different risk environments (Country, Internal/ Project Specific, Schedule and Major Contract Clauses), the overall project risk representing the total risk percentage is calculated.
- Finally, RAMSCO provides a summary giving the risk percentage for every risk environment.
- This summary is used for a decision-making process as shown in Figure 1. The decision-making process can be summarized in *three steps* after implementing Jones (2000) Criteria shown in Table 4. In the *first step*, the Country risks are first assessed based on the country risks output percentages. The criteria provided by Harner and Ewing (1985) is applied: If the Country overall risk percentage falls within 70-100%, then the business is prohibited, otherwise the user should proceed to the Internal/Project Specific risk environment and assess the internal/project specific ICJV risks. During the *second step*, the Internal/Project Specific risks' score is evaluated. If the score greater than 85 percent the user should stop as the project is likely to fail (Jones 2000). If the Internal/Project Specific is less than 85 percent then the risk assessor should proceed to the Schedule and the Major Contract Clauses risks environments with the same criteria. *In step three*, and based on the risks environments output percentages criteria and the overall project risk output percentage, the user should decide whether or not to proceed with the project.
- Table 5 to 9 give samples of the weights used by RAMSCO. These weights are the estimates used in this study based on published literature but may be changed if the user has better supporting data.

Table 4. Jones (2000) Criteria

Project Outcome	Risk Out Percentage
Likely to Fail	or Equal 85 Percent
Probably to Fail	or Equal 60 Percent
Possible to Fail	or Equal 40 Percent
Unlikely to Fail	or Equal 15 Percent

Fig.1 Risk Management Analysis Chart

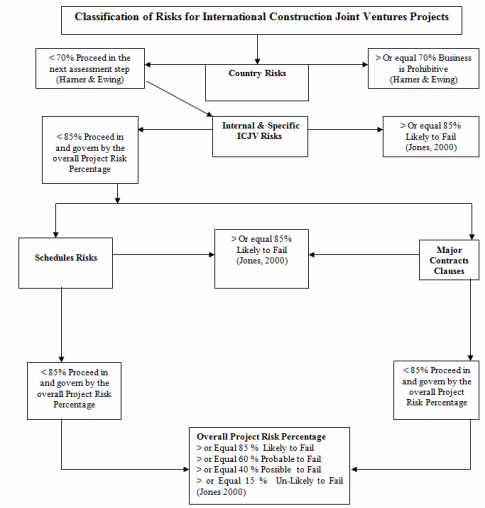


Table 5. RAMCO'S Country Operating Risks Percentages Calculation following (Harner & Ewing, 1985)

Risk	Weight (Harner &Ewing, 1985)	RAMSCO'S Percentage
1. Political continuity (inconsistency in policies, laws, regulations, different social)	3	4.0%
2. Attitude: foreign investors and profits	1.5	2.0%
3. Nationalization	1.5	2.0%
4. Monetary inflation and fluctuation	1.5	2.0%
5. Balance of payments	1.5	2.0%
6. Bureaucratic delays	1	1.3%
7. Economic growth	2.5	3.3%
8. Currency convertibility	2.5	3.3%
9. Enforceability of contracts	1.5	2.0%
10. Local cost/ productivity	2	2.6%
11. Professional services and contractors	0.5	0.6%
12. Communications and transportation	1	1.3%
13. Local management and partners	1	1.3%
14. Short-term credit	2	2.6%
15. Long-term loans and venture capital	2	2.6%
Total	**25**	**33%**

Table 6. Group 1: Internal Risk Factors Percentages Calculation- following Risk Weights (Bing et al., 1999a)

Rank	Risk factors	Mean (Bing et al. ,1999a.)	RAMSCO's Percentage
1	Partner's parent company in financial problems.	4.04	10%
2	Disagreement on accounting of profits and loss.	3.61	8%
3	Employees from each partner distrust each other.	3.57	8%
4	Policy changes in your partner's parent company toward ICJV.	3.38	6%
5	Partner's lack of management competence and resourcefulness.	3.18	6%
6	Over-interference by parent company of either partner.	3.18	6%
7	Disagreement on allocation of staff positions in ICJV.	3.02	6%
8	Disagreement on allocation of works.	2.96	6%
9	Technology transfer dispute, pollution.	2.64	6%
	Total		**62%**

Table 7. Group 2: Project-Specific Risk Factors Percentages Calculation following Risk Weights (Bing et al., 1999a)

Rank	Risk factors	Mean (Bing et al., 1999a.)	RAMSCO's Percentage
1	Cash flow problems of client	4.18	10%
2	Poor project relationship	3.77	8%
3	Incompetence of Subcontractors/suppliers	3.73	8%
4	Excessive demands and variation by client	3.42	6%
5	Disagree some conditions of contract	3.33	6%
	Total		**38 %**

Table 8. Time Schedule Risk Percentages Calculation (Mulholland & Christian, 1999)

Rank	Risk factors	Degree	RAMSCO'S Percentage
A	**Engineering Design Risk Factors**		
1	Regulatory code, safety and requirements	Medium	1%
2	Engineering design drawing control process	Medium	1%
3	Environment impact assessment	Medium	1%
4	Engineering design resources qualifications and pool depth	Medium	1%
5	Engineering estimate	High	2%
6	Project scope definition	Medium	1%
7	Early engineering deliverables	Medium	1%
8	Technology	High	2%
9	Design criteria	High	2%
10	Engineering designers productivity	High	2%
11	Material substitution procedure	High	2%
12	Site investigation	High	2%
	Total		**18%**
B	**Procurement Risks Factors**		
13	Contractor selection process	High	2%
14	Vendor bid greater than estimate	Medium	1%
15	Long lead items equipment and bulk material	High	2%
16	Identification of equipment and material	High	2%
17	Procurement management techniques and systems	High	2%
18	Specification changes affecting manufacturing	Medium	1%
19	Vendor performance and quality control	High	2%
20	Warranties	High	2%
21	Manufacturing process	High	2%
22	Material management organization concerns	High	2%
23	Tender evaluation and purchase order cycle	High	2%
	Total		**20%**

RAMSCO APPLICATIONS - CASE STUDIES: Two case studies are presented here to demonstrate the use of RAMSCO as a DSS for risk management: these two case studies were chosen from Bing et al, (1999b) and represent two joint venture case studies from Asia. Case 1 represents an unsuccessful JV in Singapore. It was the first attempt into the competitive market of Singapore by a construction company from a developing country. Both JV partners suffered financial losses. Case 2 was a successful JV. It shows how two foreign firms successfully helped their local partners manage their JV project in China. The Two ICJVs projects were analyzed using RAMSCO. RAMSCO's application summary output for the different risk environments for both case studies is shown in Table 9. In these applications, the judgments of Bing et al, (1999b) on the different risks were translated to estimates and entered to RAMSCO. RAMSCO provided a valuable tool to estimate quantifiable measures of project risks for the two case studies. Case one: the project was unsuccessful and it did not meet its objectives. RAMSCO estimated overall project risk (SPR) of 46 % and its expectations are cost and schedule overruns, possible liquidated damages and foreign exchange losses, as it is possible to fail according to Jones 2000 criteria. Case two: The project was successful and it met its objectives. The calculated overall project risk percentage (SPR) is 29% indicating that the project is unlikely to fail according to Jones 2000 criteria.

Table 9. RAMSCO Case Studies (1) and (2) Application Summary Output

Decision Support System Risks Environments	**CASE 1**	**CASE 2**
1.1 Country Risks	63	36
1.2 Internal/Specific Risks	29	26
1.3 Projects Schedules Risks	48	20
1.4 Major Contract Clauses Risks	26	20
Overall Project Risk (SPR)	**46%**	**29%**

CONCLUSIONS

The analysis of the two case studies has shown that RAMSCO could be a useful tool for achieving a successful construction JV. In general, the critical risk factors must be systematically studied from the perspectives of internal, project-specific, groups, and in combination with the ICJVs development stages. To mitigate the risk factors in a JV, one must develop appropriate strategies, particularly in the start-up and operation phases. The two case studies show that measures must be adopted when a company decides to enter into an ICJV. It must consider the local partner's financial and management ability, its industrial relationship, and its relationship with local government. Another important measure is to insist on drafting a good JV agreement that clearly defines each partner's responsibility and liability. The terms and clauses of agreement should be drafted in simple language for both partners' employees understanding. It is

preferable to adopt a one-partner-dominant style of management when one partner is strong enough to handle major construction works. When the IJV enters into the operation phase, it is critical to choose experienced and familiar subcontractors and suppliers, and to employ an influential local organization or individual, particularly as a logistic agent in a developing country to strengthen the ICJV operation. Finally, constructive discussions and amicable dispute resolution techniques must be carried out throughout the life of a JV.

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INTERRELATIONSHIPS AMONG CONSTUCTION INJURY PREVENTION STRATEGIES: A CROSS-IMPACT ANALYSIS

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ABSTRACT

The construction industry consistently accounts for the highest fatality rate of all single-service industries in the US. In an effort to design effective safety programs, several studies have quantified the relative effectiveness of injury prevention strategies (i.e., safety program elements). These studies typically examine the effectiveness of safety program elements (e.g., inspections) in isolation. The objective of this paper is to describe a recent research study that aimed to evaluate the influence that various safety program elements have on the effectiveness of one another. Using the Delphi method, the cross-impacts of fifteen highly-effective safety program elements were quantified by determining the percent increase or decrease in effectiveness that each element has on the others. The results indicate that the most influential injury prevention strategies are employing a site-safety manager, upper management support and commitment, worker participation and involvement, safety and health committees, and a site-specific safety plan. The subsequent analysis can be used to better understand the synergistic effects that exist among various subgroups of elements and to strategically create the most effective safety program when resources are limited.

INTRODUCTION

In 1996, the National Institute for Occupational Safety and Health (NIOSH) initiated the National Occupational Research Agenda (NORA), a research framework that identified critical occupational safety and health issues. To become more effective in preventing fatalities, injuries, and illnesses in construction, the NORA Construction Sector Council developed fifteen strategic goals for the "National Construction

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Agenda." One of the strategic goals was aimed at improving the effectiveness of safety and health management programs in construction and increasing their use in the industry (NORA 2008). In an effort to address that goal, there have been a number of studies that discuss the elements that constitute an effective safety program. For example, recent researchers have quantified the effectiveness of the independent implementation of various injury prevention strategies (e.g., Rajendran and Gambatese 2009; Hallowell and Gambatese, in press).

Despite these recent advancements in knowledge, the impacts of each injury prevention strategy on the effectiveness of the others remain unknown. Such information is essential to the development of an optimal safety program as elements are rarely implemented in isolation. Furthermore, understanding the potential synergistic effects of clusters of elements may allow safety managers to formalize the design of a safety program when resources are limited.

The objective of the present paper is to describe the preliminary results of an ongoing Delphi study that aims to quantify the interrelationships (i.e., pair wise cross-impacts) of highly effective and commonly implemented injury prevention strategies. It is expected that these unprecedented data can be used to identify the elements that are central to the overall effectiveness of the program and to strategically design a safety program when a subset of elements is implemented.

LITERATURE REVIEW

There are literally hundreds of injury prevention strategies that can form a safety program (Rajendran 2007). To establish an appropriate scope for this study the writers elected to narrow the focus to only the elements that have been identified as 'essential' by previous studies. During the preliminary literature review six publications were identified that discuss the essential elements of an effective construction safety program (Hill 2004; Hinze 2006; Findley et al. 2004; Jaselskis et al. 1996; Liska and Goodloe 1993; and Meridian 1994). In total, these publications identify twenty critical safety program elements. Of these twenty elements, fifteen are highlighted by all of the publications reviewed. Thus, this study focuses on these fifteen elements which are listed and described in Table 1.

When resources are limited construction firms must select a subset of available elements. Unfortunately, this selection process has not been formalized (Hallowell and Gambatese 2007). To enhance this decision process, the relative effectiveness of the strategies and the synergistic relationships among them must be known. The following sections review literature related to the relative effectiveness of common injury prevention strategies and cross-impact analyses as this information was essential to the development and implementation of the present study.

Relative effectiveness

There is a well-established body of literature that discusses the elements of an effective safety program (Hinze 2006; Hill 2004). Recently, several researchers have demonstrated that some elements are more effective than others. Jaselskis et al.

(1996) studied the effectiveness of safety program elements by measuring the ability of each element to decrease a company's experience modification rate. Sawacha et al. (1999) built upon this research by conducting a factor analysis to determine the relative impacts of various safety program elements on injury rates. Recently, Molenaar et al. (2009) created a set of best practices by evaluating five latent variables through a structural equation model and Hallowell and Gambatese (in press) used the Delphi method to quantify the individual ability of safety program elements to reduce the risk of construction injuries and illnesses. These studies have indicated that upper management support and commitment, strategic subcontractor selection and management, and job hazard analyses are the most effective of all strategies.

Table 1. Critical Elements to an Effective Construction Safety Program

Safety Program Element	Definition
Emergency response planning	Plans that include emergency response personnel, equipment, and procedures that cover emergency situations.
Frequent safety inspections	Regularly conducted safety inspections by safety manager or safety committee across the project site to identify hazardous exposures to workers
Job hazard analyses	Identification of specific safety hazards prior to a routine job, task, or process.
On-site first aid	Basic emergency treatment given to someone injured before medical services can arrive.
Project safety incentives	A tangible incentive given out on the project level for meeting a pre-specified outcome or level of performance.
Record keeping and accident analyses	The investigation, documentation, and reporting of accidents, near-misses, first-aid cases, and other incidents.
Safety and health committees	A divers group of individuals on a specific project with the sole purpose of addressing safety and health on the worksite.
Safety and health orientation	Orientation and training sessions that focus on safe work practices and company safety policies for all new hires.
Site-safety manager	Full-time employment of a safety professional with formal safety experience and/or education that is charged with site safety.
Site-specific safety plan	A safety plan developed prior to construction commencing that is specific to a project that documents safety objectives, goals and methods for achieving success.
Subcontractor selections and compliance	The selection and oversight of subcontractors to ensure effective safety protection for all workers at the site.
Substance abuse programs	The identification and prevention of substance abuse in the workforce. Drug testing programs intended to reduce safety incidents and improve productivity.
Training and regular safety meetings	Formal in informal safety and health training provided for managers, supervisors, and employ7ees. Regular safety meetings are conducted to emphasize training and commitment to safety culture.
Upper Management Support	Upper management of an organization that acknowledges worker safety is a primary goal through motivation and resources to worker safety and health.
Worker participation an involvement	Worker involvement in the planning and operation of the safety and health program.

Cross-impact analysis

The cross-impact method was originally developed to quantify and assess potential interactions among a set of variables (Asan 2006). Helmer and Gordon (1966) later

applied the technique as an extension of the Delphi method. The purpose of this extension was for estimating interactions among events that were previously considered independent of one another. The cross-impact analysis provides an analytical approach to quantifying the interrelationships between events. Specifically, the method focuses on how each attribute or element in a series affects or is affected by the other elements of the series (Dalkey 1972). The matrix gives the set of events that may influence other events along the rows, and the events that potentially are affected by the rows are located along the columns. The probability and interdependencies are then estimated for each pair wise comparison (Dalkey 1972). This study aims to conduct a pair wise cross-impact analysis to quantify the interaction among safety program elements.

RESEARCH METHODS

In order to quantify the cross-impacts among the highly-effective safety program elements, the influence of each element on the effectiveness of each the others must be rated. For this study, the number of interactions is 210. Due to the time commitment required for the survey participants to quantify all of the cross-impacts and the complex nature of the desired database, the Delphi method was selected over other research methods. In addition, Delphi was selected because it is unlikely that one person can correctly quantify all the cross-impacts.

The Delphi method was originally developed by the Rand Corporation and was designed to find unbiased information from complicated and uncertain problems (Helmer and Gordon 1966). Data are collected through formalized method of anonymous communication among panelist where controlled feedback is provided through multiple rounds of surveys (Dickey and Watts 1978). In this research study, bias was minimized by five specific techniques: randomization of questions in the survey, including reasons in controlled feedback, conducted multiple rounds of surveys, identifying individuals that have experienced recent, relevant events, and reporting results as medians rather than means. These techniques helped to minimize the following judgment-based biases: contrast effect, Von Restoroff effect, recency effect, primacy effect, and dominance (Hallowell 2009).

Delphi Format

The Delphi method is accomplished through multiple survey iterations until consensus is reached. The number of rounds included in a Delphi study may vary; however, most range from two to five rounds (Linestone and Turoff, 1975). In this study the goal was to reach an overall consensus of 10% from the average of the absolute deviations of the medians. Two to four rounds were expected to achieve this consensus rate.

The validity and success of the Delphi method relies mainly on the expertise of the panelists. When selecting and expert panel, Bryman (1996) recommends adopting a directed approach for the selection of the group of experts so that they contain the required in-depth knowledge and experience for the information being quantified. To qualify as an expert for this study, each individual was required to meet at least three

of the following requireemtns: (1) five or more publications; (2) member or chair of a committee; (3) professional registration; (4) 3 or more years employed in industry; (5) author or editor of a book; (6) employed as a professor at an institute of higher learning; (7) bachelors degree or higher in a related field. This is a more stringent criteria then the recommended number of at least two requirements by Rogers and Lopez (2002). The expert qualifications as a group are presented in Table 2 and consist of ten panelists that finished all rounds of the Dephi study. This follows the recommendation according to Linestone and Turoff (1975) of 8-10 experts.

Table 2. Expert Qualification

Requirement	Percentage of experts meeting the requirement
Primary or secondary author of at least five peer-reviewed journal articles on the topic of construction safety and health	90%
Member or chair of a construction safety and health related committee	90%
Designated as a Professional Engineer (PE) or Certified Safety Professional (CSP)	70%
At least 3 years of professional experience in the construction industry	90%
Author or editor of a book or book chapter	70%
Faculty member at an accredited higher education institution	70%
Bachelor degree or higher in civil engineering or occupational safety and health	100%

During the initial round of the Delphi survey, the expert panel members were asked to rate the influence that each construction safety program element has on the effectiveness of the other elements. This interaction was measured in terms of a percent increase or decrease in effectiveness. Figure 1 shows one element's survey page.

In round two of the Delphi method, the medians of the group were presented to each expert on a survey with their response. Each panelist was encouraged to review the medians of the group and consider revising their previous response. In the event that their rating was two or more standard deviations from the median of the group, the panelist was asked to provide a reason for their response. The goal of this round was to decrease the variability of the responses and achieve a group consensus about the correct value (Linestone and Turoff, 1975)

The third and final round was similar in nature to the second in that the medians from the second round were presented to the panelists and were encouraged to re-evaluate their score based on the consensus of the group. In the event the expert's response still varied from the rest of the experts, they were again asked to provide a reason to justify and support their response.

Figure 1. Element 1 of 15 for the Round 1 Survey Sent to the Delphi panel

DIRECTIONS: Put an "**X**" in the box that indicates the percent increase that a **SITE-SAFETY MANAGER** has on the effectiveness of each safety program elements listed.

Safety Program Element	Negative Influence	Percent increase that a SITE-SAFETY MANAGER has on the effectiveness of the indicated safety program element											
		0	10	20	30	40	50	60	70	80	90	100	>100
Project Safety Incentives													
Site-Specific Safety Plan													
Substance Abuse Programs													
Safety and Health Committees													
Training and Regular Safety Meetings													
Worker Participation and Involvement													
On-site First Aid													
Safety and Health Orientation													
Job Hazard Analyses													
Subcontractor Selections and Compliance													
Record Keeping and Accident Analyses													
Emergency Response Planning													
Upper Management Support													
Frequent Safety Inspections													

RESULTS

Out of thirteen experts, three defaulted before the beginning of the second round. This produced a response rate of 77% and the results only include the consensus of the ten experts that completed the study. During the Delphi process, the time investment required from each participant was considerable. Each participant was required to provide 210 ratings per round for a total of three rounds. Throughout the length of the study, 6,300 ratings were gathered from the experts. After the first round, the absolute deviation of the medians for each safety program element among the group was 19%. The target consensus for the group was 10% so a third round of surveys was required. In the third round, the outlying experts came closer together while most of the medians stayed within 5%. The absolute deviation of the third round came to 12%. Although the group did not come to the target consensus of ten percent, the medians of the group stayed relatively constant and therefore a fourth round was deemed unnecessary.

The medians for the elements that are central to increasing the effectiveness of other elements are listed in Table 3. These medians are in units of percent increase in effectiveness. For example, the percent increase in effectiveness that a site-safety manager has on job hazard analyses. For this paper, only the five most influential safety program elements are presented. These five elements were found to give the most in improving the effectiveness of a safety program. This was determined by comparing the sum of all of the percent increases in effectiveness that an element gives (Effect of Element in Table 3) to other elements (Effect on Element in Table 3).

Table 3. Cross-Impact Results of Selected Elements

		Effect on Element												
		Emergency Response Plan	Frequent Inspections	Job Hazard Analyses	Record Keeping & Accident Analyses	Safety & Health Committee	Safety & Health Orientation	Site-Safety Manager	Site-Specific Safety Plan	Subcontractor Selections & Compliance	Substance Abuse Programs	Training & Regular Safety Meetings	Upper Management Support	Worker Participation and Involvement
Effect of Element	Safety & Health Committee	30	54	45	40		40	53	60	33	33	60	50	80
	Site-Specific Safety Plan	40	60	60	34	53	50	50		40	50	50	35	55
	Site-Safety Manager	50	90	80	60	45	75		85	50	60	85	53	85
	Upper Management Support	55	64	50	65	79	58	80	80	80	70	66		70
	Worker Participation and Involvement	46	39	65	55	70	55	45	60	13	45	65	20	

ANALYSIS

The cross impacts for the five most influential elements are included in Table 3. It is important to recognize the elements that have the ability to influence the effectiveness of a safety program. From Table 3, the four highest percent increases in effectiveness are given by a site-safety manager to frequent inspections, site-specific safety plan, training and regular safety meetings, and worker participation and involvement. In addition, upper management support is also central to improving the effectiveness of other safety program elements. This shows that the effectiveness of individual safety program elements can be significantly increased through a site-safety manager and upper management support. From Table 3, the percent increases of 75% or greater have been included in Table 4. The influence that site-safety managers and upper management support have on other safety program elements can be seen from Table

4. It is important to note, that all but one of the percent increases over 75% are given by site-safety managers and upper management support.

Table 4. Most significant relationships between construction safety elements

Contributing Element	Receiving Element	Receiving Element's Potential % Effectiveness Increase
Site-Safety Manager	Frequent Inspections	90%
Site-Safety Manager	Site-Specific Safety Plan	85
Site-Safety Manager	Training & Regular Safety Meetings	85
Site-Safety Manager	Worker Participation & Involvement	85
Site-Safety Manager	Job Hazard Analyses	80
Safety & Health Committee	Worker Participation & Involvement	80
Upper Management Support	Site-Safety Manager	80
Upper Management Support	Site-Specific Safety Plan	80
Upper Management Support	Subcontractor Selections & Compliance	80
Upper Management Support	Safety & Health Committee	79

To find the elements that are central to the effectiveness of other safety program elements, the individual percent increases that an element gives to other elements were summed. The resulting sum indicates each elements degree of centrality measured by the collective improvement in effectiveness of other elements. This relative score is given in Table 5.

Table 5. Safety Program Elements Relative Score of Centrality

Safety Program Element	Relative Score of Centrality
Site-Safety Manager	818
Upper Management Support	816
Worker Participation and Involvement	578
Safety & Health Committee	576
Site-Specific Safety Plan	576
Training & Regular Safety Meetings	531
Frequent Inspections	519
Job Hazard Analyses	469
Subcontractor Selections & Compliance	413
Safety & Health Orientation	338
Record Keeping & Accident Analyses	319
Substance Abuse Programs	240
Emergency Response Plan	225

From Table 5, the elements that were found to be the most influential to a safety program have a higher relative score of centrality. These elements with higher scores have a greater ability to influence the effectiveness of other elements in a safety program. The resulting data from this study in Table 5 can be used to guide decisions in safety program element selection.

APPLICATION

The data collected from this study can be used by upper management and safety and health managers to evaluate their current safety program. For example, a firm that employs several elements and has resources to add a new injury prevention strategy can use the data presented in this paper and the relative scores provided by previous

literature to objectively select a new element. These data can vastly improve the current decision schemes used by most contractors. In addition, this potential improvement in effectiveness is quantifiable and can be figured into a cost-benefit analysis to see if the additional safety program element is warranted.

The findings from this study are most useful to construction firms that have limited funding to implement accident prevention strategies. Larger firms that do not have limitations in safety funding have the ability to implement all of the safety program elements. Although, for any construction safety program it is beneficial to know the central elements that have the greatest impact on the effectiveness of other elements. With this knowledge, firms will be able to focus their efforts towards further developing the central elements.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this paper was to bring out the safety program elements that are central to improving the effectiveness of other safety program elements. Out of the fifteen safety program elements that were studied, the elements that were found to be the most influential towards improving the effectiveness of other elements are: site-safety manager, upper management support, worker participation and involvement, safety and health committees, and site-specific safety plan. The quantification of these interrelationships gives insight into how safety program elements impact one another's effectiveness. Previously, these interactions have been realized (Hallowell 2009), but not quantified and the effectiveness of elements was considered in isolation. These new findings has the potential to be combined with previous research studies that have quantified ratings for safety program elements in isolation to develop a comprehensive safety decision support system. Future research may improve the effectiveness of these findings through investigating additional elements to combine with this study to determine a perimeter around the most influential safety program elements.

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Quantitative Assessment of Horizontal Directional Drilling Project Risk Using Fuzzy Fault Tree Analysis

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Abstract

Fault tree analysis is regarded as a powerful technique for assessing system reliability. The conventional approach of solving fault trees is based on applying probability theory by assigning probability distributions to basic events and propagating the probabilities to calculate the overall probability of the top event. However, applying this technique, especially in construction projects, entails several difficulties attributed to the lack of sufficient data to estimate the probability distributions for basic events. Thus, risk analysts tend to assume probability distributions of basic events, which adds further uncertainty to the analysis. To overcome these difficulties, this paper presents a simplified approach in which basic events are represented by a possibility distribution, and the possibility distribution of the top event probability is calculated by applying fuzzy arithmetic operations. The method presented herein is demonstrated using a case study to quantify the probability of failure of horizontal directional drilling (HDD). The proposed approach is able to overcome the difficulties of using the conventional approach by relying on linguistic terms rather than assuming probability distributions for basic events.

Introduction

Risk analysis represents one of the critical steps of any risk management process. The outcome of a risk analysis is the estimation of the probability of occurrence and impact of different risk events. Estimating the probability of occurrence is difficult

especially when the risk event is triggered by many independent root causes. The task of calculating the probability of occurrence becomes more difficult when data are unavailable or difficult to obtain.

Fault tree analysis represents one of the well know techniques for risk analysis to assess the probability or expected frequency of a risk event. Fault trees (FT) can be solved qualitatively and quantitatively. The qualitative assessment of the FT involves transforming the FT logic into logically equivalent forms known as minimal cut sets (MCS). The MCS provide useful information to the analyst. For instance, by looking at the MCS, the analyst can understand which logical combinations, amongst root causes, can lead to the occurrence of the top event (risk event). Any minimal cut set with one basic event indicates a critical set in which one single event is sufficient to cause the top event to occur.

To conduct quantitative assessment of fault trees, the MCS are calculated first and transformed into equations. The probability of the top event is then calculated by assigning values to the probability of basic events and substituting them into the mathematical equations. To do so, we are assuming that we have enough historical data to estimate the probability of basic events; however, this is not normally the case, since finding enough data to derive probability distributions is difficult to achieve in construction projects.

This paper presents a simple and more realistic approach for construction to solve fault trees based on applying fuzzy logic rather than probability theory. Our proposed approach is intended to overcome the limitations of using probability theory to conduct quantitative analysis of fault trees. The proposed approach supports risk analysts to conduct fault tree analysis even in scenarios where data are scarce or unavailable. Using this approach, possibility distributions, represented by fuzzy numbers, are used rather than probability distributions to represent the probability of basic events. Hence, risk analysts can use linguistic assessments rather than numerical values to assess the probability of basic events, which are referred to as fuzzy probability. Boolean algebra is then applied to calculate the MCS of the fault tree. Fuzzy arithmetic operations using alpha cuts are applied thereafter to provide a quantitative assessment of the top event fuzzy probability.

Fault Tree Analysis (FTA)

Fault tree analysis provides a graphical logic diagram that supports qualitative and quantitative assessment of the risk inherent in systems. The most commonly used logical connections to connect root causes with upper events are AND (intersection) or OR (Union) gates. The AND gate indicates that the upper event cannot occur unless all the lower events occur. The OR gate indicates that the occurrence of any of the events in the lower level is sufficient for the upper event to occur. Figure 1 shows a simple structure of a fault tree using OR and AND gates.

To construct a fault tree, the risk event is represented at the top of the fault tree. All of the root causes that contribute to the occurrence of this risk event are identified in the second level. Root causes at the second level are further decomposed to their root causes. The decomposition process is continued until basic events are identified. Basic events represent the lowest level of each branch in the fault tree and cannot be further developed.

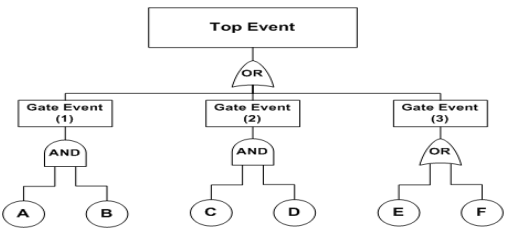


Figure 1: Example of fault tree structure

A fault tree can be simply solved by converting the fault tree logic into MCS. A cut set is defined as "a set of basic events where the joint occurrence of these basic events results in the occurrence of the top events" (Ayyub 2003). A minimal cut set (MCS) is defined as "a cut set with the condition that the non-occurrence of any one basic event from this set results in the non-occurrence of the top event" (Ayyub 2003). Calculating minimal cut sets manually is a tedious job especially for large fault trees. In the literature, there are several algorithms that have been developed to obtain minimal cut sets, e.g., Hauptmanns (1988), Vatn (1992), and Kara-Zaitri (1996).

By applying Hauptmanns' (1988) algorithm to the example shown in Figure 1, we will have the following MCS: M_1= (A, B), M_2= (C, D), M_3= (E), M_4= (F). This implies that A and B must occur together to cause the top event to occur, C and D must occur together to cause the top event to occur, E by itself is sufficient to cause the top event to occur, and F by itself is sufficient to cause the top event to occur.

In addition to qualitative assessment, fault trees can be utilized to provide quantitative assessment of the top event probability. In this regard, the probability of the top event connected by an OR gate is defined as follows (NASA 2002b):

$$Pr(Top\ Event) = 1 - \prod_{i=1}^{N}(1 - M_i) \quad (1)$$

where M represents MCS, N represents the total number of MCS, and Pr represents the probability of occurrence.

The probability of the top event connected by an AND gate is defined as follows (NASA 2002b):

$$\Pr(\text{Top Event}) = \prod_{i=1}^{N}(M_i) \quad (2)$$

To illustrate how Equations 1 and 2 work, let us assume that we have collected sufficient data to estimate the probability of basic events for the example shown in Figure 1, as follows:

Pr(A)=0.4; Pr(B)=0.6; Pr(C)= 0.7; Pr(D)=0.45; Pr(E)=0.3; Pr(F)=0.65

$$\Pr(\text{Top Event}) = 1 - \prod_{i=1}^{4}(1 - M_i)$$

Pr (Top Event) = 1-[(1-0.4*0.6)*(1-0.7*0.45)*(1-0.3)*(1-0.65)] = 0.87 (3)

Since evaluating the probability of occurrence of basic events is the most significant challenge in conducting quantitative fault tree analysis in the construction domain, the next section illustrates how fuzzy logic can be used to address this challenge.

Fuzzy Logic

The concept of fuzzy logic was first suggested by Zadeh (1965). The application of fuzzy logic to problem solving provides highly transparent and more intuitive models. For instance, fuzzy sets offer the analyst great advantages over using other models that are based on crisp sets, since it allows a gradual transition between different concepts.

Pioneering work on applying fuzzy fault tree analysis was done by Tanaka et al. (1983). Since then, this concept has been used extensively by several authors. In the proposed approach, the minimal cut sets are calculated first. Hauptmanns' (1988) algorithm is used to create a Boolean matrix .Thereafter, instead of collecting data to evaluate the probability of occurrence of basic events, each basic event will be assigned a linguistic term, which is referred to as a fuzzy probability. Each linguistic term is represented by its alpha-cuts (α-cut). The α-cut of a fuzzy set is the set of all x values in the set for which the membership value in the fuzzy set is greater than or equal to the alpha argument. The α-cut representation of fuzzy sets introduces an important connection between crisp set theory and fuzzy set theory and allows us to extend the various properties of classical crisp sets to fuzzy sets. In the proposed approach, each fuzzy set will be defined using four points as follows: *A* (a, b, c, d); were *a* represents the minimum value, *b* and *c* represents the most likely values, and *d* represents the maximum value. The OR operator is defined as shown in Equation 4 (Verma et al. 2007).

FPro (Top Event) $^{\alpha}$ =

$$\{1 - \prod_{i=1}^{n}[1 - (a_i + (b_i - a_i))^{\alpha}], 1 - \prod_{i=1}^{n}[1 - (d_i - (d_i - c_i))^{\alpha}]\} \quad (4)$$

where n is the number of cut sets connected by OR and FPro is the fuzzy probability.

The AND operator is defined as shown in Equation 5 (Verma et al. 2007).

$$\text{FPro (Top Event)}^{\alpha} = \{\prod_{i=1}^{n}[a_i + (b_i - a_i)^{\alpha}], \prod_{i=1}^{n}[d_i - (d_i - c_i)^{\alpha}]\} \quad (5)$$

Fault Trees and Risk Analysis Techniques

There are several techniques found in the literature that can be used to assess and quantify the probability of risk events. Each technique has both advantages and disadvantages. For instance, the risk matrix is one of the commonly used techniques for risk analysis in which risk events are allocated to a grid with probability (P) along one axis and impact on the other axis. A threshold is normally constructed according to a company's organizational policy. The risk matrix approach is simple, flexible, can be adjusted to fit any project, and is easily understood (Abdelgawad and Fayek 2008). However, the risk matrix method does not provide detailed calculations to support the selected probability of occurrence of risk events. Instead, experts rely on their personal judgement and experience to assign probability values to each risk event.

Monte Carlo simulation is another commonly used technique for risk analysis. The simulation process is built on iterations that make use of internally generated random numbers that follow a specific probability distribution for each risk event. Monte Carlo simulation provides more useful information as compared to the risk matrix. For instance, the confidence interval of the results can be established. However, similar to any probabilistic technique, Monte Carlo simulation requires sufficient data to select suitable probability distributions; otherwise, uncertainties in the input parameters may result in large uncertainties in the resulting risk estimate.

Decision Trees are another tool that is used for risk analysis and to choose between several courses of action. A decision tree is constructed as a graphical representation of possible outcomes of known choices and their probability of occurrence. Decision trees provide a highly effective structure within which decision options can be investigated. Moreover, decision trees support the communication of a sequence of decision alternatives. However, historical data are required to calculate accurate probability values for decision points. In addition, the sequence of decision alternatives and the nature of the project are assumed to be static (Thompson and Perry 1992).

Regression analysis is a statistical technique for developing an equation that best fits a set of observations. This technique is implemented by collecting historical data from past projects, identifying key attributes, and formulating a relationship between key attributes and the output (Ng 2006). In the field of risk analysis, regression analysis can be used to establish an equation between a set of parameters and the probability of occurrence of a risk event. Similar to Monte Carlo simulation, this technique can provide a confidence interval of the results (Ng 2006). However, this technique suffers from the same limitation of Monte Carlo simulation and decision trees, which is attributed to the lack of available data in the construction domain. In addition, regression analysis must start from scratch if a new parameter is required to be added to the regression equation, which makes this technique static and time consuming.

Fuzzy fault tree analysis (FTA) offers the advantage of solving the fault tree even if data are unavailable or difficult to obtain, which make this technique more preferable

compared to the previously mentioned techniques. In addition, this technique offers additional advantages, which are summarized as follows (NASA 2002a):

1. FTA supports the decision maker in understanding how different root causes interact to cause the top event (i.e., risk event) and provides supporting detail behind the estimated probability of occurrence of a risk event.
2. FTA can be used as a tool to identify proactive risk response strategies. For instance, by identifying vulnerable areas in the project, the project team members can work on identifying options that may correct these areas at early stages in the project.
3. FTA can be used as a diagnostic tool after the occurrence of a risk event to understand the logic that leads to the occurrence of the risk event. Understanding the logic can aid in capturing lessons learned that will help in mitigating this risk event in the future.

Fuzzy Fault Tree Analysis for Horizontal Directional Drilling

In order to assess the risk associated with HDD construction in a pipeline construction project located in northern Canada, a risk identification workshop was arranged with two risk experts. The objective of the workshop was to identify root causes associated with HDD failure and to connect them using the logical operators (OR/AND gates). After several discussions with the two experts, the top event was identified as HDD failure to meet project objectives of cost and time, and all root causes were identified and used to build the fault tree shown in Figure 2. To establish linguistic terms that will be used to assess the probability of occurrence of basic events, an interview was arranged with one of the experts. The meeting began by reviewing the risk management standard to identify the current criteria used by the company to assess the probability of occurrence of risk events. Their standard shows that five linguistic terms (Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH)), ranging from 0 to 100% are used by the company to assess probability of occurrence. To develop appropriate membership functions for the linguistic assessment of the probability of occurrence, the direct method with one expert (Klir and Yuan 1995) was used to elicit the ranges of values for each membership function. The resultant membership functions were reviewed by the second risk expert. The second expert noted his agreement with the findings. Figure 3 shows the findings from this elicitation process.

After identifying the linguistic terms that will be used to assess the probability of occurrence, another interview was arranged with the same experts to assess the probability of occurrence of different basic events expressed in linguistic terms. Table 1 shows the basic events illustrated in Figure 2, and their probability of occurrence, expressed in linguistic terms (i.e., fuzzy probability).

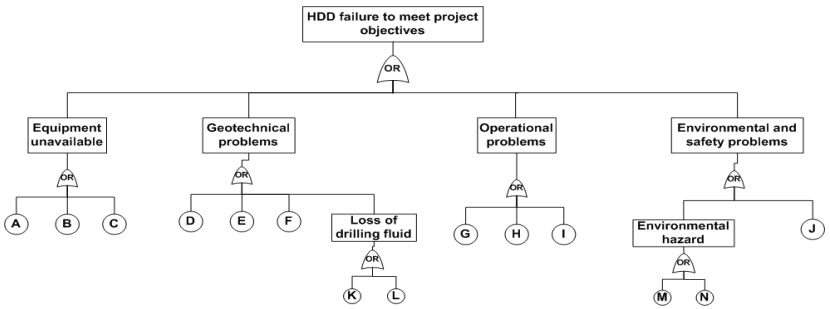


Figure 2: Fault tree diagram for HDD risk

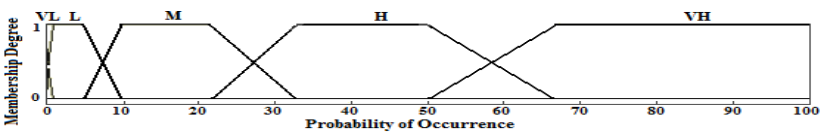


Figure 3: Membership functions for fuzzy probability (FPro) of occurrence

Table 1: Basic events and fuzzy probability assessment

Symbol	Description	Fuzzy Probability (FPro) of Occurrence
A	Emergency shutdown system trips	High (H)
B	Equipment breakdown	Medium (M)
C	Loss of communication with drilling machine	Low (L)
D	Interference with bedrock	Medium (M)
E	Interference with aquifer	Medium (M)
F	Unstable bank	Medium (M)
G	Operator lacking required skills	Low (L)
H	Fatigue of workers	Very Low (VL)
I	Lack of proper supervision	Low (L)
J	Safety incidents on site	Low (L)
K	Seepage of drilling fluid into waterway	Low (L)
L	Seepage of drilling fluid into soil	Medium (M)
M	River flooding	Very Low (VL)
N	Severe weather conditions	Medium (M)

Qualitative assessment was first conducted to identify the MCS. Hauptmanns' (1988) algorithm was utilized to convert the structure of the fault tree into a Boolean matrix.

Applying the algorithm yields fourteen MCS, where each minimum cut set is composed of one basic event as follows:

M1=(A); M2=(B); M3=(C); M4=(D); M5=(E); M6=(F); M7=(G); M8=(H); M9=(I); M10=(J); M11=(K); M12=(L); M13=(M); M14=(N) (6)

The occurrence of any of the basic events, as identified by the MCS, is sufficient to cause the top event to occur. For instance, the occurrence of basic event A is sufficient to cause HDD to fail in meeting the project objectives.

The MCS as identified from the qualitative analysis were utilized to calculate the fuzzy probability of the top event. Since the top event is connected by an OR gate with basic events, Equation 4 is used as follows:

$$FPro\ (Top\ Event)^{\alpha} = 1- [(1- FPro\ (A)^{\alpha}) * (1- FPro\ (B)^{\alpha}) *(1- FPro\ (C)^{\alpha}) *(1- FPro\ (D)^{\alpha}) *(1- FPro\ (E)^{\alpha}) *(1- FPro\ (F)^{\alpha}) *(1- FPro\ (G)^{\alpha}) *(1- FPro\ (H)^{\alpha}) *(1- FPro\ (I)^{\alpha}) *(1- FPro\ (G)^{\alpha}) *(1- FPro\ (K)^{\alpha}) *(1- FPro\ (L)^{\alpha}) *(1- FPro\ (M)^{\alpha}) *(1- FPro\ (N)^{\alpha})] \quad (7)$$

where FPro represents the fuzzy probability.

Equation 7 was used to calculate the top event fuzzy probability by incrementally increasing the value of alpha by 0.05 increments between each alpha. For instance, at α equals zero, Equation 7 can be written as follows:

$$FPro\ (Top\ Event)^{0} = 1- \{[(1-(0.215+(0.33-0.215))),(1-(0.67-(0.67-0.5)))]*[(1-(0.05+(0.1-0.05))),(1-(0.33-(0.33-0.215)))]*[(1-(0+(0.01-0))),(1-(0.1-(0.1-0.05)))]*[(1-(0.05+(0.1-0.05))),(1-(0.33-(0.33-0.215)))]*[(1-(0.05+(0.1-0.05))),(1-(0.33-(0.33-0.215)))]*[(1-(0.05+(0.1-0.05))),(1-(0.33-(0.33-0.215)))]*[1-(0+(0.01-0))),(1-(0.1-(0.1-0.05)))]*[(1-(0+(0-0))),(1-(0.01-(0.01-0)))]*[(1-(0+(0.01-0))),(1-(0.1-(0.1-0.05)))]*[(1-(0+(0.01-0))),(1-(0.1-(0.1-0.05)))]*[(1-(0+(0.01-0))),(1-(0.1-(0.1-0.05)))]*[(1-(0.05+(0.1-0.05))),(1-(0.33-(0.33-0.215)))]*[(1-(0+(0-0))),(1-(0.01-(0.01-0)))]*[(1-(0.05+(0.1-0.05))),(1-(0.33-(0.33-0.215)))]\} \quad (8)$$

By substituting the value of possibility into Equation 7 for different α-cuts, the fuzzy probability of the top event was calculated as shown in Figure 4. An excel sheet was designed to automate the α-cut calculations.

After calculating the fuzzy probability of the top event, the mean of maximum (MOM) method was selected for defuzzification. Since the membership function at α level equals 1 represents the most confident level, the mean of maximum can be viewed as the most likely estimate of probability over the most confident range. Equation 9 shows the defuzzified estimate of the fuzzy probability for HDD failure using the MOM method.

$$FPro\ (Top\ Event) = \left(\frac{0.66139+0.90947}{2}\right) * 100 = 78.54\ \% \quad (9)$$

The findings were then reviewed with the two experts to verify the results. The experts agreed with the findings and indicated the suitability of using this technique in the construction domain as compared to other risk analysis techniques, since linguistic assessment of basic events are more realistic and practical than probabilistic assessment.

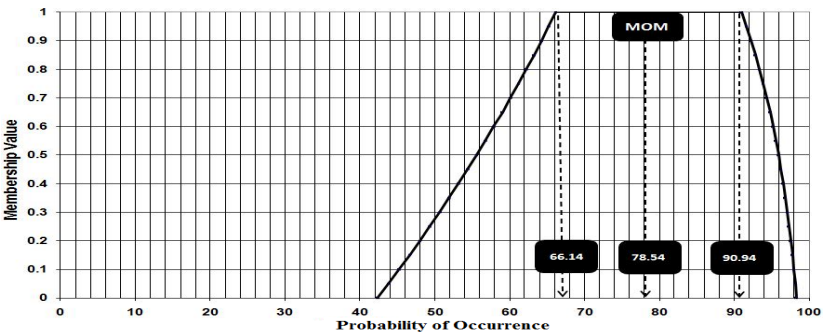


Figure 4: The fuzzy probability distribution for the HDD risk event

Conclusions

In this paper, we investigated the concept of fuzzy fault tree analysis and demonstrated the use of this technique by means of a case study project. Qualitative assessment of the fault tree was conducted by determining the minimal cut sets. The probability of occurrence of basic events were identified using linguistic terms and represented using α-cuts. Fuzzy arithmetic operations on fuzzy numbers were then utilized to calculate the top event fuzzy probability. The mean of maximum (MOM) was selected to defuzzify the top event fuzzy probability. By understanding how different root causes may interact to cause the risk event to occur, the project team members will have a better understanding of how the risk event may occur. Hence, better risk response strategies can be developed in the future to mitigate the risk event. The proposed approach provides construction practitioners with a more realistic approach to assess the probability of occurrence of risk events even if data are unavailable or difficult to obtain.

Future work is currently in progress to combine fault trees and event trees in a structured framework to support quantitative risk analysis. In this regard, the concept of fuzzy logic will be investigated to solve both. Fault trees provide a means of understanding the logical combination of different root causes to cause the risk event. Event trees provide a means of understanding and communicating different mitigation options, and supporting the assessment of the consequence of different mitigation scenarios.

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THE APPLICATION OF UTILITY THEORY IN THE DECISION-MAKING PROCESS FOR INVESTING IN ADR INSURANCE

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ABSTRACT

Since most projects today operate on tight budgets, one way to ease the potential for variations from budget is to price Alternative Dispute Resolution (ADR) techniques as an insurance product, which allows the project participants to transfer the risk of incurring unexpected high ADR cost during construction phase to the insurance company. Despite this advantage, many factors are preventing project participants from investing in ADR insurance. For example, on an, expected value (EV) basis, self-insurance almost always appears financially better than insurance premiums because of the insurance company's underwriting expenses and profit target that are included in the premium charges. However, expected value calculations miss important effects of uncertainty on the participants. In this paper, we borrow utility theory and introduce subjective loss to represent the "risk-averse" attitude of project participants when facing uncertainty. A convex subjective loss function (SLF) is used to translate the impact of ADR costs into utility-equivalent terms. Then the expected subjective loss is translated back to an equivalent certain monetary loss. Comparison between this derived certain monetary loss and the loss from investing in ADR insurance shows that even with the expense and profit loading, there is still an opportunity for a mutually advantageous insurance policy. And this opportunity grows larger as the potential ADR cost increases. Also, a numerical example is presented to illustrate how to structure a subjective loss function for project participants. It is the authors' hope that this paper could help project participants answer the question in the decision-making process: would they rather try to budget for an unknown cost in a wide range, or pay for insurance and be certain?

INTRODUCTION

In a construction project, project participants always face uncertainty about future dispute resolution cost. For example, the participants do not know at the outset whether and when a dispute will occur and how much it will cost. This uncertainty not only impedes efficient use of funds (because the participants would prudently hold funds in reserve against the contingency of a dispute), but also results in project participants' constant anxiety over what will happen in the future. One way to reduce uncertainty's negative influence over the project would be to structure and price Alternative Dispute Resolution (ADR) techniques as an insurance product, which would allow the transfer of the risk of incurring unexpected high ADR cost during construction phase from project participants to the insurance company, and thus maintain a stable dispute resolution expenditure stream. If the problem is viewed on an expected value (EV) basis, when a decision maker is facing the uncertainty about a possible random loss X, he/she would be willing to pay no more than the expected loss amount $E[X]$ in order to be relieved from the future loss (Bowers *et al* 1997). This basis generally makes insurance meaningless to the insureds from the point of expectations as the premium an insurance company charges as a return for bearing the risk is almost always going to be greater than the expected dispute resolution cost $E[X]$ (unless the insurance company and the insureds have different expectations about the number and cost of disputes) because the premium includes an expense loading to cover the underwriting expenses and target profit of the insurance company.

However, decision makers do not necessarily follow the simple and straightforward result that EV would predict. Other aspects such as the magnitudes of and attitudes towards possible outcomes may also impact on people's perceptions and thus influence the decisions. For example, as early as 1783, Bernoulli designed a scenario where individuals would not consider paying for the privilege of playing a game even with an infinitely large EV (Li 2003). This was later referred to as the St. Petersburg paradox, and it illuminated the wide gap that sometimes exists between the EV prescription and actual behavior. In the insurance industry, take life insurance for example, according to the 2003 US Mortality Table (National Vital Statistics Reports 2006), the probability of dying for a male aging between 39 to 40 is only 0.001847. However people still pay hundreds even thousands dollars of premium to purchase life insurance in order to prepare themselves for unexpected events. That is because different people have different attitudes toward risk under different conditions and most people and organizations are risk averse to some degree. Similarly in construction projects, assuming the likelihood of dispute occurrence is 0.1, an ADR implementation cost of $1,000 might be of little concern to the project participants who then might be unwilling to pay more than the expected loss ($100) to obtain insurance. However, a possible dispute resolution cost of $10,000,000 could be catastrophic to the project. In this case, project participants might be willing to pay a fixed insurance premium that is in excess of the mean expected value of the loss in exchange for shedding some uncertainty about the future (Pritchett *et al* 1996). Project participants attach a different value to the dispute resolution cost they might incur based on their degree of aversion to the risk they face during the course of the

project. This value is similar to the concept of "utils" in utility theory, which will be explained in detail later.

In this paper, concepts from utility theory have been borrowed to indicate the "risk-averse" attitude of project participants and a subjective loss function (SLF) is used to translate the impact of ADR cost into utility-equivalent monetary terms. The result shows that even with the expense and profit loading, there is still an opportunity for a mutually advantageous insurance policy. Finally, a numerical example is presented to illustrate how to structure a subjective loss function for project participants and how to calculate the optimal premium based on the function.

PROBLEM STATEMENT

Without loss of generality, the risk of incurring ADR implementation costs in any construction project can be mathematically represented by:

1) n, the total number of disputes occurring in the period from the notice to proceed (NTP) ($t = 0$), to the project completion ($t = T$ days, $m < T/30 < m+1$ months); $n = N_1, N_2,.., N_k$ with probability $q_1, q_2,.., q_k$ respectively, where N_1 is the minimum possible number of disputes and $N_1 \geq 0$, while N_k is the maximum number of possible disputes;
2) c_i, the amount of ADR cost for each dispute resolution process, where $i = 1, 2,\ldots, n$ represents the dispute number. For purposes of illustrating this paper, we assume that the cost of each dispute is independent from others and bears m possible outcomes for each dispute, c_1 (resolved at ADR1), c_2 (resolved at ADR2), …, c_m (go to litigation), with probability p_1 p_2, and p_m respectively where $j = 1, 2,\ldots, m$ is the resolution type and $\sum_{j=1}^{m} p_j = 1$;
3) For the ith dispute, define $x_{ij} = 1$ represents that the ith dispute is resolved with the jth resolution type, while $x_{ij} = 0$ otherwise. Thus $x_j = \sum_{i=1}^{n} x_{ij}$ represents the total number of disputes that are resolved with the jth resolution type, and follows a multinomial distribution $M(n, p_1\ p_2,\ldots, p_m)$, with the expected value $E(x_j) = n\ p_j$, where $j = 1, 2,\ldots, m$. Specifically, when $m = 2$, then x_j follows binomial distribution $B(n, p_1\ p_2)$.
4) Among all n disputes, there are a total of R different possible outcomes. For each outcome, there could be x_j disputes resolved with the jth ADR. Consequently, the total ADR implementation cost throughout the time horizon for the rth outcome is $C_r = \sum_{j=1}^{m} c_j x_j$ with a probability of $P_r = \prod_{j=1}^{m} p_j^{x_j}$, given a total of n disputes. And the number of outcome which bears the same total cost and probability is $\binom{n}{x_1 \cdots x_j \cdots x_m}$.

Then assume for a specific project, the expected number of disputes is $E(n)$, which also represents the frequency of dispute occurrence; and the expected average ADR cost per dispute is $E(c_i)$ which also represents the expected severity of dispute resolution cost. Then, according to previous work by the Song (2009b) and by drawing analogy from health insurance, the gross premium for the ADR insurance is:

$$P = E(C) = E_P(C) + \alpha \qquad \text{Eq. (1)}$$

Where $E_P(C)$ is called pure premium in the case of not carrying the premium, while α is an expense loading factor to cover the expenses and the target profits of the insurance company (Song *et al* 2009a). Specifically, we have

$$
\begin{aligned}
E_P(C) &= \sum_{n=N_1}^{N_k} q_n \sum_{r=1}^{R} \binom{n}{x_1 \cdots x_j \cdots x_m} C_r P_r \\
&= \sum_{n=N_1}^{N_k} q_n \sum_{r=1}^{R} \binom{n}{x_1 \cdots x_j \cdots x_m} \sum_{j=1}^{m} c_j x_j \prod_{j=1}^{m} p_j^{x_j} \\
&= \sum_{n=N_1}^{N_k} q_n \sum_{j=1}^{m} c_j \left(\sum_{r=1}^{R} \binom{n}{x_1 \cdots x_j \cdots x_m} \prod_{j=1}^{m} p_j^{x_j} \right) x_j \\
&= \sum_{n=N_1}^{N_k} q_n \sum_{j=1}^{m} c_j (n p_j) \\
&= \sum_{n=N_1}^{N_k} n q_n \sum_{j=1}^{m} c_j p_j \\
&= E(n) * E(c)
\end{aligned}
\qquad \text{Eq. (2)}
$$

is called pure premium in the case of not carrying the premium, while α is an expense loading factor to cover the expenses and the target profits of the insurance company. As mentioned before, as long as α is not zero, not purchasing is always going to look better than insurance on an expected value basis. However, for this case using expected value to make decisions ignores the range of possible values and does not capture risk attitudes where insurance might be an advantageous risk management method to transfer away this financially catastrophic outcome (Clemen 1997). For example, assume for a certain project, the expected total ADR implementation cost is $ 1,000,000, where the mean expected number is 20 and the average ADR cost per dispute is estimated to be $50,000. However, the actual number of disputes likely has a range of possible outcomes (e.g., from 5 to 50), and the average ADR cost also likely has a range (e.g., from $15,000 to $100,000) depending on the nature of the disputes that arise, the effectiveness of the ADR utilized and the maximum allowable time for each step on the contractually agreed project dispute resolution ladder (Song *et al* 2009a). Then the actual total cost may vary from $75,000 to $5,000,000. If using expected value, any insurance with premium higher than $ 1,000,000 is not favorable to project participants. However, to the insureds, if the negative prospect of the possibility of incurring an unexpected large ADR implementation cost as high as $5,000,000 is taken into consideration, then the interpretation may be different and there is a motivation for project participants to consider investing in ADR insurance, even with a premium cost greater than $1,000,000. In utility theory, the prospect of this negative impact is the “negative utility” project participants attach to a certain

ADR cost, and it is not the expected loss value but the "subjective loss value" of a loss that plays an important role in project participants' decision making process regarding whether to invest in ADR insurance or not (Hoshiya *et al* 2004).

UTILITY THEORY IN ADR INSURANCE

Utility theory is an attempt to infer subjective value, or utility, from choices (Bell *et al* 1988, Keeney *et al* 1993, Norstad 2005). It has been developed to provide insights into decision making in the face of uncertainty (Bowers *et al* 1997). Generally a utility function *u (w)* is used to indicate the value or utility that project participants attach to a certain wealth of amount *w* (Bowers *et al* 1997). Different from the traditional positive definition of a utility function, "subjective loss" employed in this paper is quantified by a subjective loss function (SLF) to indicate the negative utility *u(c)* that project participants attach to a given loss amount of ADR cost *c* resulting from dispute resolution. Following the notation in the problem statement, we have the total expected subjective loss

$$E\big(u(C)\big) = \sum_{n=N_1}^{N_k} p_n SL_n$$

Where

$$SL_n = \sum_{r=1}^{R} \binom{n}{x_1 \cdots x_j \cdots x_m} p_r u(C_r) = \sum_{r=1}^{R} \left(\binom{n}{x_1 \cdots x_j \cdots x_m} \prod_{j=1}^{m} p_j^{x_j} u\left(\sum_{j=1}^{m} c_j x_j \right) \right) \quad \text{Eq. (3)}$$

is the expected subjective loss for a total of *n* disputes. Then from the viewpoint of the insured, the maximum acceptable gross premium *P* for assuming loss *C* is determined from:

$$u(P) = E\big(u(C)\big) \rightarrow P = u^{-1}\Big(E\big(u(C)\big)\Big) \quad \text{Eq. (4)}$$

The left hand side of the equation represents the situation where the project has ADR insurance thus all project participants need to pay is the premium; while the right hand side is the case without insurance, where project participants should bear all the loss. In each case, the participant views the undesirable financial outlay (either the certain premium or the uncertain ADR costs) subjectively (the function u). It is natural to assume that *u(c)* is an increasing function because "the more loss, the worse (more negative utility) it gets". As mentioned earlier, while an ADR implementation cost of $1,000 might be of little concern to the project participants, a possible dispute resolution cost of $10,000,000 could certainly be worthy of a second thought. In addition, however, each additional equal increment of loss results in a larger increment of associated negative utility – a loss of $2 million has more than twice as much negative utility as a loss of $1 million. This is the mirror image of the principle of decreasing marginal utility in economics; we could call it "increasing marginal negative utility" in this case, which is schematically illustrated in Figure 1.

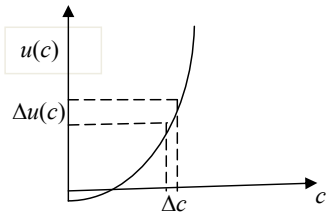


Figure 1 Example of Subjective Loss Function

The two properties suggested by Figure 1 are $u'(c) > 0$ and $u''(c) > 0$. The second inequality indicates that $u(c)$ is a strictly convex upward function.

According to Jensen's inequalities (Bowers *et al* 1997), for a random variable X and function $u(c)$ with a convex characteristic,

$$\text{If } u''(c)>0, \text{ then } E(u(X)) \geq u(E(X)), \text{ vice versa.}$$

In other words, project participants with SLF $u(c)$ are risk averse if, and only if, $u''(c) > 0$.

In Eq.(4) there is the expression of the maximum premium the risk-averse participant should be willing to pay:

$$u(P) = E(u(C))$$

Combining this with

$$E(u(C)) \geq u(E(C))$$

for a risk averse project participant, there should be an acceptable maximum premium:

$$P \geq E(C)$$

meaning that the participant is willing to pay an amount greater than the expected value of ADR cost for insurance to get rid of the risk of uncertainty.

HOW TO CONSTRUCT A SUBJECTIVE LOSS FUNCTION (SLF)

There is a simple step-by-step approach to establish project participants' SLF (Bowers *et al* 1997). First assign two utility values to two losses $c_1$and c_2 (specifically $c_1 = 0$ to illustrate the situation where there is no loss). Then ask the question: assume that project participants are facing a loss of c_2 with specified probability p, what is the maximum amount G they would be willing to pay for complete insurance protection against this random loss to remain at the status of no loss ($c_1 = 0$) with probability 1-p? Expressing this in mathematical terms, the question is for project participants to fix a value G such that:

$$u(G) = \mathrm{E}[u(C)] = (1-p)*u(c_1) + p*u(c_2) \quad \text{Eq. (5)}$$

Once the value $G=c_3$ is available, the point $[c_3, (1-p)*u(c_1)+p*u(c_2)]$ is determined as another point of the SLF. Following these steps, project participants could add as many points as necessary and with enough points a smooth function with a second

derivative may be fitted to provide for a SLF that characterizes the risk-aversion of the participants.

For example, assuming for a project, there are two points on project participants' SLF, which we assign utilities of zero and one units of utility, respectively: $u(0) = 0$ *and* $u(20{,}000) = 1$. Suppose an ADR cost of \$20,000 might be incurred with probability 0.5, or no ADR cost would be incurred with probability 0.5 (this is an oversimplified example to help explain the approach clearly. In reality there are more scenarios regarding ADR cost. An Event Tree Analysis (ETA) might be used to analyze the event of incurring ADR cost c_n with probability p_n). According Eq. (4), project participants are asked to determine the value G so that:

$$u(G) = 0.5*u(20{,}000) + 0.5*u(0) = 0.5.$$

Here if they pay G, then their loss will certainly remain at G, instead of the uncertain \$20,000. The equal sign indicates that project participants are indifferent between paying G with certainty and accepting the expected subjective loss expressed on the right hand.

Assume the project participants decide that for them, $G = 12{,}000$. Therefore,

$$u(12{,}000) = 0.5$$

The result is plotted on the dash line in Figure 2. From it we can conclude that there is a possibility that participants would be willing to pay an amount for insurance (G = \$12,000) that is greater than the expected value of the loss ($E(C)$ = 0.5*0+0.5*20,000 = \$10,000).

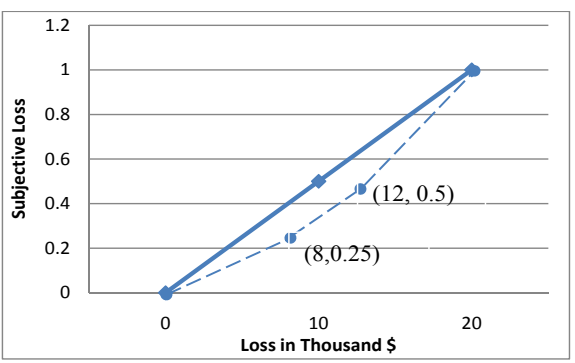


Figure 2 Determination of a SLF

The approximate SLF of Figure 2 consists of straight line segments with positive slopes. If we continue this process with the participants and obtain more points on the curve, we can generate a smooth curve which bears the properties of $u'(c)>0$ and $u''(c)>0$, as long as we are dealing with risk averse project participants.

Building project participants' SLF is a way to replace their qualitative preference from among alternatives that have uncertain payoffs with a consistent numerical comparison. As simple as the procedure appears, this could, however, turn out to be a rather complicated process. This is because the process is a matter of subjective

judgment and depends on many factors such as conflicting attitudes toward risk among project participants, project type, and environment of financial market, etc. (Bowers *et al* 1997). Even for the same project participants, different projects will have different subjective loss functions, thus requires re-evaluation. In utility theory, there are several elementary functions that can be used as utility function such as exponential, fractional power, quadratic functions, to name a few (Bowers *et al* 1997). In this paper, quadratic function (as in Eq.(6)) is adopted as project participants' SLF due to three reasons. First, it bears the properties necessary to represent a risk-averse attitude. Second, it is the closest function form which can be used to estimate our pilot data. Last but not the least, it is one of the fundamental functions and is easy to comprehend and calculate.

$$u(x) = ax^2 + bx + c \qquad a, b > 0, x > 0 \qquad \text{Eq. (5)}$$

Using the approach described above, the values of constant a, b, and c could be estimated using regression. To elaborate, first a financial survey should be conducted for project participants to show their different perception of a given series of loss values. Then with several points plotted on the SLF line, the regression of the actual loss values and the impact of those losses (valued by project participants in comparison to previous established utility values) would be the subjective loss function. An illustrative example is presented in the next section to explain how can we calculate the subjective loss and its corresponding monetary term.

IILUSTRATIVE EXAMPLE

Assume there is a highway bridge project where project participants decide to include a three-stepped DRL in the contract for dispute resolution. In this DRL, a dispute goes through Architect/Engineer or Supervising Officer (ADR1) to mediation (ADR2), then arbitration (ADR3) if the first two fail to provide a satisfactory settlement. More specifically, when the dispute resolution process starts, the dispute is first turned to Architect/Engineer or Supervising Officer. To calculate this expense, assume for this illustrative calculation that the unit cost is \$500 per day for this step. If the initial attempt fails to achieve the settlement within the maximum allowable time of d_1 = 60 days, the dispute escalates to the next level with mediation between the owner and contractor representative; assume the cost at this level is at a unit cost of \$1,500 per day and d_2 = 30 days. Finally, if the dispute is not resolved at the previous levels, it is turned to the final step of arbitration. Assume for this illustration that the cost at this level is \$3,000 per day with d_3 = 60 days. Assume that the estimated duration of this project is T=1,450 days after NTP (assume there are 30 days in each month, $m = 48 < T < m+1 = 49$).

For illustration purpose, we make the following simplified assumptions. Based on statistical data and past experiences on similar projects, the owner estimates that

1) The above DRL will be required to resolve a total of 1, 2 or 3 potential disputes resulting from different dimensions of the project with a probability of 25%, 50%, and 25% respectively.

2) Each dispute will cost on average \$63,850 with two possible outcomes: a) for a probability of p = 98% it will stay on the DRL and cost $c1$=\$27,500; and b) for a probability of (1-p) = 2% it will escalate to litigation and cost $c2$= \$1,845,000 (with expected value equals to the average cost \$63,850).

Based on our assumptions, when there are n potential disputes, there will be potentially n+1 outcomes for total ADR implementation cost: 0, 1, 2,…, n ADR resolutions (or n, n-1, n-2, …,0 litigation resolutions). The number of ADR resolutions follows Binomial distribution $B(n,p)$.

According to Song *et al* (2009a), the estimated pure premium (PP) is:

$$PP = E(n) \cdot E(c_i) = 2 \times \$63{,}850 = \$127{,}700$$

Add an Expense Loading Factor (ELF) of 35% (illustrative value, including a provision for profit, assumed for this example), the Gross Premium (GP) should be:

$$GP = \frac{PP}{1 - ELF} = \frac{\$127{,}700}{1 - 35\%} = \$196{,}462$$

Follow Eq. (4) and ask project participants to attach their perceptions to develop equivalences to a series of loss values in utility terms. Then, fit a Polynomial Regression to the paired responses to estimate the participants' subjective loss functions. As shown in Figure 3, the regressed function is:

$$u(x) = 0.00003 * x\text{^}2 + 0.8 * x$$

Because $u'(c)>0$ and $u''(c)>0$, this function meets the requirements for risk-averse project participants .

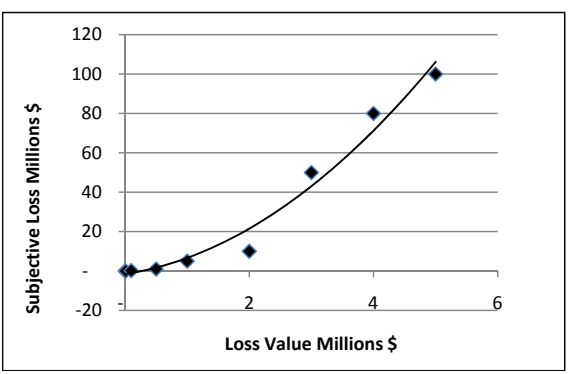


Figure 3 Subjective Loss Function for project participants

To determine the SLF of project participants, we calculate the SL_n for each possible number of disputes over the time horizon. Eq.(3) is simplified to

$$SL_n = \sum_{r=0}^{n} \binom{n}{r} p^r (1-p)^{n-r} u(rc1 + (n-r)c2) \qquad \text{Eq. (6)}$$

When *n*=1, we have two possible outcomes, either the only dispute is resolved with ADR or with litigation with probability *p* and 1-*p* respectively. Then,

$$SL_1 = pu(c1) + (1-p)u(c2) = 2{,}115{,}730$$

When *n*=2, we have three possible outcomes for the time horizon: zero ADR, one ADR, or two ADR resolutions. Then,

$$SL_2 = (1-p)^2 u(2c2) + 2p(1-p)u(c1+c2) + p^2 u(2c1) = 4{,}476{,}066$$

When *n*=3, we have four possible outcomes for the time horizon: zero ADR, one ADR, two ADR, or three ADR resolutions. Then,

$$SL_3 = (1-p)^3 u(3c2) + 3p(1-p)^2 u(c1+2c2) + 3p^2(1-p)u(2c1+c2) + p^3 u(3c1) = 7{,}081{,}014$$

Thus the total subjective loss

$$E\big(u(C)\big) = \sum_{n=1}^{3} p_n SL_n = 4{,}537{,}219$$

According to Eq.(4), to make insurance attractive to a participant, there should be a maximum amount of money *P** which satisfies $u(P^*) \leq E[u(C)]$ or

$$P^* \leq u^{-1}(E[u(C)]) = \$375{,}792$$

The results are summarized in Table 1. From the Expected Value perspective, project participants are willing to pay up to $127,700 for certain to shirk the risk of uncertainty. To assume the same amount of risk, the insurance company charges a gross premium of $196,461. In this case, insurance is never an attractive option because neither the project participants will pay more to invest in insurance nor the insurance company lower its premium. From the subjective loss perspective, however, risk-averse project participants are willing to pay up to $375,792 for certain to shirk the risk of unusually large ADR expense. Their maximum acceptable certain loss is much higher than the premium charged by the insurance company. Consequently, investing in insurance becomes much more attractive.

Table 1 Loss value for the project participant

	Project participant perspective	
Loss valuation basis	Without insurance	With insurance
Expected value basis	$127,700	$196,461
Subjective loss basis	$375,792	$196,461

CONCLUSION

This paper investigated the application of utility theory in the decision-making process for project participants to invest in ADR insurance. We first introduced the concepts of subjective loss, and then explained how subjective loss can better represent risk-averse project participants in evaluating uncertainty, thus providing a possible explanation for the validity of third-party insurance in construction management. Our study shows that despite insurance company's additional expense

underwriting and profit loading, there may still exist the opportunity for a mutually advantageous ADR insurance. This ADR insurance, while not a tool to eliminate the possibility of a possible dispute resolution cost, is a powerful alternative in risk management to transfer the financial risk to a third party.

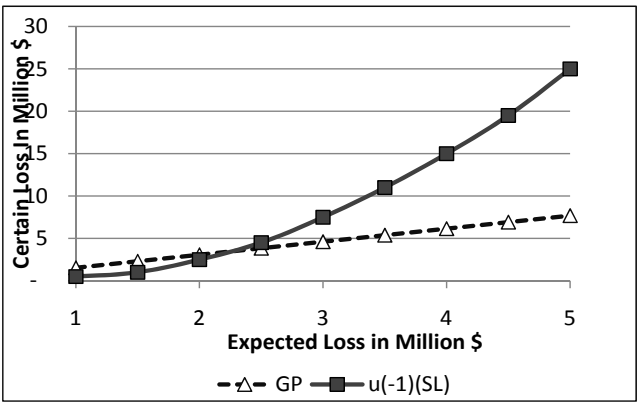


Figure 4 Expected Payouts for Project Participants (Simplified example for illustration)

We also conclude that a Subjective Loss Function could be constructed to indicate the "risk-averse" attitude of project participants and quantify the impact of ADR cost in utility terms. As shown in Figure 4, when the expected loss for risk-averse project participants is low, their maximum acceptable certain loss based on subjective loss perspective could be lower than the gross premium by the insurance company. However, as the expected loss increases, this maximum acceptable certain loss increases at a higher ratio then the gross premium. After a certain point, investing in insurance becomes an attractive option for the project participants. Future research could focus on how to determine the range of premiums acceptable to both project participants and the insurance company.

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The impact of regulatory licensing processes on U.S. civilian nuclear power plant project performance

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Abstract: Due to increasing U.S. energy demand, the Nuclear Regulatory Commission is currently reviewing permit applications for 25 new nuclear power reactors. However, the previous generation of nuclear plant construction was beset by significant cost and schedule overruns. Several researchers have identified "regulatory ratcheting," increases in retroactive regulations, as one of the primary causes of the poor performance of these projects. Regulatory ratcheting was enabled, in part, by the two step nuclear power plant licensing process (10 CFR Part 50) that required plants under construction to meet all current regulatory requirements before receiving an operating license. This two step licensing process has been replaced by a single step process (10 CFR Part 52). How will this single step licensing process impact project performance? This question is investigated using a dynamic simulation model of the technical and social feedback processes that impact U.S. nuclear plant construction. The research reveals that under 10 CFR Part 52 society's amplified perception of nuclear power risks can still drive regulatory growth leading to potentially significant cost and schedule overruns.

Introduction and Problem Statement

To meet the growing demand for low carbon sources of electricity U.S. electric utilities are currently planning a second generation of nuclear power plant (NPP) construction. The Nuclear Regulatory Commission (NRC) is currently reviewing 25 new unit license applications and expects to receive 10 more applications by the end of 2010 (NRC 2008). However, the previous generation of U.S. civilian NPP construction was plagued by poor project performance with an average 338% cost overrun and 239% schedule overrun (Taylor and Ford 2008). If the second generation of NPP construction is to be successful the problems encountered during the previous generation must be mitigated. Several researchers have identified "regulatory ratcheting" as one of the primary causes of the poor cost

and schedule of the first generation of U.S. civilian nuclear power plants (Cohen 1990; Olyneic 1985; Friedrich et al. 1987; Lillington 2004). Regulatory ratcheting refers to the retroactive increase and changing of governmental regulations that apply to nuclear power construction. U.S. NPP construction was regulated using a two-step licensing process, 10 CFR Part 50, in which utilities were issued a license to construct the plant and then, once construction was completed, applied for a separate operating license (NRC 2004). Because the operating license was issued at the end of construction, plants had to meet all current NPP regulations to receive an operating license. The result of this regulatory structure was continuous, high levels of construction rework due to the increase of retroactive NPP regulations.

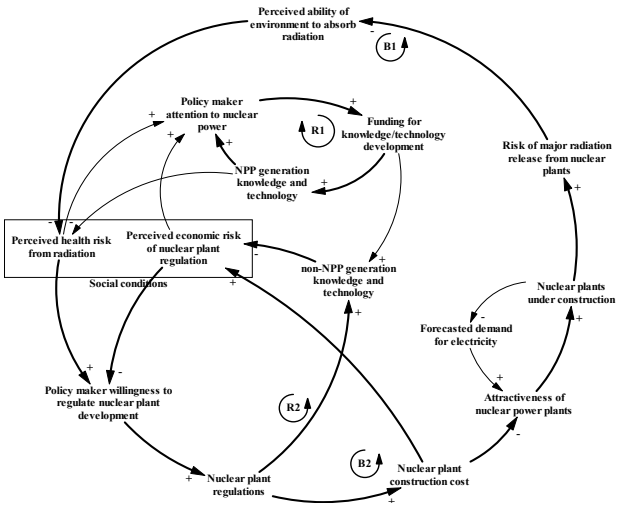
The proposed next generation of nuclear power plants constructed in the U.S. will be developed under a new licensing process, 10 CFR Part 52, which features a combined construction and operating license (NRC 2004). This combined license is designed to eliminate regulatory ratcheting during the construction phase of NPP development. Under this new licensing process NPPs would receive the combined license once their plant design completes the NRC review process. A plant may begin commercial operation once construction is complete, provided the plant is built according to the approved plans.

Despite the potential of this new licensing process to address the problem of regulatory ratcheting in U.S. NPP construction, no plants have been constructed under the new regulatory system. How will this new regulatory process impact the next generation of NPP construction? This question is difficult to answer because little data exists on new U.S. NPP construction. However, extensive data are available on the previous generation of U.S. NPPs constructed between 1960-2000. By examining how 10 CFR Part 52 would have impacted the previous generation of U.S. NPP construction insight can be gained into the new regulatory structure's possible impact on future NPP construction. The current work investigates the impact of the 10 CFR Part 52 regulatory process on NPP construction using a simulation model of the first generation of U.S. NPP construction industry. The model is used to better understand the causes of regulatory ratcheting in NPPs and offers insight to utility and project managers involved in the next generation of NPP development.

Causal Perspective of Regulatory Ratcheting in NPP Construction

To better understand the drivers of regulatory ratcheting, Figure 1 presents a conceptual model of the cause and effect feedback relationships present in the U.S. civilian NPP construction industry. Because of the complex nature of the causes of regulatory ratcheting, these relationships include elements of NPP construction, NPP operation, knowledge and technology development, societal risk perception, and public policy. The polarity of causal arrows linking variables in Figure 1 describes the impact of variable X (at the tail) on variable Y (at the arrowhead). A "+" indicates a direct relationship (if X increases, then Y increases, all things being equal, and vice versa). A "-" indicates an inverse relationship (if X increases, then Y decreases, all things being equal and vice versa). Loops are labeled as either "B," balancing loops (self correcting) or "R," reinforcing loops. For a more detailed description of causal loop diagrams see Sterman (2000).

During the 1950's and 1960's the rapid projected growth in the "forecasted demand for electricity" increased the "attractiveness of nuclear power plants" (Cohn 1997), leading to an increased number of nuclear plants on order, under construction, and in operation ("nuclear plants under construction" Figure 1). During this time society largely shared the belief of many scientists, engineers, and politicians that the benefits of nuclear power far outweighed any potential risks (Nealey et al. 1983).



Partial Feedback Loop Legend:

B1 – Control of NPP radiation risk loop
R1 – NPP knowledge and technology creation loop
B2 – Risk of regulation loop
R2 – non-NPP knowledge and technology creation loop

Figure 1: Casual relationships in the U.S. civilian nuclear power industry

Beginning in the late 1960's the public began to doubt this belief and came to believe that nuclear power was exceedingly risky (Duffy 1997). This was due in large part to worries over increased radiation health risks from potential large radiation releases from nuclear power plants (Nealey et al. 1983) ("risk of major radiation release from nuclear plants," "perceived ability of environment to absorb radiation," and "perceived health risk from radiation" and associated causal links in Figure 1). To address these safety concerns policy makers responded to this pressure by increasing the number of regulations associated with nuclear plant construction ("policy maker willingness to regulate nuclear plant development" and "nuclear plant regulations" and associated causal links in Figure 1). These regulations increased the construction cost of nuclear plants which eventually slowed project completion and essentially halted nuclear plant construction in the United States ("nuclear plant construction cost," "attractiveness of nuclear power plants, and "nuclear plants under construction" and associated causal links in Figure 1). This desire to limit radiation health risks by

limiting the number of nuclear plants built is described by feedback Loop B1 in Figure 1.

In addition to the pressure from the public to address the perceived health risks of radiation, policy makers were also facing pressure from the utility industry regarding the economic risk of limiting nuclear plant construction. During the 1950's, 1960's, and 1970's utilities projected that electricity demand grew at 7% per year (Cohn 1997; Duffy 1997). Utilities argued that large base load units, such as nuclear plants, were needed to meet this demand (Greenhalgh 1980). This would reduce policy maker willingness to increase NPP regulations, which would keep the cost of nuclear plants relatively low, which would decrease the economic risks of nuclear plant regulation ("policy maker willingness to regulate nuclear plant development," "nuclear plant regulations," "nuclear plant construction cost," and "perceived economic risk of nuclear plant regulation" and associated causal links in Figure 1). The desire to control the economic risks of prohibiting nuclear plant development is described by Loop B2 in Figure 1.

Scientists and engineers contribute to the NPP case through their development of knowledge and technology. Increased knowledge of NPP generation (described by Loop R1 in Figure 1) could lower the "perceived health risk from radiation." The development of environmentally benign alternatives to nuclear power (described by Loop R2) would reduce the "perceived economic risk of nuclear plant regulation," (from the policy maker perspective) which would increase the "policy maker willingness to regulate nuclear plant development, which would increase the "nuclear plant regulations." This feedback hypothesis of regulatory ratcheting is next tested with a formal simulation model.

Formal Model of NPP Construction

A formal model of the feedback relationships (Figure 1) that enable regulatory ratcheting was developed using the system dynamics methodology. A system dynamics model was selected because of the methodology's ability to describe and model feedback relationships in complex systems (Sterman 2000). The model is a multi-sector model with the model structure within each sector based on existing models or theories (described below). The interaction between sectors is based on the conceptual feedback model described in Figure 1. The model is a series of difference equations based on feedback relationships that represent interactions between elements of a system. The system dynamics methodology assumes that system changes occur in small increments over continuous time. System conditions are calculated at each time step based on the conditions in the previous time period and the difference equations. The model is simulated between the years 1960-2000 with system conditions calculated in time intervals of $1/16^{th}$ years. A brief description of the model is provided here. A more detailed model description is available in Taylor (2009). The model is available from the authors.

The NPP construction and operation sector is based on the underlying regulatory and construction processes that exist within the NPP utility industry. The construction and operation of NPP capacity is described using a third order exponential delay (Figure 2).

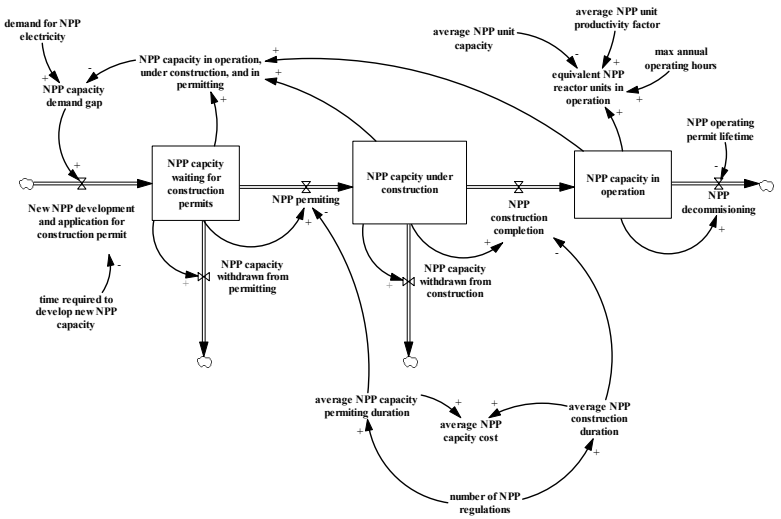


Figure 2: NPP construction and operation sector

New capacity is ordered based on the forecasted demand (described later) for NPP generation. When a generation capacity gap exists, new NPP generating capacity is developed. Once new NPP capacity is developed and ordered the developer submits an application for a construction permit to the NRC. NPP capacity receiving a construction permit flows into a stock of NPP capacity awaiting construction. After capacity is constructed and awarded an operating license the capacity is available for operation. NPP generating capacity is removed from operation through NPP decommission based on the permitted service life for NPP generation (~60 years for most plants). This construction and regulatory process is consistent with the U.S. NPP licensing process described in the Federal Register 10 CFR Part 50 (NRC 2004). Flows between the stocks of the aging chain are constrained by development, permitting, and construction delays. These delays can be increased by increased NPP regulation (described later) and are consistent with causal relationship within the real system (Fredrick et al. 1987; Duffy 1997; Lillington 2004).

The non-NPP generation construction and operation sector describes the construction and operation of non-NPP generation. The demand for new non-NPP generating capacity is determined by the forecasted demand for electricity and the relative attractiveness of NPP generation. As the relative attractiveness of NPP generation decreases, the construction of non-NPP generation increases to meet the forecasted electricity demand. Non-NPP demand is removed from the electricity generation fleet as it is retired from service. The model assumes that electricity demand is either met though NPP or non-NPP generating sources. The forecasted demand for electricity is determined from the actual annual electricity demand for the current year (EIA 2008) and the estimated annual electricity demand growth rate

(Sutherland et al. 1985). The model assumes that utility companies use a 20 year time horizon for electricity demand forecasts (EIA 1992).

The societal risk perception sector in the model is based on Kasperson et al.'s (2005) risk amplification framework. This framework argues that individuals in society learn of risks through different communication channels and events. Research has shown that the general public's perception of the risks associated with NPP is greater than scientifically estimated NPP risk (Rothman and Lichter 1987). Slovic et al. (1979) demonstrated that the general public increased the estimated risk of nuclear power fatalities by 100 times over a conventional scientific risk estimate. The NPP model uses two scientific estimates of the fatality risks associated with nuclear plant operation. The first risk estimate represents the "pro-nuclear power" estimate and is taken from the WASH-1400 *Reactor Safety Study* (NRC 1975). The second risk estimate represents the "anti-nuclear power" estimate and is based on a response report to WASH-1400 published by the Union of Concerned Scientists (UCS 1977). In the model, society's risk perception is based on a weighted average of these risk assessments. The weighting factor depends on the trust society places in NPP science and engineering.

The public policy model sector is based on Kingdon's (2003) agenda setting framework. The framework views agenda setting in the U.S. as the joining of three concurrent elements or streams that describe problems, solutions, and the political environment. The problem stream contains all issues that certain people or groups define as a problem. The solutions stream contains potential solutions (in the form of policies, technology, or ideas) to problems. The political stream describes the current political climate. An issue is placed on the agenda (and eventually acted upon) when these three streams "join." In the NPP model the problem stream describes the perceived health risk of NPP operation, the solutions stream describes increased NPP regulation, and the political stream describes the willingness of policy makers to allow increased regulation. The growth of NPP regulations is based on the relative attention of policy makers to NPP health risks. The science and technology sector is based on Sterman's (1985) model of Kuhn's (1962/1970) theory of scientific revolutions .

The model was tested using standard test methods for system dynamics models (Sterman 2000). Basing model sectors on established theory improves the model's structural similarity to processes within the real system. To test the ability of the model to replicate real system behavior, the model was calibrated to the U.S. civilian nuclear power case. Simulated system behavior was compared to actual system behavior to test the model's ability to replicate the historical U.S. civilian nuclear power case. Figure 3 compares the simulated development and construction of NPP units to actual system data. Figure 3 also provides several summary statistics for assessing the fit between simulated data and actual data in terms in the coefficient of determination (R^2) and the mean square error (MSE). The MSE is further disaggregated into error due to bias (Bias component of MSE), unequal variation (Variation component of MSE), and unequal covariation (Covariation component of MSE) using Theil's inequality statistics (Sterman 2000). Based on these tests the model was assessed useful for investigating the impact of regulatory systems on NPP project performance.

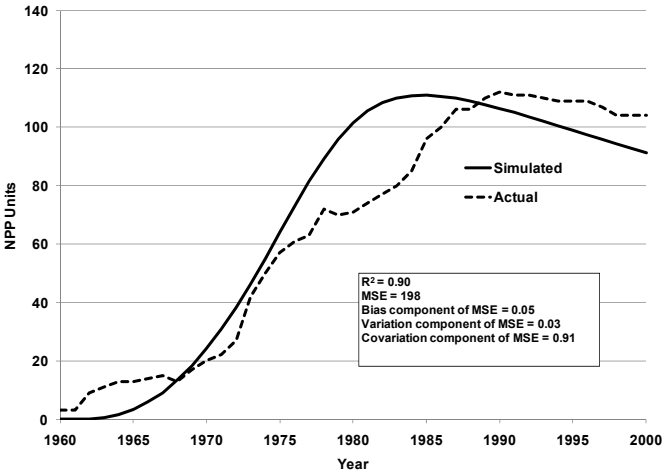


Figure 3: NPP units in operation in the calibrated case (data from EIA1988; 2008)

Regulatory System Testing

The model can be used to simulate the impact of combined licensing (10 CFR Part 52) on the previous generation of NPP construction. To simulate the impact of a combined license regulatory process, the model structure is modified by eliminating the causal link between the "number of NPP regulations" and the "average NPP construction duration" in Figure 2. The elimination of this causal link prevents the growth of NPP regulations from impacting NPP construction durations. The model is then simulated, assuming the same system characteristics as the calibrated case (Figure 3). Figure 4 compares the number of nuclear reactors built under a combined license process (10 CFR Part 52) and a two-step license process (10 CFR Part 50).

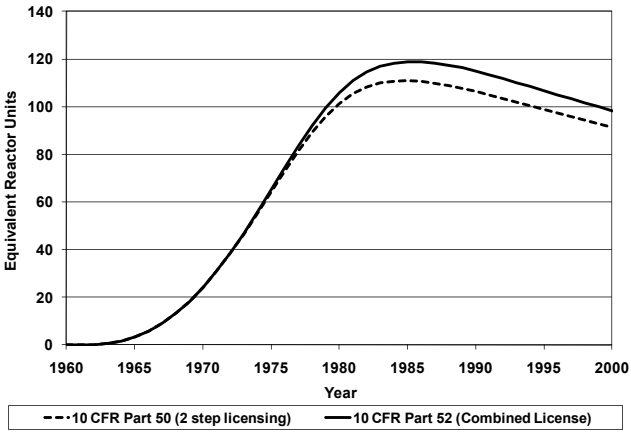


Figure 4: Comparison of operating equivalent NPP under different licensing

Figure 4 shows that under the combined licensing process 7% more NPPs are constructed than under a two step licensing process. While the new licensing process shows an increase in total NPP construction the behavior model of NPP development remains the same (i.e. a period of increase in operating NPP followed by a period of declining NPP operation). In both simulations NPPs become less attractive to utilities over time. This is due to the costs associated with increased regulation growth. While the combined licensing process breaks the causal link between "number of NPP regulations" and the "average NPP construction duration" (Figure 4.2) the link between "number of NPP regulations" and "average NPP capacity permitting duration" still exists. This allows regulations to still impact NPP development duration and costs through the permitting process. The increase in costs associated with design changes ultimately reduces the attractiveness of NPP generation to utilities and, over time, utilities turn to non-NPP generation to meet electricity growth demands.

The reason that the combined licensing process does not change the behavior mode of NPP construction is because the combined licensing process does not lower the public perception of NPP operations risks. This is better understood by examining the model's sensitivity to society's NPP risk amplification factor (Figure 5). Society's amplification of NPP operation risk produces a threshold system behavior. Without a significant reduction in society's NPP risk perception (e.g. a 90% reduction from the calibrated case) the behavior of the NPP system will not significantly change from the calibrated case.

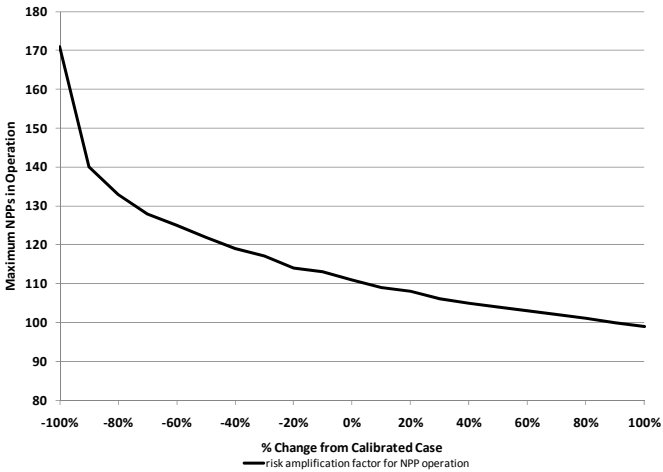


Figure 5: NPP model sensitivity to society's NPP risk amplification factor

Conclusions

The current work examines the impact of regulatory licensing processes on regulatory ratcheting in NPP construction. The results indicate that the new combined licensing process (10 CFC Part 52) would not have dramatically increased the number of NPPs constructed during the first generation of NPP construction. Paradoxically this licensing process actually *strengthens* the B1 control loop towards the later periods of the simulation because more plants are built which increases the public's risk perception of NPP operation, which increases pressure on policy makers to increase NPP regulation. The reason for this unintended consequence is because the combined license regulatory process does not reduce the public's perception of NPP operation risks. This indicates that public policy and societal risk perception have a larger influence on the number of NPPs constructed than improved design and construction methodologies. Unless society's perception of NPP risks can be lowered the NPP radiation risk control loop will still dominate system behavior, making NPP construction difficult.

The current work offers insight to utilities and nuclear steam supply contractors involved with developing the next generation of U.S. civilian NPPs. The industry has spent considerable resources developing new reactor designs which are marketed as safer and more efficient units. However, unless the public's perception of the risks associated with NPP operation is significantly reduced, these designs may encounter similar resistance to the previous generation of NPP technology. The results presented here indicate that applying significant effort and resources to reduce society's NPP risk perception would result in fewer NPP regulations and better NPP construction project performance. The current work also offers contributions to researchers. The feedback model of scientists and engineers influence on the public

policy process offers a conceptual framework that could be applied to other issues including transportation infrastructure policy and environmental issues.

The current work has several limitations that can be addressed in future research. The NPP licensing process policy analysis assumes that other system parameters (e.g. society's risk perception, non-NPP generation technology) are unchanged from the previous generation of NPP construction. Future work could test this assumption and provide additional model calibration data. The model used in the current work focuses solely on NPP regulation as a driver of poor cost and schedule performance. Other factors such as workforce availability, material supply, and deregulated electricity markets could also impact project performance. Future work could quantify the impact of these and other factors on NPP construction project performance.

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A FINANCIAL MARKET ENTRY DECISION MODEL FOR INTERNATIONAL CONSTRUCTION BUSINESS USING REAL OPTION ANALYSIS AND MONTE CARLO SIMULATION

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ABSTRACT

Recent trends in the international construction markets indicate a growing number of projects that require a long-term investment strategy on the part of a construction firm. Therefore, this changing market environment calls for businesses to shift their paradigm from individual projects with limited decision-making tasks to projects with long-term investments and complex decision-making issues. The majority of the latest studies on international market entry address decision-making models based on risk analysis. When a contractor ventures into foreign markets, the consideration of various financial circumstances that he faces poses certain inevitable limitations. Therefore, this study developed a model that is based on real option analysis and Monte Carlo simulation, and is capable of incorporating uncertainties in the market during the evaluation of the market development proposal and the financial evaluation. The model allows for integrative consideration of both market risk and private risk. Applying the proposed model is believed to offer reasonable support to construction firms with maximum accommodation of each market's circumstances.

KEY WORDS: International Construction, Market Entry Decision, Monte Carlo Simulation, Real Option Analysis, Risk Analysis.

INTRODUCTION

Recent trends in the international construction markets indicate a growing number of projects that require a long-term investment strategy on the part of a construction firm; such a strategy should cover all aspects—from direct investment to financing to localization (Chen 2008). Therefore, this changing market environment calls for businesses to shift their paradigm from individual projects with limited decision-making tasks to projects with long-term investments and complex decision-making issues. Given that, leading industry players with a competitive edge are now analyzing the market risks involved in their target countries from a mid-term to long-term perspective, and are applying a system that allows them to reasonably assess the marketability of the target countries and the feasibility of entering into overseas markets. However, there are lacks in the existing study of the market entry decision making based on financial analysis. The object of this study is to build a financial market entry decision making model using RO method for international construction business. To effectively take into account the market risk and the private risk that arouse regarding decision making for international construction market entry, we suggest an analysis method that integrates RO and Monte Carlo Simulation. By using these integrated valuation method, the proposed model enables construction firms to evaluate their entry and investment alternatives in international construction market strategically, with maximum accommodation of each market's circumstances.

EXISTING VALUATION METHODS

The traditional approach such as DCF and NPV is lacking in offering the firm's dynamic and flexible decision-making under the variable and uncertain market conditions (Dixit 1989). Consequently, these limitations of traditional NPV method have led to the recommendation of either real option (RO) or decision analysis (DA) (Mattar and Cheah 2006; Smith and McCardle 1998). The RO approach pays careful attention to market opportunities related to the decision problems. By explicitly constructing a portfolio of securities, and a trading strategy that perfectly replicates the cash flows, one determines investment values based entirely on objective market information. Despite these strengths, however, RO has limitations in terms of applicability to reality due to its complicated assumptions and prerequisites for application. Since most decision making issues regarding construction business are non-traded, it is hard to assume a 'complete market' in every case, which is critical in applying RO (Ng and Björnsson 2004). Also, though decision-making can be affected by various risk factors other than the 'market (or public) risk' that can be traded in the market, RO hardly reflects the project-specific risks (Mattar and Cheah 2006).

There have been many studies trying to compensate for these limitations of RO, the representative of which is 'integrated valuation process (IVP).' First suggested by Smith and Nau (1995), IVP is RO with DA applied. IVP separates the market risk and the private risk, applies the market risk to RO as volatility, and takes the private risk into account by organizing the issues through DA and constructing the utility curve for a decision-maker. Through this process, IVP can apply the option pricing not only to a complete market, but also to an incomplete market. However, the subjectivity that lies in the process of quantifying the private risks in DA, and the difficulty to derive a common utility function that can be shared across companies (Mattar and Cheah 2006) prevent it from being widely used for various financial decision making issues

of the construction business. Therefore, the objective of this study is to present a model that considers a combination of the market risk and the private risk for construction companies' financial decision-making on international market entry.

MARKET ENTRY MODEL

Framework of Integrated Valuation Method

When considering entry into the international construction market, it is very important to analyze and evaluate the uncertainty of the corresponding market. That is, the core of the international construction market entry model is whether it can comprehensively reflect into the financial valuation the factors concerning a host country, i.e. the market risks, and the factors concerning a contractor's competitiveness and a project, i.e. the private risks. For this purpose, it is necessary to organize the cash flow at the point of market entry, and to set apart influences of the market risks from those of the private risks. The NPV at the point of market entry indicates the annual operating revenue that can be generated in the target market, minus the initial entry cost, and the construction and operating costs of each project.

For simplification of market entry issues, this study assume the new contract amount expected to be generated by a contractor will be influenced by the market risks, and the construction cost by the private risks. By categorizing cash flow elements according to each risk's influence in this way, the process to reflect the risks can be further simplified. As market risks that can be traded in the market can be applied to the RO through volatility, this study will reflect the potential size of a target market using the GDP volatility of the construction market. The annual operating revenue expected to be generated in a host country will be derived based on the total size of the country's construction market (annual size and average number of orders, average contract amount per order, etc.) and the number of companies that have made inroads into the corresponding market. Then the annual operating revenue will follow the market risk, i.e. the GDP volatility of the host country, and by reflecting this, RO can show changes during the analysis period using binominal tree.

Meanwhile, private risks will be reflected through the data of actual results the contractor or other similar company has achieved in the target market. The contractor's cost performance, which represents its average capability, is to be calculated based on the ratio of the construction cost to the contract amount of each project. Since the cost performance data does not change by time, it is difficult to take it into account in the same way of calculating the volatility in RO. Therefore, we first derive the optimal distribution function by fitting the entire cost performance data with a probability distribution, and then perform Monte Carlo simulation. Through this procedure, the financial value of the target market can be assessed with the market risk and private risk taken into account using RO and Monte Carlo simulation.

NPV of Market Entry

To explain the procedure to apply aforementioned analysis framework step by step, it is prerequisite to derive the value calculation process that employs the traditional NPV method. In this study, the calculation Equation of the expected return from the overseas market entry, i.e. NPV, is defined as the following Eq. (1):

$$NPV = \sum_{t=1}^{n} \frac{(OR_t - CC_t - OC_t)}{(1+r)^t} - IC \quad (1)$$

where, OR_t = operating revenue in year t, CC_t = construction cost in year t, OC_t = operation cost in year t, IC = Initial cost, r = discount rate

Operating revenue (OR_t) is the total value of the positive cash flows that the projects delivered by the contractor are expected to generate in year t. The following Eq. (2) is used to calculate operating revenue from the annual construction project contract amount of the host country in consideration of the country's level of competition, annual number of bidding trais, average term of works, etc. On the right side of Equation, the first half corresponds to the amount of each ordered project, and the other half to the estimated number of orders in a year considering the level of competition. These two values multiplied together equal the operating revenue (OR_t).

$$OR_t = [(CA_t/NC_t)/d] \times [(NP/NF) \times b] \quad (2)$$

where, CA_t = annual average contract amount, NC_t = annual number of contracts, d = average duration of project, NP = annual average number of projects in the market, NF = number of contractors in host country, b = annual average number of bidding trials

Construction cost (CC_t) is determined by the ORt ratio based on the ratio of the cost to the contractor's average contract amount. Assuming the contractor will establish a branch in the host country, initial cost (IC) includes a capital, corporate registration fee, resettlement cost, etc., and operating cost (OC) includes bidding cost, sales cost, overheads, etc. The cash flow during the analysis period is to be derived based on these aforementioned cash flow elements, and to be discounted with the current value to determine the future asset in the target market.

Estimating Market Risk: Real Option Analysis

The estimated order amount can fluctuate according to changes in the management environments, so this sort of uncertainty needs to be considered through the RO and the Monte Carlo Simulation. Also, the actual value of the investment that can help strategic decision making can be derived by reflecting into the NPV the value of an option the contractor can choose. In consequence, it derives the more realistic dynamic NPV by adding the value of volatility and flexibility to the static NPV. First, calculate the future operating revenue which is the basis of analysis, by deriving changes during the analysis period using volatility. The volatility of the future operating revenue, which means the annual inflow estimated by annual order amount in the host country, reflects the market risk. The volatility means the band of fluctuation of the future underlying asset price, and its change affects the range of the future underlying asset price. In general, volatility in the RO is defined as a standard deviation of the cash flow return's natural logarithm.

In this study, we calculated the volatility based on the GDP fluctuation data of the host country's construction industry. GDP fluctuation can be a good index that represents a country's market risk (Baek et al. 2005), and since we calculate the future operating revenue based on the size of the host country's entire construction market, the GDP fluctuation of the construction industry is most appropriate for this study. After determining the volatility, the market fluctuation during the analysis period can be derived from the initial operating revenue (OR_0) using the binomial lattice. In this case, the risk-neutral valuation method shall be used to derive the parameters of the binomial lattice under the assumption that influences of the market risk are tradable as

in the complete market (Ng and Björnsson 2004). Major parameters of the binomial lattice can be calculated with the following formulas using the volatility (σ).

$$u = e^{\sigma\sqrt{\delta t}}, d = e^{-\sigma\sqrt{\delta t}} = \frac{1}{u}, p = \frac{e^{r_f \delta_t} - d}{u - d} \quad (3)$$

where, σ = volatility, δ_t = time step, r_f = risk free rate

In Eq. (3), u and d indicate functions of underlying asset volatility with up and down factors respectively. p means risk-neutral probabilities derived from functions of u, d and *risk-free rate* (Luenberger 1998). Based on these parameters, we can estimate the future operating revenue during the analysis period in the binomial lattice. Compared to the expected returns from the market in year 0, the next year's return may increase or decrease, therefore the up factor (u) or the down factor (d) needs to be multiplied accordingly. In this way, it can be propagated to cover the entire analysis period. The value 'p' derived from Eq. (3) indicates the probability that market will increase, and '1-p' the probability that market will decrease. The NPV that reflects the market risk can be derived by converting the asset value propagated by a binomial model as shown above into current value. The NPV value derived in such way is the NPV without flexibility since it does not reflect the option value. We can consider the value of strategic options a company can choose. In general, the real option includes options to expand, to contract, to choose, to wait. Calculate the exercise price of each option, and reflect the result in the binomial lattice in comparison with the propagated asset value. Further details on the application procedure and method, which differ according to the case characteristics, will be explained in the notional example below.

Estimating Private Risk: Monte Carlo Simulation

This study employs the Monte Carlo Simulation to reflect the private risk in the NPV value derived from the RO that considers the market risk. As described above, the Monte Carlo simulation, designed to make up for subjectivity of analysis methods of DA or IVP, assess the private risk more objectively based on the performance data retained by a company. To reflect the private risk, it derives the probability distribution for the construction cost (CC_t), on the basis of the company's performance data. If the company has the data of its own performance in the host country's market, it will use this data, and if not, it will use the company's data for a similar country, or other similar company's data for the host country. This sort of cost performance data is affected not by the time, but rather by the company's capability such as site manager's capacity, and organization structure. Therefore, there exist limitations in applying volatility to RO. For this reason, Monte Carlo simulation through data fitting is more appropriate way to reflect the private risk. It is shown that the cost performance in the overseas construction market is significantly influenced by contractors' ability and experience, ability of owner, bidding competition, quality of estimation, etc. (Kim et al. 2008), though, these risk factors needs to be considered as the private risks, because they are not available for security in the market.

NOTIONAL EXAMPLE: QATAR CASE

A notional example is provided to explain the application procedure and usefulness of the Financial Market Entry Decision-Making Model suggested in this study. First, say a Korean construction company ("Company A"), which is one of the ENR

(Engineering News Record) Top 225 global contractors, considers entry into the industrial plant market in Qatar. We assume the followings for simplification: (i) all construction companies that have already entered the Qatar market have the same capability, therefore the same chance to win a project in bidding; (ii) The competitive ratio is a constant variable; (iii) the markets for entry are limited to the public sector; (iv) the analysis period is ten years; (v) there is no return generated in the first year of entry. Table 1 and 2 show basic conditions and cash flow components of the Qatar market. The numbers indicated here are derived from market data (Proleads 2009) analysis and experts' advices on the Qatar market.

Table 1. Basic Conditions Regarding the Qatar Market and Company A

Market Condition		Condition of Firm A	
# of construction firm	74	Annual avg. # of bidding trial	3
Annual avg. # of new project	25.9		
Annual avg. budget spent/ project	$349.42 mil.	Probability of wining contract	11.8%
Avg. contract duration of project	4.55 years		

Table 2. Cash Flow Components of the Qatar Market (USD: current price)

Category		Cash Flow Components	Amount	Remark
Inflow		Potential OR in year 0	$123.24 mil.	GDP volatility
Outflow	Initial Cost	Required capital	$2.50 mil.	Fixed
		Administration	$0.03 mil.	Fixed
		Subsidiary initiation	$0.80 mil.	Fixed
	Construction Cost	Ratio of cost to contract amount	96.19%	Private risk
	Operating Cost	Annual admin. fee	$0.05 mil.	Fixed
		Annual marketing cost	$0.50 mil.	Fixed
		Annual bidding cost	$1.43 mil.	Fixed
		Annual indirect cost	$0.15 mil.	Fixed

Calculate the market value using the traditional NPV method based on the basic conditions and assumptions, and the static NPV will be 14.62 million USD when the discount rate is 12%. To analyze the RO, the volatility of Qatar's construction GDP over the last 15 years is calculated. The result shows σ =12.3%. This σ can be used to determine parameters for RO analysis, as shown in Table 4. The numbers in Table 3 are derived by the risk-neutral valuation method of Eq. (3). Using the parameters in Table 3, binomial model can be propagated to cover possible scenarios over the next 10 years. Table 4 shows the estimation results that have taken the market risk into account based on the current value of operating revenue. To calculate the True NPV without flexibility, which corresponds to 19.70 million USD herein, add up the sums of each column after discounting to the year 0. Even when only the market volatility is considered, the average gap with the static NPV is 5.08 million USD.

Now the value of the option shall be calculated. In this example, we assume that a company has chosen the option to abandon under unfavorable market conditions. What is important here is to determine the exercise price of the option, which is assumed to be 1.76 million USD herein, given that the company will retrieve part of invested capital and resources and also have to pay the withdrawal cost. That is, the company will exercise the option to abandon if the expected returns from the market fall below 1.76 million USD. Calculated in the same way as above – summing up after discounting, the true NPV with option to abandon corresponds to 20.10 million USD, therefore the value of the option to abandon is 0.40 million USD (20.10-19.70).

Table 3. RO Parameters (Qatar case)

Input parameters		Calculated parameters	
1. annual risk-free rate (r_f)	10.0%	1. up movement per step (u)	1.13
2. current operating revenue (OR_0)	123,240	2. down movement per step (d)	0.88
3. Analysis period (year)	10	3. risk neutral prob. (up: p)	0.88
4. Volatility (σ)	12.3%	4. risk neutral prob. (down: 1-p)	0.12

Table 4. Binomial Lattice for the Future Operating Revenue (unit: 1,000 USD)

0	1	2	3	4	5	6	7	8	9	10
123,240	139,341	157,547	178,131	201,405	227,719	257,472	291,111	329,146	372,151	420,774
	108,999	123,240	139,341	157,547	178,131	201,405	227,719	257,472	291,111	329,146
		96,403	108,999	123,240	139,341	157,547	178,131	201,405	227,719	257,472
			85,263	96,403	108,999	123,240	139,341	157,547	178,131	201,405
				75,410	85,263	96,403	108,999	123,240	139,341	157,547
					66,696	75,410	85,263	96,403	108,999	123,240
						58,989	66,696	75,410	85,263	96,403
							52,173	58,989	66,696	75,410
								46,144	52,173	58,989
									40,811	46,144
										36,095

To visualize the results more effectively, the Value at Risk and Gain (VARG) curve can be used. The VARG curve, the cumulative frequency distribution plotted as a function of the value metric, makes it possible to check the option value according to the probability distribution (Cardin and de Neufville 2008). Figure 1 shows both the static NPV and the true NPV indicated on the VARG curve. The VARG curve shows that the graph is moved to the right as the company considers the option to abandon, consequently decreasing the size of potential damage.

Lastly, the private risk will be reflected based on the company's cost performance data. We used the data of 18 projects executed by a Korean construction company in Qatar, which collected in a previous study (Kim et al. 2008). We performed data fitting for the cost performance distribution of these 18 projects using @Risk software, and the result has shown that the beta distribution is appropriate. And it is run through the Monte Carlo simulation for one thousand iterations to check changes in the NPV value. When the private risk is reflected, the NPV value shows overall increase compared to when the average cost performance is reflected, and the value of the option to abandon increases to 28 million USD.

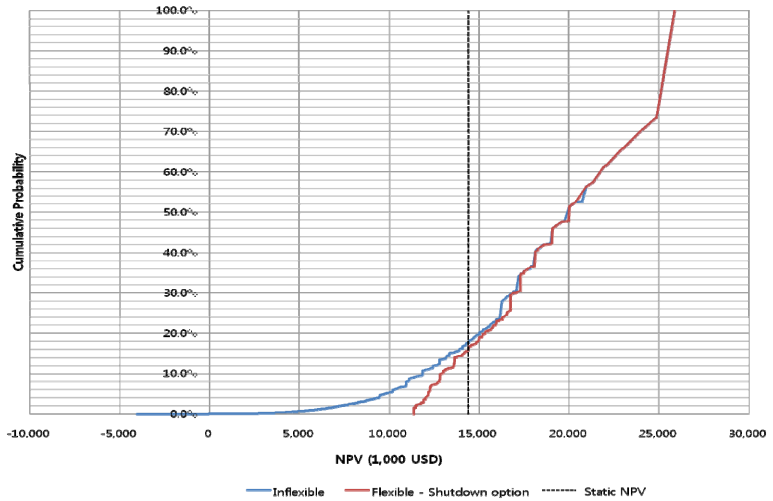


Figure 1. VARG Curve

CONCLUSIONS

This research proposes an analytics framework based on real option and Monte Carlo simulation for deciding on a new construction market entry. The proposed approach helps to support more realistic decisions by assessing values in strategies available for companies and reflecting both market risk and private risk together. The model attempts to reflect both market risks and private risks by utilizing GDP volatility indicative of a host country market climate and contractor's cost performance data. The results of the proposed model showed that the market entry decision model proposed herein can be applied to practical corporate decision-making scenarios under changing market condition. In addition, the proposed model can support a comprehensive decision-making framework, as it support a variety of dimensions to corporate decisions including go/no-go decision, timing to go, and entry modes to mitigate market risks. In summary, for construction contractors prospecting a new entry into overseas construction, long-term perspective with an aid of flexibility valuation deemed to ensure more reasonable market entry decision. However, future procedural study is required, as justification of estimation of market risk and private risk are not fully verified in statistical terms. Furthermore, more realistic options need to be tested by evaluating diverse scenarios based on broadened historical cases and verifying applicability of each entry mode in relation to the amount of initial entry cost and operating expenses, projected size of incoming revenues and predicted performance of cost expenditure, etc.

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An Application of ELECTRE III to Contractor Selection

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Abstract

Contractor selection is carried out in order to choose a competent and capable contractor to do the work. To help in this selection, baselines are established to ensure that the contractors have the required skills, resources, and abilities to execute the project. Contractor selection is a multiple criteria decision making wherein several criteria are required to be evaluated simultaneously. This paper proposes a decision-making model for contractor selection utilizing ELECTRE III modeling. The steps of ELECTRE III model include; estimation of concordance indices, estimation of discordance indices, estimation of credibility scores, performing distillation procedure, and performing complete ranking. To assess alternatives via ELECTRE III, three associated thresholds are defined which are indifference (q), preference (p), and veto (v). These thresholds produce outranking relations with an allowance for data uncertainly. The complete procedure of ELECTRE III modeling is described in the paper. The proposed model is generic and can be used as a tool to evaluate alternatives in several applications such as value engineering, optimum organization structure, and constructability analysis. It enables its users to define the criteria that are deemed important for evaluation. The proposed multiple criteria decision making is novel to construction can be utilized as a successful tool in contractor selection problem. A numerical example is presented to demonstrate the use of the proposed methodology.

Key Words

Procurement, Bidding, Contractor Selection, Contractor Prequalification, Multiple Criteria Decision Making (MCDM), ELECTRE.

Introduction

During tender evaluation stage, two essential processes take place: i) contractor prequalification and ii) contractor selection. The former is carried out to minimize the possibility of contractor default by limiting the number of participating contractors to those who are satisfying certain measures. Contractor prequalification is an important process for both owners and contractors (Bubshait and Al-Gobali 1996; Russell and Skibniewski 1988). The importance for owners is attributed to screening out the incompetent, insufficiently financed, and inexperienced contractors. While it works as an appraisal tool that provides contractors with their abilities (Sonmez et al. 2002). On the other hand, contractor selection is performed to elite capable contractor in order to reduce the common problems, associated with construction projects. Such problems might result due to: i) cost and schedule overruns, ii) reducing quality and safety measures, and iii) claims and litigation. The selection is based on standard level for measuring and assessing the capabilities of contractors.

Selection of the contractor based on the lowest tender price is considered one of the main reasons that causes project delivery problems (Hatush and Skitmore 1998). Shortage of work leads contractors to bid with low prices in order to stay in business. Contractors compensate such low prices with either reducing the quality of work or submitting claims. Despite the problems encountered in selecting lowest bidder, many public sector owners are constrained to follow such procedure. However, it was observed that the lowest bidder selection is not the most economical solution in the long term (Kumaraswamy 1996). The complexity of contractor selection is attributed to its uncertainty nature. Such uncertainty exists due to the fuzziness and randomness associated with contractor performance, qualifier experience, prequalification criteria, and qualitative judgment (Lam et al 2001)). A number of models have been developed for contractor selection and prequalification. These can be grouped into five categories: i) analytic hierarchy process (AHP), analytic network process (ANP), and multi-attribute utility theory (MAUT) models (Hatush and Skitmore 1998, Cheng and Li 2004, Singh and Tiong 2005]; ii) fuzzy models (Lam et al. 2001, Singh and Tiong 2005]; iii) artificial intelligent models including expert systems and neural networks (Russell et al. 1990, Lam et al. 2000); iv) evidential reasoning models (Sonmez et al 2002), and v) superiority and inferiority ranking (SIR) (Marzouk 2008).

Description of ELECTRE III

ELECTRE (in its various forms) was conceived by Roy (1991) in response to deficiencies of existing decision making solution methods. Different versions of ELECTRE which have been developed including ELECTRE I, II, III, IV and TRI. All methods are based on the same fundamental concepts but differ both operationally and according to the type of decision problem. Specifically, ELECTRE I is designed for selection problems, ELECTRE TRI for assignment problems and ELECTRE II, III and IV for ranking problems. ELECTRE III is utilized to assess alternatives in different applications (Roy 1990, Figueira et al. 2005). For Criterion j being considered, three associated thresholds are defined which are indifference (q),

preference (p), and veto (v). These thresholds produce outranking relations with an allowance for data uncertainly. To use ELECTRE III, the following must be defined by decision makers for all criteria:

1) Criteria indifference (q), preference (p), and veto (v) thresholds; where ($v \geq q \geq p$), and
2) Importance rating (w_j) for each criterion j.

The complete description of ELECTRE III model is summarized in the following subsections.

Concordance Index

Concordance index, $C(a,b)$, is estimated for each pair of alternatives a and b based on a general comparison of the performances of alternative a and alternative b for all criteria. Concordance index ranges from 0 to 1; a value of 0 indicates that alternative a is worse than alternative b for all criteria. Concordance index is calculated based on a weighted comparison of the performances over each criterion individually $c_j(a,b)$ as per Eq. 1.

$$C(a,b) = \frac{1}{W} \sum_{j=1}^{n} w_j c_j(a,b) \qquad (1)$$

Where; $W = \sum_{j=1}^{n} w_j$

The separate comparison indices $c_j(a,b)$ for each criterion are calculated based on one of the following cases:

Case 1: Alternative a is equivalent to or better than b minus the indifference threshold for criteria j as per Eq. 2.

$$c_j(a,b) = 1 \quad \text{if } g_j(a) + q_j(g_j(a)) \geq g_j(b) \qquad (2)$$

Case 2: If the performance of alternative a plus the performance threshold is less than that of alternative b, then alternative a is treated as not better than b for this criteria as per Eq. 3.

$$c_j(a,b) = 0 \quad \text{if } g_j(a) + p_j(g_j(a)) < g_j(b) \qquad (3)$$

Case 3: Otherwise the relationship is between these two extremes and is represented as a linear variation as per Eq. 4.

$$c_j(a,b) = \frac{g_j(a) - g_j(b) + p_j(g_j(a))}{p_j(g_j(a)) - q_j(g_j(a))} \qquad (4)$$

Discordance Index

The veto threshold for each criterion is assigned to introduce discordance into the outranking relations. It should be noted that any outranking of *b* by *a* indicated by the concordance index can be overruled if there is any criterion for which alternative *b* outperforms alternative *a* by at least veto threshold even if all the other criteria favor the outranking of *b* by *a* as per Eq. 5.

$$g_j(b) \geq g_j(a) + v_j(g_j(a)) \qquad (5)$$

So, if alternative *a* is better than alternative *b* generally, there may be some criteria (possibly one) where alternative *a* is worse than alternative *b*. This situation is reflected by discordance index, $D_j(a,b)$, for that criterion. The discordance index ranges from 0 to 1 and it is calculated according to one of the following cases:

Case 1: Alternative *b* is not better than alternative *a* by a margin greater than the veto threshold as per Eq. 6.

$$D_j(a,b) = 0 \quad \text{if } g_j(b) \leq g_j(a) + p_j(g_j(a)) \qquad (6)$$

Case 2: Alternative *b* is better than alternative *a* by a margin greater than the veto threshold as per Eq. 7.

$$D_j(a,b) = 1 \quad \text{if } g_j(b) \geq g_j(a) + v_j(g_j(a)) \qquad (7)$$

Case 3: Otherwise the relationship is linear between the two as per Eq. 8.

$$D_j(a,b) = \frac{g_j(b) - g_j(a) - p_j(g_j(a))}{v_j(g_j(a)) - p_j(g_j(a))} \qquad (8)$$

Credibility Score

The degree of credibility of outranking is calculated based on concordance and discordance indices according to one of the following two cases:

Case 1: The degree of outranking is equal to the concordance index if there is no criterion that is discordant or where no veto threshold id used as per Eq. 9.

$$S(a,b) = C(a,b) \quad \text{if } D_j(a,b) \leq C(a,b), \forall_j \qquad (9)$$

Case 2: The degree of outranking is equal to the concordance with a reduction as the level of discordance increases above a threshold value as per Eq. 10.

$$S(a,b) = C(a,b) \prod_{j \in \Psi(a,b)} \frac{1 - D_j(a,b)}{1 - C(a,b)} \qquad (10)$$

Where, $\Psi(a,b)$ is the set of criteria for which $D_j(a,b) > c_j(a,b)$

Distillation Procedure

Alternatives are ranked in two pre-orders which are constructed in different ways. The first pre-order is obtained in a descending manner (*Descending Distillation*), selecting the best rated alternatives initially, and finishing with the worst. The second pre-order is obtained in an ascending manner (*Ascending Distillation*), selecting the worst rated alternatives initially, and finishing with the best. The two pre-orders which are set based on a qualification score for each alternative as follows:

Step 1: Set λ_0 equals to the maximum value of $S(a,b)$ in credibility matrix (A) as per Eq. 11.

$$\lambda_0 = \max_{a,b \in A} S(a,b) \tag{11}$$

Step 2: A cutoff level of outranking λ_1 is defined as the largest outranking score which is just less than the maximum outranking score minus the discrimination threshold as per Eq. 12.

$$\lambda_0 = \max_{\{S(a,b) < \lambda_0 - s(\lambda_0)\} \in A} S(a,b) \tag{12}$$

Where, $s(\lambda_0)$ is the discrimination threshold at the maximum level of outranking λ_0. At initial cutoff level, a outranks b if $S(a,b)$ is greater than the cutoff level and $S(a,b)$ exceeds $S(b,a)$ by more than the discrimination threshold (see Eq. 13) satisfying the condition, given in Eq. 14.

$$s(\lambda) = 0.3 - 0.15\lambda \tag{13}$$

$$aSb \text{ iff } S(a,b) > \lambda_1 \text{ and } S(a,b) - S(b,a) > s(\lambda) \tag{14}$$

Step 3: Every time a outranks b, a is given a score of +1 (strength) and b is given -1 (weakness). For each alternative, the strengths and weaknesses are added together to give a final qualification score.

Step 4: Within *Descending Distillation*, the alternative with the highest qualification score is assigned to a rank and removed from the procedure, and the process is repeated for all remaining options.

Step 5: Within *Ascending Distillation*, the alternative with the lowest qualification score is assigned to a rank and removed from the procedure, and the process is repeated for all remaining options.

Complete Ranking

The results of the two procedures *Descending Distillation* and *Ascending Distillation* are combined to form complete ranking that consistent with the two procedures.

Numerical Example

A hypothetical example is presented to illustrate the use of the proposed model. The example considers a project in which the owner estimated cost is 10 million L.E. Five potential contractors (A, B, C, D, and E) have been prequalified in order to award the contract to one of them. A variety of criteria have been proposed in literature for contractor selection (Hatush and Skitmore 1998, Topcu 2004). The example assumes, without loss of generality, that five criteria are deemed important to be evaluated. These are: i) capital bid (L.E.), ii) financial stability (%), iii) length of time in industry (years), iv) management organization (%), and v) experience of technical personnel (#). These criteria constitute for failed contracts g_1 to g_5, respectively. Table 1 lists the five contractors and their respective criteria values. The threshold values for indifference (q), preference (p), and veto (v) are listed in Table 2 for the two case scenarios. ELECTRE III model is applied and the credibility matrix is obtained as per Table 3. Then, the distillation procedure is applied to obtain the *Descending* and *Ascending* pre-orders as per Figure 1. The complete ranking of alternatives is depicted in Figure 2. Contractor A and Contractor E are selected as best alternatives, whereas, Contractor B is ranked as worst alternative.

Table 1: Criteria values for the contractors

ID	Criteria	Preferred Limit	Weight	Unit	Contractor				
					A	B	C	D	E
g_1	Capital bid	Min.	0.25	Million (LE)	13	11	9.8	10.1	10.8
g_2	Financial stability	Max.	0.15	%	70	75	60	70	80
g_3	Length of time in industry	Max.	0.10	Years	15	8	10	15	10
g_4	Management organization	Max.	0.15	%	80	70	45	65	80
g_5	Experience of technical personnel	Max.	0.10	#	25	10	8	10	15

Table 2: Criteria threshold values

Threshold	Value	
	g_1	g_2 to g_5
Indifference (q)	$0.05\, g_j(a)$	$0.1\, g_j(a)$
Preference (p)	$0.1\, g_j(a)$	$0.2\, g_j(a)$
Veto (v)	Not used	

Table 3: Estimated credibility matrix

	Contractor A	Contractor B	Contractor C	Contractor D	Contractor E
Contractor A	1	0.67	0.67	0.67	0.58
Contractor B	0.65	1	0.53	0.65	0.65
Contractor C	0.4	0.47	1	0.4	0.47
Contractor D	0.67	1	1	1	0.58
Contractor E	0.73	1	0.72	0.77	1

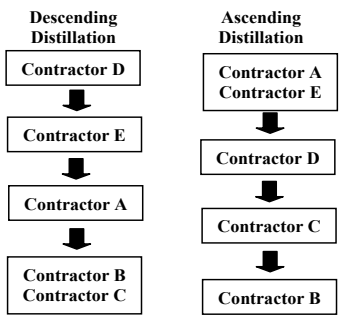


Figure 1: Output of distillation procedure

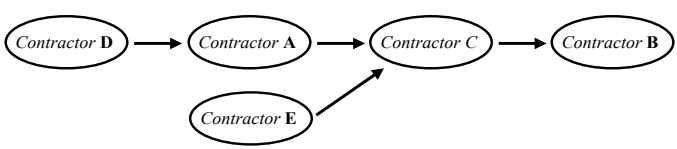


Figure 2: SIR partial ranking diagram

Summary and Conclusions

Contractor selection is performed to select capable contractor in order to reduce the common problems, associated with construction projects. This paper presents a model

for contractor selection utilizing ELECTRE III model as an outranking model that aids in facilitating the evaluation of contractors. The paper described the procedure steps of ELECTRE III model which are: estimation of concordance indices, estimation of discordance indices, estimation of credibility scores, performing distillation procedure, and performing complete ranking. A numerical example was presented to demonstrate the practicality of using ELECTRE III model to outrank construction contractors.

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EMBEDDEDNESS AND COLLABORATIVE VENTURE NETWORKS FOR OVERSEAS CONSTRUCTION PROJECTS

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ABSTRACT

Finding competent collaborators while executing construction projects overseas is of paramount importance for project success. The partner choice and project performance cannot be understood only from an economic viewpoint since it is constrained by the firms' embeddedness in social relations. Based on this premise, this paper provides not only a theoretical explanation of the impact of structural and relational embeddedness on firms' economic behavior and outcomes, but also empirical evidence by analyzing collaborative cases jointly performed by Korean construction firms working overseas during the past 18 years. Three conclusions are drawn. First, the inter-firm network has scale-free network properties. Second, the network retained endogamic characteristics in that a great majority of smaller firms had worked with only one large firm, forming strong subgroups. Last, there is plausible evidence of the impact of structural embeddedness as well as relational embeddedness on the level of profit.

KEY WORDS: International Construction, Networks, Firms Management, Profit

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INTRODUCTION

Collaborative ventures have been widely used to mitigate and avoid expected risks in international construction. Large contractors want to form collaborative ventures because they can (1) utilize a partner's specialty, (2) maximize organizational flexibility and effectiveness, (3) substitute a partner when there is a perceived lack of qualified local specialty contractors in the host country, and (4) share costs and risks. Small to medium sized firms, on the other hand, benefit from collaborative ventures because they can (1) overcome their inexperience in risk management, (2) gain access to contracts that would be unreachable otherwise, and (3) diversify from intense competition in domestic markets.

A firm's partner choice and resulting project performance is determined not only by physical capital, economic capital, and cultural capital, but also social capital. According to Moran (2005), the social capital of a firm can be effectively modeled by taking both aggregate network structural properties (*structural embeddedness*) and the strength and quality of relations (*relational embeddedness*) into account. In this paper, we offer an explorative examination of both structural and relational embeddedness in an inter-firm network particularly established for overseas construction projects. This paper first presents the results of a preliminary survey study of strategic motives for contactors when establishing collaborative ventures for overseas construction projects. argue that firms' partner choice is determined not merely by economic reasons but also by structural embeddedness and relational embeddedness in an inter-firm network. We also provide the results of social network analysis and statistical analysis for collaborative venture formation data step-by-step so as to pragmatically address the problem of embeddedness in an inter-firm network. The paper concludes with implications for managing international projects and recommendations for future research.

THEORETICAL BACKGOUND

Collaborative Entry for Overseas Projects

Executing overseas projects involves several risks ranging from those shared with domestic projects to those specific to overseas projects including political (Ashley 1987), cultural (Chan and Tse 2003), economic (Demacopoulos 1989), financial (Bing et al. 1999) and institutional risks. Strategic alliances have been widely used by firms in intense global competition to mitigate and avoid expected risks. A strategic alliance is "a trading partnership among firms that enhances the effectiveness of the competitive strategies of participating firms by providing for the mutually beneficial

trade of technologies, skills, or products based upon them" (Yoshino and Rangan 1995). A collaborative venture in this paper refers to a special type of strategic alliance among contractors - in general between a large firm and small to medium sized firms.

The Problem of Embeddedness in Networks

Firms are not independent from each other since their economic behavior cannot but be constrained by social interactions in firm networks. Often times, firms are connected by trust and personal relationships along with contractual relations. Granovetter (1985) termed such a process, by which ongoing social relationships affect economic behavior, *embeddedness*. The embeddedness has significant influence on the economic behavior of firms in two dimensions - *structural embeddedness* and *relational embeddedness*. Structural embeddedness pertains to the overall configuration of the network structure such as presence of relations and patterns of relations including density, connectivity, and hierarchy. In contrast, relational embeddedness concerns the particular quality of relations that actors relate to. In other words, whereas structural embeddedness relates to the extent to which firms can reach business-related information and resources in the network, relational embeddedness focuses on how much of this potential will be realized (Moran 2005).

EMBEDDEDNESS AND COLLABORATIVE VENTURE NETWORKS

Preliminary Study: Strategic Motives for Collaborative Entry

Prior to investigating the effects of embededness in inter-firm network, the writers conducted a survey to collect information on why firms want to form collaborative ventures for executing overseas projects. Our survey identified that large firms primarily have intended to establish collaborative ventures to benefit from their partners' complementary roles in executing projects, whereas small to medium sized firms have desired not only to exploit large firms' management ability but also explore new markets by constituting collaborative ventures (Table1).

From an atomistic market model view, the results above seem to indicate that the partner selection of a firm to constitute a collaborative venture is purely a self-interested and profit-seeking process. Presumably, a large firm who has access to perfect information about market conditions evaluates candidate partners and chooses a firm that can provide the greatest economic returns and vice versa. Specifically, a large firm would be content to work with a partner who is most skilled and able to share cost risk while a small to medium sized firm would desire to engage with a

large firm that is well experienced enough to cope with various risks in overseas projects. Consequently, it is likely that the network would have only a few prestigious firms. Furthermore, it can be assumed that the inter-firm network for overseas projects has the properties of a scale-free network which follows a power-law distribution, considering the existence of exceedingly prestigious actors, called hubs, produced by a preferential attachment process (Barabási and Albert 1999). The most significant characteristic of scale-free networks is that a few hubs are linked with many actors and the others are connected to a few.

Table 1. Strategic Motives for Collaborative Entry

Large Firms' Perspective	Mean
Need for a partner's ***specialty***	5.37
Desire to maximize ***organizational flexibility*** and effectiveness by outsourcing	5.27
Lack of local specialty contractors and ***human resources***	5.17
Desire to share ***cost risk*** with partners	5.13
Lack of trust regarding responsibility and sincerity of domestic partners	4.89
Late participation in a project that a partner led off	4.55
No language barrier with domestic partners	3.86
Enforcement of collaborative entry by agreements	3.82
Small to Medium Sized Firms' Perspective	
Lack of ability for ***risk management***	5.27
Executive's initiative	4.92
Difficulty of receiving independent orders from foreign contractors	4.78
Intense competition in domestic market	4.50
Requirement for collaborative entry for a project that it already led off	4.35
Possession of superior specialty competence in international construction market	4.25

* Questionnaires consisted of seven-point Liker-scale questions

** 160 samples were extracted for a response rate of 36.2%

Structural and Relational Embeddedness

A firm's partner choice in a wide inter-firm network cannot be solely a self-interested and profit-seeking action, but one constrained by the firm's embeddedness in social relations. In other words, it is not merely an economic process but one sustained by and anchored in a social context (Jack and Anderson 2002). In effect, it is unlikely that a firm behaves in an economically optimized manner all the time in a complex and dynamic market such as overseas construction. We should take into consideration firms' relational properties and overall network structure as well as economic behavior models.

The reasons why firms' economic behaviors become embedded in inter-firm networks can be threefold. First, a firm cannot have perfect information regarding

other firms unlike the assumptions in neoclassical economics. Second, a firm is myopic in the sense that it cannot have perfect information on a complex inter-firm network. A firm might not be fully aware of not only who plays in the network but also who has connections with whom. It might be able to recognize only a partial boundary of the whole network such as a partner's partner at the geodesic distance of two. Last, firms are often connected by personal, trust-based, or conglomerate-based relationships. A firm sometimes makes relationships via personal routes or wants to develop trust-based relations with partners rather than using an optimized partner-evaluation method. Such decisions may seem irrational or altruistic undertakings. However, this are consciously opportunistic and selfish decisions going after a superior position in the network, by which it can establish long-term relationships with promising partners and secure sustainable business opportunities in overseas markets.

As such, this paper primarily assumes that resulting aggregate network configuration (*structural embeddedness*) affects the economic behavior of a firm by facilitating or inhibiting social interactions as a whole. A firm having diverse relations would increase the chance of having valuable information and involvement in profitable undertakings. Another possibility is that a firm participating in a closure or cohesive subgroup can take advantage of proximity and trustworthiness. As opposed to the perspective that highlights the benefit of having dense relations, a firm whose relationships are sparse but span split groups can create a competitive advantage (Granovetter 1973). This is probably because a firm of cohesive relations is likely to have redundant information circulating with the group, whereas a firm filling with holes among different groups is more likely to obtain information that are non-redundant and additive. Similarly, Bonacich (1987) also upheld the significance of possessing a central position that has potential for control of information flow.

In addition, the writers assume that the economic behavior of a firm is constrained by the strength and quality of relations beyond the density and quantity (*relational embeddedness*). The strength and quality of relations are determined by past experience, trustworthiness, reciprocity, and alliance stipulations among firms. Strong relations constitute a base of trust that can reduce resistance and provide comfort in the face of uncertainty (Krackhardt 1992) and also avoid disruptive conflicts (Nelson 1989). It consequentially affects how likely firms are willing to share accesses to critical information and provide resources and know-how.

DATA ANALYSIS

Based on the considerations above, we analyzed the collaborative entry cases among Korean construction firms for overseas construction projects during the past 18 years. A total of 384 projects conducted by 207 companies were collected. Social network analysis and statistical methods were employed not only to present the evidence of structural embeddedness but al so to examine the impact of embeddedness on project performance. An ethnographic study was also conducted to address the problem of relational embeddedness.

Data Description

Our data is summarized in Table 2 and graphically depicted in Figure 1.

Table 2. Descriptive Summary

Number of Nodes	207	Number of Ties	384
Network Size	7	Density	0.009005
Average Degree	1.855	Average Distance	2.830

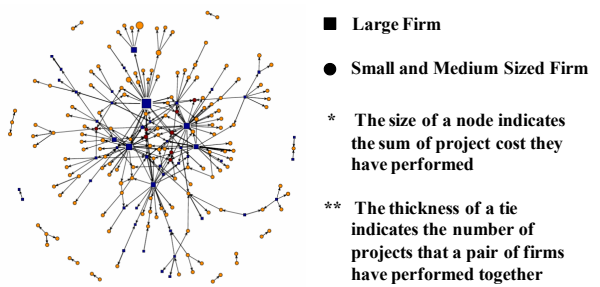


Figure 1. Inter-Firm Network

Results

(1) Indegree distribution was examined to test the extent to which it follows a power-law distribution and therefore have the properties of a pseudo scale-free network. Indegree distribution is fitted following Clauset et al. (2007) method using a "plfit" fuction (Dubroca 2008). In particular, power-law distributions have the form: $p(x) = Cx^{-\alpha}$. On a log-log space, the power-law equation is $\log(p(x)) = c - \alpha\log(x)$ which has the form of a linear relation with the slope of α. When the α of a network is between 2 and 3, the network is called a scale-free network. Our analysis estimates the α in the inter-firm network as 2.37 (Figure 2), showing Kolmogov-Smirnov d-statistics

(0.0795) is less than a critical value (0.0945) at the .05 of significance level. It is identified that the inter-firm network has the properties of a scale-free network in the range of indegree>1.

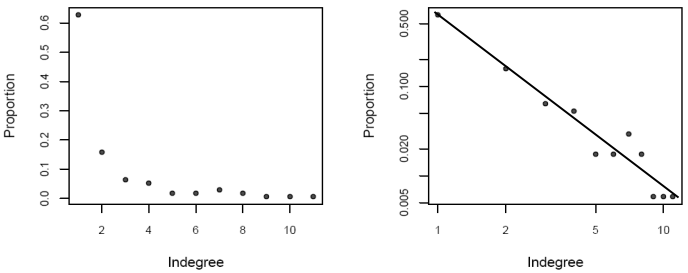


Figure 2. Log-Log Space Transformation

(2) This paper also tested the extent to which firms form cohesive relations. As a whole, the weighted overall graph clustering coefficient is 0.020. This is rather high as compared with the overall density (0.009005) of the network, implying that local neighborhoods are denser than the overall network and so there seems to be a tendency to form local cohesive subgroups. In order to determine this phenomenon closely, firms are separated through a partitioning method that searches for a combination of subgroups in a way that maximizes relations within a group and minimizes relations between different groups. The result is portrayed with the form of a simplified density table (Table 3). As a result, it turns out that there are 14 cohesive subgroups, 4 semi-isolated subgroups, and 1 isolated subgroup.

Table 3. Density Table

Group	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14
G1	**0.07**	0	0	0	0	0	0	0	0	0	0	0	0	0
G2	0	**0.08**	0	0	0	0	0	0	0	0	0	0	0	0
G3	0	0	**0.04**	0	0	0	0	0	0	0	0	0	0	0
G4	0	0	0	**0.07**	0	0	0	0	0	0	0	0	0	0
G5	0	0	0	0	**0.05**	0	0	0	0	0	0	0	0	0
G6	0.01	0	0	0	0	**0.06**	0	0	0	0	0	0	0	0
G7	0.01	0	0	0	0	0	**0.06**	0	0	0	0	0	0	0
G8	0.01	0	**0.06**	0	0	0.02	0.02	**0.10**	0	0.02	**0.05**	0	0	**0.03**
G9	0	0	0	0	0	0	0	0	**0.06**	0	0	0	0	0
G10	0.01	0	0	0.01	0.02	0.01	0.02	0.01	0	**0.09**	0	0	0	0
G11	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0
G12	0.01	0.01	0	0	0.02	0	**0.03**	0.01	0	**0.03**	0	**0.07**	**0.03**	0.01
G13	0.02	0	**0.03**	0	**0.03**	0	0.01	**0.12**	0	0	0.02	0	**0.07**	0
G14	0.01	0	0	0.01	0	0	0	**0.04**	0	0.01	0.01	0	0	**0.07**

(3) We tested to determine the extent to which social network characteristics explaining structural embeddedness of firms (indegree, outdegree, efficiency, Bonacih-power, and clustering coefficient) are related to their performance. In particular, *indegree* intuitively is the number of incoming relations a firm has (i.e., obtaining subcontracts from large contractors) whereas *outdegree* is the number of outgoing relations (i.e., endowing subcontracts to small or medium sized firms). *Efficiency* is employed to examine the tendency of structural hole, which formulates the effective size of a firm's network by its actual size. It tells us how much impact a firm has for partners (Hanneman and Riddle 2005). *Bonacich-Power* (Bonacich 1987) is used to measure centrality. Bonacich-Power is more versed for our purpose than other centrality measures since it considers not only a firm's relations but also its neighbors' relations to compute centrality. Last, *clustering coefficient* at a firm level is used to show the extent to which a firm lives in clustered neighborhoods. Results show that the average profit has a positive relation with indegree, outdegree, and efficiency but a negative relation with Bonacich-Power centrality and clustering coefficient (Figure 3). Although only indegree exhibits a significant outcome at the 0.1 level, other measures also provide plausible evidence of the impact of structural embeddedness on profit, which deserves further investigation.

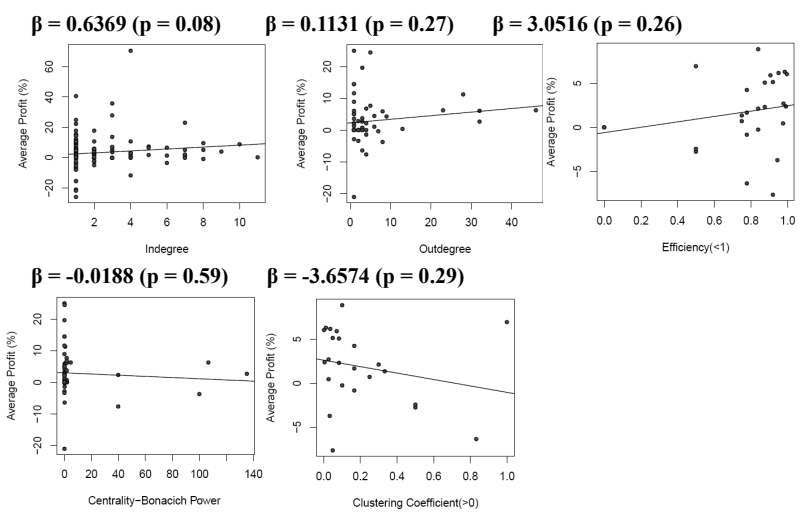


Figure 3. Relation of Average Profit of Firms with Network Properties

(4) Following the investigation of structural embeddedness, an ethnographic study was conducted to get supporting evidence on the effect of relational embeddedness. To this end, the writers interviewed fourteen industry experts, half from large firms and the half from small to medium sized companies, who have around 25 years' experience on average in marketing and managing overseas projects. A semi-structured face-to-face interview method was used. Interviewees were guided to recall past experiences and present their opinions. Consequently, most interviewees empirically indicated the impact of relational embeddedness in the inter-firm network. In particular, they pointed out that it is essential for firms to maintain trust-based long-term relationships with strong partners as well as to extend their network boundary to take a central role as network-makers, emphasizing the fact that the quality of a network on a trust basis could significantly affect the firms' performance. They also confirmed that such trust-based relationships enabled firms to reduce uncertainty in entering new businesses and in insuring more business opportunities through sharing information and know-how, guaranteeing market share, and negotiating more reasonable unit prices. Because of the unavailability of data to measure relational embeddedness, we could not perform an integrated analysis as in Uzzi (1996). Yet, we believe that it is feasible to look at the formation of collaborative ventures from a network standpoint.

CONCLUSIONS

The problem of embeddedness in an inter-firm network for overseas construction projects is investigated in this paper. Three main conclusions are drawn. First, our inter-firm network of overseas construction projects exhibits the properties of scale-free networks (i.e. follows a power-law distribution). However, the degree distribution does not fit into a power-law distribution for all ranges. This could be explained as transactions in the inter-firm network do not follow a pure preferential attachment process but rather they are affected by the social context. In this regard, the result underpins the claim that the partner selection of firms is determined by social relations as well as economics reasons. Second, a strong tendency of firms making cohesive subgroups was identified. However, it should be noted that they are not densely interconnected clans but rather hierarchical structures starting from a large firm reaching to separate small to medium sized firms. This finding also sustains the affirmation that firms often like to maintain personal, trust-based, or conglomerate-based relationships rather than merely arm's-length relationships by contracts. Last, social network analysis on past inter-firm network and ethnographic

studies revealed that there is plausible evidence of the impact of structural embeddedness on profit and relational embeddedness.

This study has several limitations. First, it does not include an integrated analysis of both structural embeddedness and relational embeddedness due to the difficulty of getting data to evaluate relational embeddedness. Second, although the evolution of the inter-firm network is a dynamic process in nature, no longitudinal analysis is conducted. Last, this research effort is meant to expand the traditional view toward the behavior of economic entities by integrating social aspects but does not yet fully incorporate a realistic model of economic entities and social environments.

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Field Measurement of Concrete Lateral Pressure in Formwork

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Abstract
Knowledge of concrete lateral pressure is critical for the economical and safe design of concrete formwork. Innovations in concrete mixtures and construction techniques are frequently implemented. As a result, frequent updating of the recommended theories in the ACI 347 standard for predicting the maximum lateral pressure has become necessary. Some important parameters, such as pore water pressure, cannot be fully represented in a small lab scale experiment. Thus, field studies on full scale placements are necessary. This paper reports on measurement methods used to collect data under field conditions in studies conducted by this researcher and others. The objective of the paper is to present the experimental approaches for the benefit of other researchers contemplating similar research.

Introduction
Formwork is a temporary structure used in construction to support and control the shape of the concrete until it hardens to sufficient strength to become self supporting. The contractor is responsible for both the design and performance of the formwork in meeting project requirements for safety and dimensional tolerances. Over the past 30 years, changes in concrete mixtures and construction techniques have been widely implemented such as the addition of super-plasticizers and self-consolidating admixtures to increase initial flowability, use of slag and fly ash for environmental reasons, and increased placement rates with improved concrete pumps.

The fresh concrete initially acts somewhat like a liquid (Fig. 1) and exerts lateral pressures, sometimes of great magnitude, particularly on forms for walls and columns. Stiffening as placement continues and internal friction within the concrete

are among the reasons that the pressures encountered are less than the full liquid head. Although some attempts have been made to do small scale lab experiments for assessing lateral pressures, important parameters, such as pore water pressure, cannot be fully represented at a small scale. Thus, field studies on full scale placements are generally necessary. As hydration of the cement proceeds during placement, the concrete begins to stiffen and the water contributing to pore water pressure is being absorbed, thus characteristics of the mixture, rate of placement, concrete temperature, and height of placement are all major influences on lateral pressure.

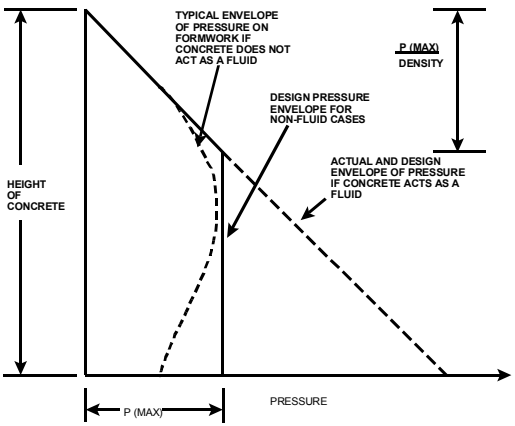


Fig. 1 – Concrete lateral pressure envelopes

Research by the author on projects ranging from nuclear power plants to residential foundation walls and analysis of cumulative data [Johnston, Khan and Phillips 1989; Dunston, Johnston and McCain 1994; Barnes and Johnston 2003] led to significant revision of ACI Committee 347 approaches for determining the predicted pressure in ACI 347-01 [ACI 2001] and again ACI 347-04 [ACI 2004]. Nevertheless, continued research by multiple investigators is needed currently and will be needed in the future if this standard is to keep up with changing concrete properties and field conditions.

Knowledge of concrete lateral pressure is critical for the economical and safe design of formwork for concrete construction. Designing for more than a reasonably safe pressure adds to the cost of the structure. Formwork is usually 40 to 60% of the cost of a completed concrete structure [Hurd 2005]. Concrete is a major material used in the constructed infrastructure. Thus, methods for predicting accurate design pressures have the potential of significant savings in formwork materials and labor, affecting the competitiveness of the U. S. construction industry in the global marketplace and reducing cost of the infrastructure or allowing the savings to be invested in more durability for sustainability.

Methods of Measurement

Two basic methods of measurement have been used in research in modern times. One is direct measurement with pressure transducers or cells in contact with the semi-fluid concrete. The second is by measurement of form tie tension forces and back calculation of the pressure based on tributary area supported by the tie.

Direct measurement would seem to provide a direct indication of the lateral pressure; however, things are more complicated than is apparent on the surface. As the concrete begins to stiffen (even while the placement continues at higher levels), there is a tendency for the concrete to bridge over the face of the pressure cell and for the measured pressure to be less than the actual pressure. Small pressure transducers appear to work satisfactorily when the concrete is very fluid and the time to the beginning of stiffening is long compared to the placement time. Large but more costly cells such as those used for measuring earth pressure are less affected by stiffening but tend to be more difficult to install in formwork and more difficult to recover.

Indirect measurement typically involves installation of a load cell to measure the tie force. In some cases, the tie itself is converted into a load cell by installing strain gages on the steel tie. In other cases, an independent load cell is slipped on the tie between the wale and the tie nut for the measurement. Use of load cells eliminates the need to penetrate the form sheathing and provides easier reuse.

Methods of Direct Pressure Measurement

Use of Small Pressure Transducers – Pressure cells in a range of small diameters (Fig. 2) are commercially available for measurement of fluid pressures. For concrete pressure measurement, a diameter of 0.75 in (20 mm) or larger is advisable. A convenient approach for mounting the transducer is to use compatible sizes of PVC plumbing fittings as shown in Fig. 3.



Fig. 2 – Small pressure transducer



Fig. 3 – Secured in PVC plumbing parts

Modification of the fittings by machining is sometimes necessary to allow a flush surface on the inside of the form. The pressure transducer design varies but a flush

plate face is needed for concrete applications. The transducer often involves strain gage technology so that, typical of many electronic sensors based on internal strain gage deformation, a strain indicator (Fig. 4) can be used for excitation and readout. It is necessary to calibrate the sensor to the strain indicator to allow a direct numerical readout of the pressure. Here the use of plumbing fittings facilitates connection to a regulated source of air pressure which the author has found works equally well to fluid pressure for calibration. Installation through the plywood or metal form sheathing (Fig. 5) is accomplished by drilling the sheathing and then using a pipe tap die to thread the hole to match the plumbing fitting. An alternate approach is to bolt or screw a mounting ring to the form to hold the pressure cell in place. An example installation in a prefabricated aluminum wall forming panel is shown in Figs. 6 and 7.

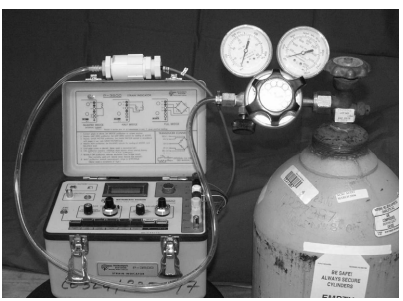


Fig. 4 – Calibration of small pressure cell

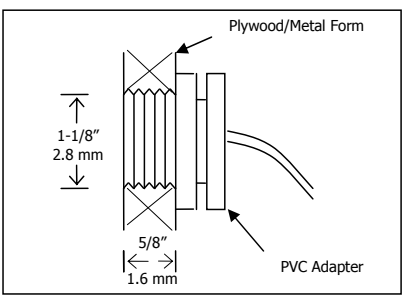


Fig. 5 – Installation of small pressure cell



Fig. 6 – Pressure cell in aluminum panel



Fig. 7 – Field setup

The distribution of sensors in the form is often more concentrated in the mid-height and lower portions of the form where pressures are expected to be higher as shown in Figs. 7 and 8. When sufficient sensors are available, it is desirable to have more than one vertical row in order to determine the variation in the pressure at each elevation.



Fig. 8 – Pressure cell distribution in column with plywood sheathing

Use of Earth Pressure Cells – Larger earth pressure cells, with a face diameter of about 6 in (150 mm), are typically used for measuring earth vertical pressure due to loads, lateral earth pressure against wall structures, or earth pressures in slurry walls. The larger diameter helps avoid under-measurement of concrete pressure associated with bridging of stiffer concrete over the pressure cell face. An example jackout style pressure cell is shown in Fig. 9. This transducer type often involves hydraulic fluid, sealed between two plates, which transmits the pressure to a vibrating wire strain gage transducer. Again, a strain indicator can be used for excitation and calibrated for readout as well as a variety of other indicators that are commercially available.

Calibration is necessary to a known fluid pressure. A means of calibrating to a concrete pressure is shown in Fig. 10 where a pressure cell has been mounted under a circular container filled with fluid concrete which is pressurized by a circular top plate in a universal testing machine. Comparison of the performance of small pressure transducers and large earth pressure cells can be made by mounting them adjacent as shown in Fig. 11. A field installation of earth pressure cells in wall formwork is shown in Fig. 12.



Fig. 9 – Earth pressure cell
(Image courtesy Geokon, Inc. | www.geokon.com)



Fig. 10 – Calibration of earth pressure cell for concrete under pressure
(Image courtesy N. J. Gardner)



Fig. 11 – Pressure cell comparison
(Image courtesy N. J. Gardner)



Fig. 12 – Earth pressure cell installed
(Image courtesy N. J. Gardner)

Methods of Indirect Pressure Measurement

The usual indirect measurement method involves determining the tension force in the form ties and calculating the average pressure within the tributary area supported by each tie. This approach is practical in wall forms and in columns of large lateral dimension. Basically, there needs to be sufficient width to accommodate three ties at each level measured so that edge effects will not confuse determination of a reasonable tributary area for each tie.

Measurement is accomplished either with a load cell in compression (see Fig. 13) due to the tension tie bearing force under the nut, or by installing strain gages directly on the form tie. Theoretically, solutions could be found for measuring the force in almost any type of tie. However, small pencil size snap ties are much less suitable and they are less likely to be used on tall walls that are usually preferred for investigation. When strain gages are to be installed on tie, a she-bolt tie is preferred because the she-bolt can be easily reused after the forms are stripped.

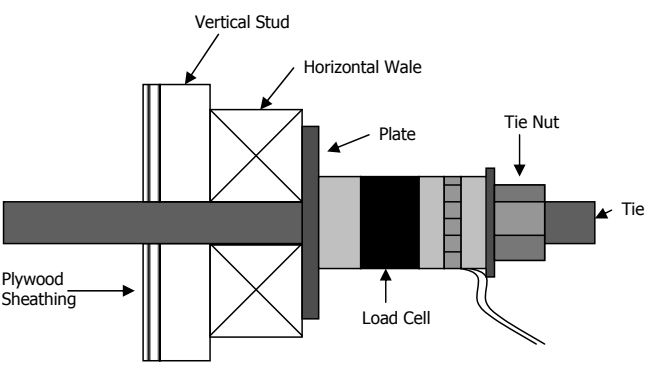


Fig. 13 – Tension tie force measurement by load cell.

The usual commercial load cell configuration available with a center hole for the tie is the flat load cell as illustrated in Fig. 14. In use, load is applied on one side to the flat ring of the central hub and is reacted on the opposite side flat face of the wide outer ring (or the reverse). An example installation is shown in Figs. 15 through 17. Critical to the performance is having correct bearing conditions for each face of the load cell. It is desirable to calibrate the load cell with bearing conditions matching those expected in the field to assure the arrangement will work and yield correct readings. Either strain indicators or calibrated digital weight indicators can be used for monitoring and recording data. One limitation of the commercial units is their cost since they are typically manufactured for high levels of accuracy.

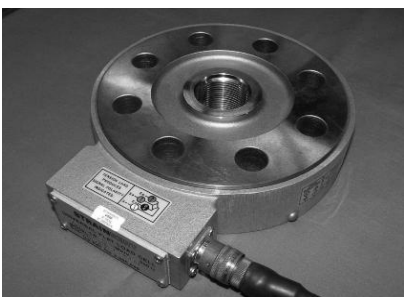


Fig 14 - Flat universal load cell



Fig. 15 - Installed flat load cell
(Image courtesy J. Erson)



Fig. 16 – Flat load cell with washer for inner ring contact against wale
(Image courtesy J. Erson)

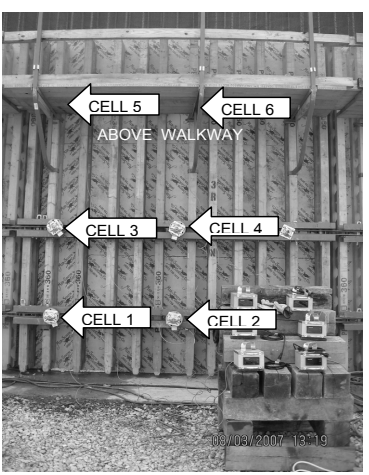


Fig. 17 – Load cell layout for wall formwork and digital recorders
(Image courtesy J. Erson)

An alternate approach is to make center hole compression load cells capable of accommodating a range of tie diameters. Making the load cells also adds excellent knowledge and capabilities to the background of the student researcher. The cells can be made of suitable size solid rod machined to provide the center hole. Aluminum is often selected because, relative to steel, it is easy to machine, has a low elastic modulus resulting in higher strains, and its generally higher yield stress provides appropriate strength. Making the cell length about twice the diameter (Figs. 13 and 18) lessens the end bearing effects that can cause problems in using flat load cells. A full bridge strain gage pattern is desirable to compensate for both temperature changes and the possibility of bending due to eccentric tie seating on the load cell. The gages and lead wires must be waterproofed (Fig. 19) and protected from field conditions of moisture and handling. A heat shrink casing was applied in this instance as shown in Fig. 20. Calibration of the load cells can either be done in a universal testing machine or against other load cells with a center hole hydraulic cylinder as shown in Fig. 21.



Fig. 18 – Center hole load cell and gages



Fig. 19 – Waterproofing application



Fig. 20 – Field use of fabricated load cell

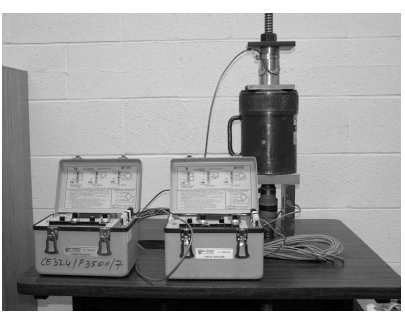


Fig. 21 – Fabricated load cell calibration

Form ties can also be instrumented with strain gages to directly serve as a tension load cell as shown in Fig. 22. A full bridge of gages performs best to compensate for

bending that may be induced by seating eccentricities and for temperature changes. As before, waterproofing and handling protection is needed for the gaged area. In the case illustrated (Fig. 23), a combination of PVC and neoprene plumbing fittings were used effectively. However, in installations where the wales are close together (Fig. 24), the encasement often needs to be more compact. In positioning the ties, it is desirable when multiples of full vertical rows of instrumented ties can be used such as in the wall form shown in Fig. 25 where three vertical rows, each of 7 ties were employed in a 30 ft tall wall.



Fig. 22 – Demo instrumented she-bolt

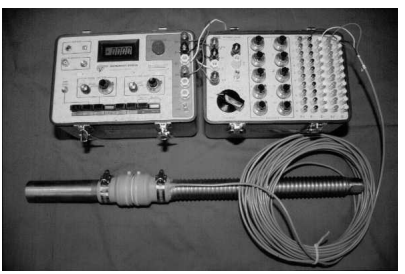


Fig. 23 – Completed 1.5 in (38 mm) dia. she-bolt



Fig. 24 – Installed instrumented she-bolt



Fig. 25 – Wall formwork with 21 instrumented ties

Implementation of Research Results and Conclusions

ACI Committee 347 standards and guides have long been recognized in the US as the source of recognized recommendations on concrete lateral pressure in formwork. Thus, researchers interested in conducting such research should become involved with that committee to learn both the needs and the expectation for types of data that should be collected during tests. Generally, to have long term value, the following minimum types of information is needed for each concrete placement evaluated:

- Concrete mix design, admixtures and dosages;
- Concrete density, slump, air content, temperature, and initial setting time;
- Type of vibrator and depth of immersion of the vibrator;
- Placement depth versus time;
- Pressure or force measurement device readings versus time; and
- Type (wall or column) and dimensions of the formed concrete element.

Some of this information is noted on the batch tickets from the ready-mix supplier. Other items must be measured in the field. Proper analysis of the data collected, comparison to existing theories, integration of data with historical data, and analysis of the total data can form a basis for updating the committee recommendations. These standards are only modified through a consensus process as mandated by ACI and ANSI; thus, involvement is typically essential to having results adopted.

Methods of instrumentation for measuring concrete lateral pressure have been summarized for the benefit of researchers desiring to pursue this area. This topic has been of frequent interest to construction engineers since the first recorded studies in the early 1900's. Research in this area is needed from multiple sources. Increasing problems arising due to new concrete admixtures are a cause for concern and without new research-based knowledge to support revision of standards, construction engineers must design conservatively, reducing the cost-effectiveness of the constructed facility.

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FORECASTING ENR CONSTRUCTION COST INDEX: A TIME SERIES ANALYSIS APPROACH

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Abstract

Every month, Engineering News-Record (ENR) publishes Construction Cost Index (CCI), which is a weighted-aggregate index of the 20-city average prices of construction activities. Although CCI is increasing in the long-term, it is subject to considerable short-term variations, which make it problematic for cost estimators to prepare accurate estimates. The ability to predict CCI can result in more-accurate bids and avoid under- or over-estimation. We conduct time series analysis and develop a CCI forecasting model based on the Seasonal Auto-Regressive Integrated Moving-Average (SARIMA) methodology. SARIMA investigates the underlying characteristics of the CCI data and makes systematic forecasts. The predictability of the developed SARIMA model is better than the predictability of the ENR subject matter experts' forecasts. The developed forecasting model can be used to prepare more-accurate estimates for contractors and budgets for owners and reduce construction costs by better-timed project execution.

Keywords: ENR, Construction Costs Index, Seasonal ARIMA, Forecast

1. Introduction

Engineering News-Record (ENR) monthly publishes the Construction Cost Index (CCI), which is widely used by cost estimators in America to estimate construction project costs or prepare budgets for owner organizations. However, historical ENR CCI data shows considerable short-term variations while increasing in the long-term, as shown in Figure 1. Variation of CCI will severely affect the accuracy of the estimation of construction cost or budget. Recent study shows variability in construction cost is one of the most important risks impacting the contractor's profit and owner's budget (Ervin 2007; Gallagher 2008). Additionally, contractor will suffer higher construction costs, delayed progress or even insolvencies accompanied with high variation of CCI. In consequence, owner will also take corresponding risks transferred by contractors, such as higher bids, large hidden contingencies or short bid guarantees.

In order to avoid the loss caused by variation of CCI, we will apply time series method to develop forecast model to provide more accurate CCI prediction. Our research process would be following. Our research will investigate time series properties of CCI data with respect to stationary and seasonality; apply Seasonal Auto-Regressive Integrated Moving-Average (SARIMA) approaches to fit historical CCI dataset; conduct diagnostic analysis test the model applicability; compare time series model and ENR's subject matter experts' CCI forecast with respect to predictability.

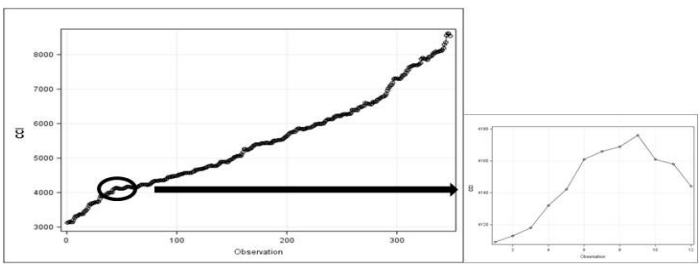


Figure 1: The long term increasing trend and short-term variations of CCI data

2. Research Background

There will be two categories of predictive modeling in previous works (Taylor and Bowen, 1987): the causal method and the time series method. The causal method assumes that the predicted variable is determined by independent explanatory variables, i.e. regression. The causal method has been applied to predict tender price indexes (Akintoye and Skitmore 1994; McCaffer et al. 1984), building price (Runeson 1988), construction cost (Koehn and Navvabi 1989), early cost estimation (Trost and Oberlender 2003), and construction labor cost in Hong Kong (Wong, 2005).

On the other hand, the time series method determines future trends based on past values and corresponding errors. Since time series method only require the historical data of forecast variable itself, it is widely used to develop predictive models. The time series method has been used to forecast Taiwan's construction cost indexes (Wang and Mei 1998), property prices (Chin and Mital 1998), building costs (Taylor and Bowen 1987), and tender price index (Fellows 1991; Ng et al. 2000). In a rare study of ENR CCI by (Williams 1994), exponential smoothing method was compared with linear regression and neural network models with respect to predictability.

Following Williams study, our research will explore more advanced SARIMA model to forecast CCI and investigate forecasting accuracy of SARIMA model with comparison to ENR's subject matter expert forecasts.

3. Time Series Properties of ENR CCI Data

The historical ENR CCI dataset {I(t); t = 1, 2, …, 348} we collected consists of 348 monthly data from January 1980 to December 2008. As shown in Figure 1, CCI time series subject to considerable short-term variations despite increasing long-term trends.

Stationary is one of the important time series properties, showing whether the time series has constant mean and time invariant correlations (Tsay, 2005). The Autocorrelation Function (ACF) plot is generally used to investigate whether a time series dataset is stationary. ACF plot in Figure 2 shows the ACF value bars of {I(t): t = 1, 2, …, 348} decays slowly and linearly to zero (grey area), indicating clearly non-stationary property of this dataset (Tsay, 2005).

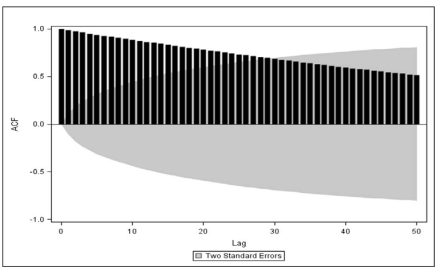


Figure 2. The ACF Plot of the CCI dataset

Seasonality is another important property exhibiting certain cyclical or periodic behaviors in time series data. Generally, a period of 1 year (12 month) is considered for monthly data such as CCI. The box plot in Figure 3 (left) shows that the monthly increment of CCI peak in July, decrease through December, and then begin rising until the next July peak. The ACF Plot of the monthly increment of CCI in Figure 3 (right) shows that CCI increment has relatively higher autocorrelations at lag levels of multiple 12, which are lags 12, 24, 36, and 48. This is a strong evidence for the seasonality of CCI increment dataset with the period of 12 months (Tsay, 2005).

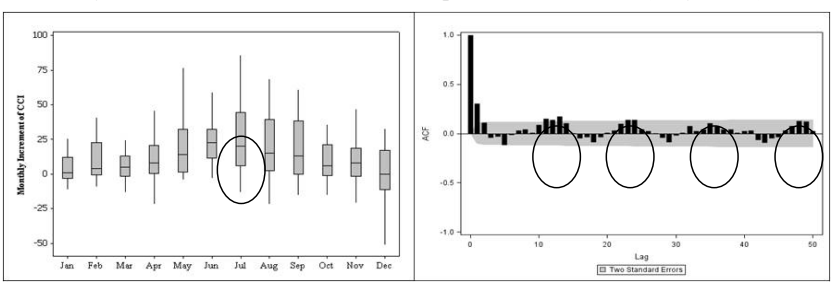


Figure 3. Box plot & ACF plot of monthly increment of CCI

4. Fitting Time Series Models - SARIMA

The Seasonal Auto-Regressive Integrated Moving-Average (SARIMA) approach is an extended ARIMA technique that is developed to handle both non-stationary behavior and seasonality in time series data. Firstly, it applies a regular differencing operation to transform the original dataset to a stationary time series dataset. Then, it applies seasonal differencing operation on the stationary time series to remove the seasonality. A SARIMA model is determined by six parameters: (p, q, d) and (P,D,Q). Parameters (p, d, q) are integers describing the orders of regular Auto-Regressive (AR), regular differencing operation and regular Moving Average (MA) parts ,

respectively; parameter (P, D, Q) describe the order of seasonal AR, seasonal differencing operation and seasonal MA parts. A SARIMA(p, d, q)(P, D, Q) model is defined by the following equation:

$$(1-B)^d(1-\mathrm{B}^s)^d I(t) = \mu + \frac{\theta(\mathrm{B})\Theta(\mathrm{B})}{\phi(B)\Phi(B)}\varepsilon(t) \quad (1)$$

Where:

- d is the differencing order, e.g., for d = 1, (1 – B)I(t) = I(t) – I(t – 1)
- D is the seasonal differencing operator
- S is the period of seasonality
- μ is the constant mean of time series $(1–B)(1–B^S)I(t)$
- B is the Backshift operator, i.e., BI(t) = I(t – 1)
- $\phi(B)$ is the AR operator, i.e., $\emptyset(B) = 1 - \phi_1 B^1 - \phi_2 B^2 - \odot\odot\odot - \phi_p B^p$
- θ(B) is the MA operator, i.e., $\theta(B) = 1 - \theta_1 B^1 - \theta_2 B^2 - \odot\odot\odot - \theta_q B^q$
- Φ(B) is the AR operator for the seasonal part of the ARIMA model, i.e., $\Phi(B) = 1 - \Phi_1 B^1 - \Phi_2 B^2 - \ldots - \Phi_P B^P$
- Θ(B) is the MA operator for the seasonal ARIMA model, i.e., $\Theta(B) = 1 - \Theta_1 B^1 - \Theta_2 B^2 - \ldots - \Theta_Q B^Q$
- ε(t) is the white noise time series sampled from a random variable with mean 0 and finite variance $\sigma^2 < \infty$

Fitting a SARIMA model to CCI historical dataset will be conducted following steps below.

4.1. Apply the regular and seasonal differencing operator to remove non-stationary behavior and seasonality

Firstly, we apply the regular differencing operator of order d=1 on the original CCI dataset to create the stationary time series dataset {L(t): t = 1, 2, ..., 347}.

$$\mathrm{L(t)} = (1-\mathrm{B})^1\mathrm{I(t)} = \mathrm{I(t)} - \mathrm{I(t-1)}$$

Time series plot of dataset {L(t): t = 1, 2, ..., 347} is shown in Figure 4. It can be seen that dataset {L(t): t = 1, 2, ..., 347} does not show clear increasing or decreasing trends and just varies around a constant mean value. This is visual evidence about the stationary property of the transformed time series data (Tsay, 2005).

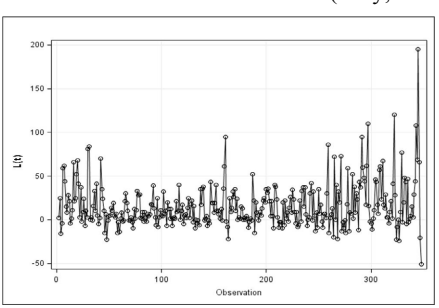


Figure 4. Time series plot of the transformed dataset {L(t): t = 1, 2, ..., 347}

As discussed in section 3, dataset {L(t): t = 1, 2, ..., 347} represents the monthly increment of CCI dataset, which shows seasonality. Therefore, the seasonal differencing is then applied on this transformed dataset {L(t): t = 1, 2, ..., 347} to remove the seasonality. Since the period of seasonality is 12 months, we set the seasonality s=12 and seasonal differencing order D=1 to create the transformed time series {Y(t): t=1, 2,…, 335} described by the following equation:

$$Y(t) = (1 - B^{12})L(t) = L(t) - L(t - 12)$$

Box plot (left) and ACF plot (right) in Figure 5 shows there is no clear seasonal behavior observed in dataset {Y(t): t = 1, 2, …, 335}.

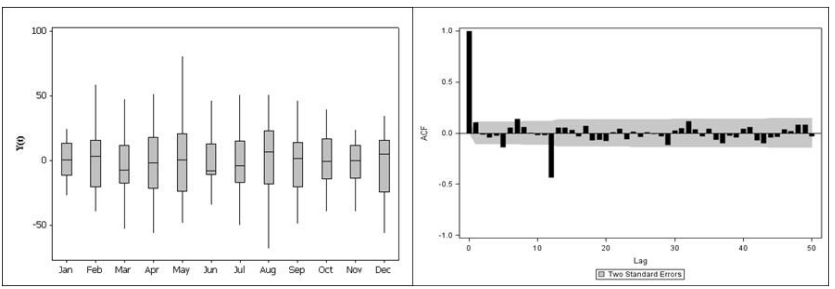


Figure 5: The Box plot & ACF plot of dataset {Y(t); t = 1, 2, …, 335}

At last, we have to verify the stationary of the transformed dataset {Y(t): t = 1, 2, …, 335} for further modeling. Time series plot of dataset {Y(t): t = 1, 2, …, 335} in Figure 6 shows it varies around a constant mean, visually showing stationary behavior. More specifically, we conduct the Augmented Dickey–Fuller (ADF) unit root test on {Y(t); t = 1, 2, …, 335} to check stationary (Brockwell and Davis, 2002). ADF test is a test for stationary property of time series sample data. It's null hypothesis is there is a unit root (nonstationary) in the sample data at certain confidence level. We choose the test under test equation with constant mean according to the observation in Figure 6. Table 1 summarizes the values of ADF test statistic τ and corresponding p-values at lag levels of 0, 1, and 2, respectively. The low p-values show that the null hypothesis of non-stationary is strongly rejected at any significant level. Consequently, regular differencing parameter d=1 and seasonal differencing parameter D=1 is selected to generate stationary and non-seasonal time series dataset {Y(t): t = 1, 2, …, 335} for further modeling.

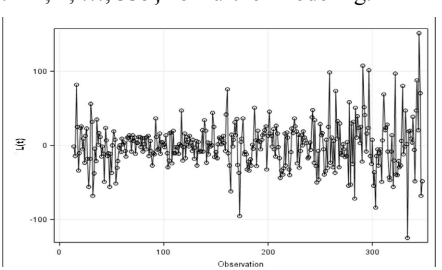


Figure 6. Time series plot of dataset {Y(t); t = 1, 2, …, 335}

Table 1. ADF unit root test for {Y(t); t = 1, 2, …, 335}

Type of Dataset	Lag Level	τ-statistic	P-value
Constant Mean	0	-30.85	<.0001
	1	-30.94	<.0001
	2	-30.91	<.0001

4.2. Tentative selection of parameters p, q, P, and Q

Parameters P and Q of seasonal model parts can be identified by observing ACF and Partial Autocorrelation Function (PACF) plots of the transformed dataset {Y(t); t = 1, 2, …, 335} at multiples of lag 12, which is the seasonality period removed from the dataset. PACF plot plays an important role in determining the parameter of lag p for AR(p) model or an extended ARMA(p, q) model. While ACF plot can be used to determine the parameter of lag q for MA(q) model or an extended ARMA(p, q) model (Brockwell and Davis, 2002). The ACF plot (left) and PACF plot (right) are presented in Figure 7. It can be seen that ACF bars cuts off after lag 12 while the PACF bar gradually dies down to zero (gray area) at multiples of lag 12. According to the visual rules for model type selection (Watson and Teelucksingh, 2002), which are summarized in Table 2, the MA model should be selected to describe the seasonal model part and therefore, P=0 and Q=1.

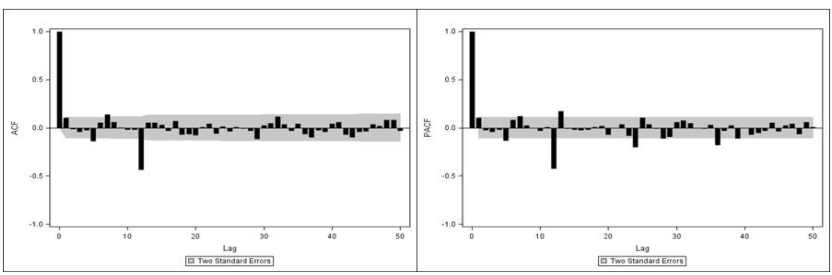


Figure 7: The ACF plot & PACF plot of {Y(t); t = 1, 2, …, 335}

Table 2: model selection rules based on ACF and PACF plots (Watson, 2002).

Time Series Models	ACF	PACF
White Noise	all equal to zero	all equal to zero
MA(q)	cut off after lag q	die down
AR(p)	die down	cut off after lag p
ARMA(p, q)	die down	die down

However, ACF and PACF cannot provide clear evidence to determine the parameter p and q of non-seasonal model parts, since the ACF and PACF bars close or equal to zero within 12 lags period. Then we apply Bayesian Information Criterion (BIC) rules to select the tentative parameters p and q (Brockwell and Davis 2002). Various models with different pairs of initialization value of (p, q)(P=0,Q=1) are tried to compute the BIC values. The tentative model parameter p and q will be selected with the lowest BIC value. Table 3 summarizes the BIC values with different combinations of p and q.

Table 3: Values of BIC for different SARIMA(p,1,q)(0,1,1) models

Lags	q=0	q=1	q=2
p=0	**6.6204**	6.6331	6.6440
p=1	**6.6306**	6.6477	6.6569
p=2	6.6462	6.6631	6.6727

It can be seen that the top two models with lowest BIC values are SARIMA(0,1,0)(0,1,1) and SARIMA(1,1,0)(0,1,1) respectively. Therefore, these two models are selected as initial tentative models for fitting the CCI dataset.

4.3. Estimate model coefficients and develop SARIMA models

Coefficients for AR and MA parts in the model, i.e., $\phi(B)$, $\theta(B)$, $\Phi(B)$, and $\Theta(B)$ in Equation 1, are estimated based on the Maximum Likelihood Estimation (Brockwell and Davis 2002). Table 4 summarizes the estimated coefficients for tentative model SARIMA(0,1,0)(0,1,1) and SARIMA(1,1,0)(0,1,1) respectively. The low p-values of each coefficient show that all estimated coefficients are significantly different from zero under 5% significant level.

Table 4. Coefficients estimation for three tentative SARIMA models

Model	Coefficients	Estimate	Standard Error	t-Value	p-Value
SARIMA(0,1,0)(0,1,1)	$\Theta(1)$	0.79415	0.04727	16.80	<.0001
SARIMA(1,1,0)(0,1,1)	$\Theta(1)$	0.83203	0.04573	18.19	<.0001
	$\emptyset(1)$	0.22724	0.05297	4.29	<.0001

4.4. Diagnostic analysis for tentative models

According to model assumption presented in Equation 1, the error term $\varepsilon(t)$ should be a white noise process with mean zero and finite variance σ^2. Therefore, we apply the Ljung-Box Q test to check whether residual series $\{\hat{e}(t): t=1, 2, ..., 335\}$ of the above tentative models follow the white noise assumption (Brockwell and Davis 2002). Figure 8 summarize the p-value plot of Ljung-Box Q test at different lag levels on residual datasets of above two tentative models. It can be seen that the p-value plot for SARIMA(0,1,0)(0,1,1) are obviously over the threshold line of the 5% significance level at various lags, indicating the null hypothesis that the residuals is white noise process can be rejected at 5% significant level. Similarly, since the p-value plot for SARIMA(1,1,0)(0,1,1) are all below 5% significant threshold line, we cannot reject the null hypothesis of white noise process at 5% significant level.

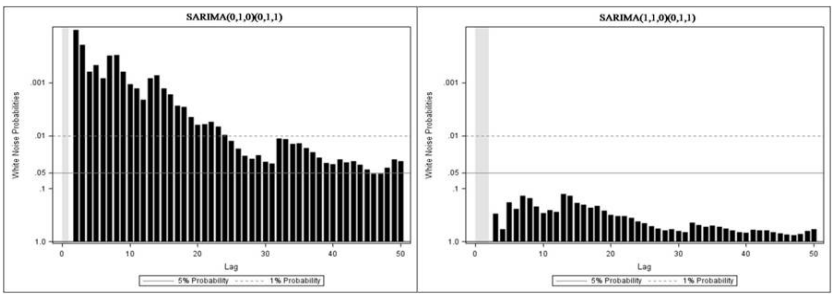


Figure 8. White noise p-value plots of residuals in two tentative SARIMA models

Finally, we develop an applicable SARIMA(1,1,0)(0,1,1) model fitting our CCI dataset best, which is defined by following equation.

$$(1-B)^1(1-\mathrm{B}^{12})^1 I(t) = \frac{(1-0.83203\mathrm{B}^{12})}{(1-0.22724\mathrm{B}^1)}\varepsilon(t)$$

5. Out-of-sample Forecasting

Out-of-sample forecasting is conducted to make 12-month ahead prediction of CCI, i.e. prediction of CCI for next December based on historical data available till December this year. In order to compare the predictability of time series model and ENR Subject Experts' CCI Forecast published in Four-Quarter Cost Report every year, we investigate 12 months ahead out-of-sample forecasting for CCI in December starting from 1987 to 2008 based on their historical dataset respectively. For example, the subset dataset used to predict CCI in December 1987 contains historical data from January 1980 to December 1986. We will fit SARIMA models on each subset datasets, and then make 12 month ahead out-of-sample prediction according to their best fitting models respectively.

Three general error measures Mean Absolute Percentage Error (MAPE), Mean Square Error (MSE), and Mean Absolute Error (MAE) are used to measure the predictability of time series model and the ENR's forecast. The less the error measures, the more accurate the prediction is. Table 5 summarizes the error measures for these two models. Figure 9 shows time series plot of actual CCI, ENR's forecast CCI and SARIMA forecast CCI.

Table 5. Out-of-sample forecast error measures of ENR's Forecast & SARIMA

Error measures	ENR's Forecast	SARIMA
MAPE	1.22%	1.04%
MSE	12910.00	12068.04
MAE	73.33	68.17

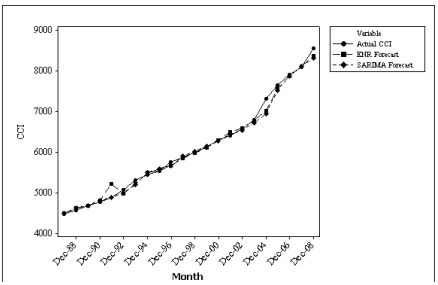


Figure 9. Comparison of forecast CCI with actual CCI value

It can be seen that both ENR's forecast and SARIMA forecast are close to the actual CCI values, presenting an accurate prediction with MAPE much smaller than 10%, which is an acceptable threshold recommended by Wong (2005). However, the predictability of SARIMA model is even better than the ENR's forecast with smaller error measures.

6. Conclusions and Future Work

ENR CCI data shows increasing in the long-term and frequent variations in short-term. The ability to provide more accurate prediction of construction cost trends can lead to more-accurate bids and avoid under- or over-estimation. Our research in investigating applicability and predictability of SARIMA method on the historical CCI dataset shows that SARIMA model provides high level of accuracy in forecasting of CCI.

However, the predictability of SARIMA model does not perform well when CCIs make discrete jumps. For instance, Figure 9 shows SARIMA underestimate the CCI in December 2004 and December 2008 when there is a large jump in CCI. Poisson (jump) processes (Dixit and Pindyck, 1994) should be tried in the future research to investigate whether they could create more realistic forecasting models to capture infrequent but discrete jumps of CCI.

With more accurate prediction of construction cost trend, contractors and owners can benefit in cost control and risk management by better-timed project execution. SARIMA model can also be used by other researchers to develop predictive models for other construction indexes, such as the ENR's Building Cost Index.

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INFLUENCE FACTOR-BASED SAFETY RISK ASSESSMENT METHODOLOGY FOR CONSTRUCTION SITE

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Abstract

Many work-related risk factors can cause construction site hazards. As well, risk for the same trade can vary due to different combinations of inherently changeable construction site characteristics. However, construction safety management has been executed similarly to other industries without reflecting the unique characteristics of the construction industry. To address these issues, this paper proposes a risk assessment methodology that considers the risk influence factors of construction sites and the risk of trade. Through a literature review and expert surveys, this study extracts risk influence factors and develops a weighting system for their classification. Risk of trade is calculated based on frequency and severity of risk. By integrating risk influence factors and risk of trade, this methodology can determine risk according to specific construction site conditions, thus enabling more effective safety management.

Risk Influence Factor.

Introduction

As construction projects become more complex, large in scale, and involve higher worker mobility, construction-related risks have increased. In fact, the Korea Occupational Safety and Health Agency's (KOSHA) 2007 report indicates that the second highest number of injuries and fatalities among all industries occurred in construction. Nevertheless construction industry has less than 10% of GDP and the employed, it has more 20% of injuries and fatalities (Korea Ministry of Labor 2007).

High injury rate and number of injuries show that safety management do not perform effectively in construction industry. Safety management has been improved by safety managers' efforts like safety training and prevention of accident. But there is much room for improvement in construction comparing with other industries.

Though there has been extensive researches in safety management and especially risk assessment, applying these to construction sites is difficult. The object of this paper is developing risk assessment methodology which can be applied to construction sites.

Risk management consists of four interdependent components: (1) hazard identification; (2) risk analysis; (3) risk control selection; and (4) risk control implementation and maintenance (Chua and Goh 2005). Hazard identification and risk control can be performed effectively when based on many hazard cases and knowledge informed by experience. In the construction industry, similar hazards often occur repetitively. However, the magnitude of risk inherent in risk factors is calculated by qualitative standards and dealt with perfunctorily. This subsequently leads to ineffective safety management and difficulties for hazard prevention. Therefore, to develop a reliable risk prevention method, the magnitude of risk must be accurately measured.

A construction hazard is an event caused by the interrelation of risk factors such as outside work, various work environments, worker characteristics, type of work, equipment, and etc. So construction safety management should be performed to be different from other industries due to characteristics of construction. Risk assessment from among safety management steps is an important criterion to decide handling an expected risk.

Existed risk assessment researches indicate various methods to define the magnitude of risk. However these researches focused on accident cases or specific factors. But construction sites are the place where various factors have relations with each others, accident can be regarded as combination of these factors (Toole 2002, Hinze & Gambastese 2003, Mohamed 2002). Thus, risk assessment method considering characteristics of construction is needed.

Risk assessment method satisfies two conditions. First, process and result of method are quantitative. Second, various risk influence factors are fully considered in the method. So the purpose of this paper presents a quantitative risk assessment methodology that considers the risk influence factors of construction site.

In construction industry, risk means uncertain events or conditions which can affect construction project negatively. In this paper, risk represents only worker's injuries and fatalities which mean occupational risk.

The proposed methodology is developed in the following five steps:

(1) 10 influence factors are extracted through a literature review and expert surveys.

(2) The selected factors are weighted through the Analytic Hierarchy Process (AHP).

(3) The risk of different trades are evaluated based on accident cases that include 536 injuries and 76 fatalities.

(4) The weight of the influence factors and the risk of trades are integrated.

(5) Finally, the methodology is developed to safety risk assessment program.

Previous Research

Literature Review

Table 1 shows that contents and factors is considered by researchers. Existed studies about risk assessment are based on number of days away from work, insurance

compensation, frequency of occurrence. And some studies are performed by occupation and age of worker, type of facilities for assessing risk.

Several studies examine risk assessment. For example, Baradan and Usmen (2006) conducted quantitative analysis to determine the cost of lost time and the median number of days away from work. They also introduced a formula that combines nonfatal injuries and fatalities to obtain a risk score. In addition, Jannadi and Almishari (2003) developed a risk assessor model using two risk calculating equations. Finally, Seo and Choi (2008) constructed a risk assessment matrix that classifies frequency and severity by three steps. These studies select specific factors, and then risk is assessed by these factors.

However, more factors should be considered to be much reliable risk assessment. In the case of constructing same type of facility, safety management can be performed to analyze accident cases. But past risk is different from the present risk because construction sites that affect risks consist of many changeable factors, conditions and subject matters that can be changed by process of activity, workers' mobility which is higher than other industries.

Table 1. Safety Management Research by Factors

Classi-fication	Detailed Classification	Quanti-zation	Site characteristic				Author
			Site Info.	Work er	Work	Work Condition	
Safety Manage-ment & Perform-ance	Safety training	X	X	●	X	X	Kim et al (2008)
		X	X	X	●	X	Kim (2003)
	Safety Management Performance	X	X	▲	▲	X	Mohamed (2002)
		▲	X	●	▲	X	Hinze and Gambatese (2003)
Risk Assessme nt & Risk Influence Factor	Accident Cases	●	X	X	●	X	Baradan and Usmen (2006)
		●	X	X	●	X	Lee et al. (2006)
		●	X	X	●	X	Jang et al. (2007)
		●	X	X	●	X	Lee et al. (2000)
		●	●	▲	●	X	Korea Occupational Safety and Health Agency(1999)
	Risk Matrix	▲	X	X	●	X	Jannadi and Almishari (2003)
		▲	X	X	●	X	Seo and Choi (2008)
	Climate	X	X	X	▲	●	Son and Kim (2005)

* ●, ▲, X are marked by degree of quantization and reflection of site characteristics.

●: concrete factors in study, ▲: consideration and mention of author, X: unmentioned

Influence Risk Factors

Many studies show that there are various factors affecting accident occurrence. Also accidents are occurred by interaction and combination of factors. In this chapter, factors affecting frequency and severity of accident occurrence are extracted from literature review and expert survey. And extracted factors are weighted by expert surveys and analytic hierarchy process (AHP). Finally, risk of classification is suggested.

Risk Factor Extraction Process

Human and material causes occurring accidents include various factors. It means that safety managers must consider these factors to prevent such events from happening. An event is a result of combinations and interrelation of factors. To calculate higher precise values of risk, it is good to use various factors. But, factors causing accidents are too many to consider at risk assessment process. To select proper factors, the methodology shown in this paper gets effectiveness to calculate the risk. To extract the predominant risk factors, the following process was executed:

First, the factors were extracted through a literature review. 27 factors were drawn from various researches and literature. From these 27 factors, 17 factors were filtered off considering measurable and statistical data. Then, preliminary surveys based on the remaining 17 factors were conducted with 42 safety managers who have more 10 years experience for safety management. Safety managers suggested that 17 factors are too many to manage in a construction site. So, the survey asked the respondents to rank the priority of risk influence factors. And finally, 10 factors are extracted. The factors identified through this process are shown in Fig. 1.

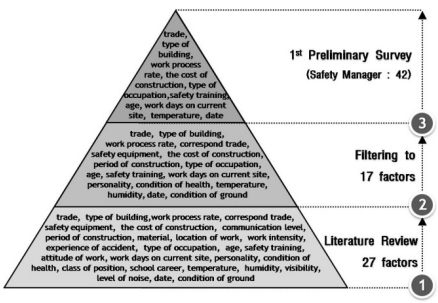


Fig. 1 Extracting Factors

Nevertheless some factors are judged to affect occurrence of accidents, these are not included in process of risk assessment. These are visibility, work intensity, personality. The reasons why these factors are excluded are lack of statistical data and difficulty of getting data. Because these don't belong in the category of KOSHA's accident investigation, the values with public trust cannot be obtained.

Weighting Influence Risk Factors

To use extracted factors in fig 1, a factor is known how much to affect occurrence of accident. The weight derivation method which is needed in this study should be able to translate qualitative one to quantitative one. The analytic hierarchy process (AHP) is the one of the methods that satisfies the condition. So, AHP is used to weight influence risk factors in this chapter.

The AHP was used to weight the predominant influence risk factors. The AHP is a structured technique for handling complex decisions. However, in this study, the AHP

was only used to weight factors. 9 factors were surveyed by pairwise comparison. Only nine factors excluding trades were surveyed by pairwise comparison. These nine factors were used because construction safety management is performed as the trades are proceeded and accident cases are summarized by trades. Therefore, nine factors and risk by trade are integrated; then, they are used to assess risk by considering construction site characteristics.

The trades have been selected as the most affective base factors in risk assessment. Safety management is centered around the trades in construction. In table 2, the trades are shown to have the highest values in risk indices that provide detailed classifications of maximum value / minimum value ratios. The trades are thus the prime factors in the assessment of risk. Centering safety management around the trades therefore is more advantageous than centering it around any other factors.

Table 2. Max/Min Ratio of Detailed Classifications

	Work process rate	Cost of construction	Type of Building	Trades	Age	Type of occupation	Work days on current site	Safety training	Date	Temperature
Maximum Value	72.932	87.164	79.586	85.639	95.367	79.532	76.949	99.300	98.443	93.851
Minimum Value	49.877	41.223	53.819	4.214	40.194	10.525	26.543	18.918	38.201	41.575
Max/Min Ratio	1.462	2.114	1.479	20.321	2.373	7.556	2.899	5.249	2.577	2.257
Rank	10	8	9	1	6	2	4	3	5	7

7 of the 13 collected surveys that had contingency indexes below 0.1 were analyzed. These 7 surveys were analyzed separately, and the weights were calculated by geometric average. As the table 3 indicates, weight of work process rate and safety training are relatively higher values than other factors. Work process rate is 0.167 and safety training is 0.172. And contingency index is 0.0049 which can be said that respondents are consistent and reliable.

Table 3. Result of AHP

	(f1)	(f2)	(f3)	(f4)	(f5)	(f6)	(f7)	(f8)	(f9)
(f1)	1.000	1.952	1.292	1.842	1.511	1.258	0.960	3.524	2.479
(f2)	0.512	1.000	0.869	1.292	0.944	1.000	0.689	1.768	1.575
(f3)	0.774	1.150	1.000	2.034	1.042	1.042	0.635	2.420	1.952
(f4)	0.543	0.774	0.492	1.000	0.662	0.635	0.445	1.486	1.219
(f5)	0.662	1.060	0.960	1.511	1.000	1.000	0.624	2.000	2.065
(f6)	0.795	1.000	0.960	1.575	1.000	1.000	0.635	2.627	2.155
(f7)	1.042	1.450	1.575	2.246	1.601	1.575	1.000	2.918	2.380
(f8)	0.284	0.566	0.413	0.673	0.500	0.381	0.343	1.000	1.000
(f9)	0.403	0.635	0.512	0.820	0.484	0.464	0.420	1.000	1.000
Avg.	0.167	0.104	0.126	0.077	0.115	0.122	0.172	0.054	0.062

where: (f1): work process rate, (f2): the cost of construction, (f3): type of building, (f4) age, (f5): type of occupation (f6) work days on current site, (f7): safety training,

(f8): date, (f9): temperature,

Classifications of Risk Factors

To arrange detailed classification of 9 factors mentioned above, KOSHA's industry disaster investigation of code standard and expert suggestion are used. But detailed classification of safety don't present on construction accident case and type of safety training varies from every construction site. So detailed classification of safety training is characterized by frequency of safety training.

Number of accidents, non-fatalities injuries, fatalities and commitment of worker etc. are considered in calculating process of risk of classifications. Formula 1 summarizes the calculating process of risk classifications mentioned above.

$$\text{Risk of Classifiaction} = \sqrt{\frac{\text{Loss Days of Injuries and Fatalities given factor}}{\text{Number of Accident cases of all trade} \times \text{Labor Input ratio given trade}}} \quad (1)$$

And site weights are assessed by ratio of average of risk of classifications and risk of classifications. The reason for introducing site weight is that numbers of classification of factor are different from each others. The detailed classifications by factors are represented in Table 4.

Table 4. Classification of Factors

Factors										
Work process rate	Definition	Ratio of work process								
	Classification (%)	~10	11~20	21~30	31~40	41~50	51~60	61~70	71~80	81~90	91~100
	Risk of classification	0.083	0.092	0.124	0.111	0.085	0.099	0.111	0.088	0.107	0.100
	Site weight	0.830	0.920	1.240	1.110	0.850	0.990	1.110	0.880	1.070	1.000
Cost of the construction	Definition	Cost of construction Project								
	Classification (billionwons)	~5	5~10	10~30	30~50	50~100	100~500	500~1000	1000~		
	Risk of classification	0.139	0.174	0.132	0.143	0.116	0.084	0.114	0.098		
	Site weight	1.112	1.392	1.056	1.144	0.928	0.672	0.912	0.784		
Type of building	Definition	Type of building								
	Classification (%)	Social sports facilities		Housing accommodation	Hospital and school facilities		Apartment		Commercial public facilities	
	Risk of classification	0.220		0.159	0.174		0.216		0.231	
	Site weight	1.100		0.795	0.870		1.080		1.115	
Age	Definition	Number of years since born								
	Classification (%)	Twenties	Thirties		Forties		Fifties		Sixties	
	Risk of classification	0.061	0.197		0.208		0.270		0.264	
	Site weight	0.305	0.985		1.04		1.35		1.32	
Type of occupation	Definition	Type of occupation								
	Classification	Scaffold worker	RC worker	Roof worker	Framing carpenter	Paint worker	Plaster worker	Carpenter	Electronic worker	Finishing worker
	Risk of classification	0.139	0.134	0.112	0.139	0.137	0.065	0.060	0.042	0.037
	Site weight	2.504	2.403	2.012	2.503	2.466	1.170	1.077	0.753	0.671
	Classification	Brick worker	Sheet metal worker	Common worker	Watertight worker	Re-bar worker	Plumber worker	Tile worker	Concrete finish worker	Earth worker
	Risk of classification	0.030	0.029	0.015	0.018	0.011	0.007	0.006	0.005	0.014

	Site weight	0.536	0.516	0.265	0.332	0.201	0.117	0.115	0.098	0.259		
Work days on current site	Definition	The days of working in current site										
	Classification	~10 days	10~20 days	20~30 days	1~2 month	2~3 month	3~4 month	4~5 month	5~6 month	6~12 month	12~ month	
	Risk of classification	0.242	0.199	0.147	0.125	0.097	0.068	0.052	0.038	0.021	0.011	
	Site weight	2.42	1.99	1.47	1.25	0.97	0.68	0.52	0.38	0.21	0.11	
Safety Training	Definition	The number of safety training in three month										
	Classification	0	1	2	3~4	5~6	7~8	9~10	11~15	16~20	21~	
	Risk of classification	0.327	0.232	0.158	0.092	0.053	0.045	0.037	0.026	0.018	0.012	
	Site weight	3.27	2.32	1.58	0.92	0.53	0.45	0.37	0.26	0.18	0.12	
Date	Definition	Correspond date of site										
	Classification (month)	1	2	3	4	5	6	7	8	9	10	11	12
	Risk of classification	0.068	0.086	0.173	0.068	0.080	0.086	0.080	0.111	0.049	0.086	0.056	0.056
	Site weight	0.82	1.03	2.08	0.82	0.96	1.03	0.96	1.33	0.59	1.03	0.67	0.67
Temperature	Definition	Temperature of site										
	Classification (℃)	~0	0~4	4~8	8~12	12~16	16~20	20~24	24~28	28~		
	Risk of classification	0.196	0.163	0.109	0.082	0.054	0.043	0.101	0.125	0.128		
	Site weight	1.76	1.47	0.98	0.74	0.49	0.39	0.91	1.12	1.15		

Risk Assessment by Trade

Risk Assessment Method and DATA

In this study, risk assessment is based on 3 steps: (1) assessing the severity of risk; (2) assessing the frequency of risk; and (3) integrating the severity and frequency of risk.

The data for assessing risk was collected from 4 general contractors who provided information on accident cases over 5 years (2003~2007). The total number of cases is 596, with 536 non-fatalities and 76 fatalities.

The trades that are used in Korea are classified by 22 types of work. Landscape architecture, Ondol, and special building trades are excluded because they have few accident cases, and the Ondol trade is only applied in Korea.

Assessing Severity and Frequency

Two measuring indexes are loss days and insurance fees (Knab 1978). Considering various distribution of construction site, type of occupation and wage, and insurance fees have a large distribution. Therefore, severity of risk is assessed based on loss days.

Loss days are the days away from work including days away from work due to both non-fatal injuries and fatalities. According to Korea's disaster investigation standards, loss days are designated not by a confirmed value but by a range of days. Thus, severity of risk is determined by dividing the amount of loss days by the number of accident cases in a given trade.

$$\text{Severity} = \text{Amount of Loss Days} / \text{Number of accident cases in a given trade} \quad (2)$$

To determine the frequency of risk of a given trade, the number of accidents of a given trade is divided by the multiple total number of accident cases multiplied by the ratio labor input ratio given trade.

Frequency =Number of accident cases / (Total number of accident cases * Labor Input Ratio given trade) (3)

Integrating Severity and Frequency

A conversion process is required to integrate the two indexes mentioned above. To convert the indexes, a relative severity index and relative frequency index are introduced. The largest value is converted to 100. Then, other values can be represented as a ratio of that. Relative indexes are calculated separately by both severity and frequency. Next, relative risk is determined by the geometric mean of relative severity and frequency. This process and corresponding results are summarized in Table 5.

Table 5. Results of Risk by Trade

Work	No. Accident	No. Injuries	No. Fatalities	Loss days of Injuries	Loss days of Fatalities	Severity	Frequency	Relative Severity	Relative Frequency	Labor Input Ratio	Risk given trade
Roof	12	8	4	2185	9000	932.08	0.04	73.34	100.00	0.55	85.64
E/V	5	3	2	354.5	6000	1270.90	0.03	100.00	71.61	0.32	84.63
Curtain wall	8	5	3	996.5	5250	780.81	0.02	61.44	43.14	0.85	51.48
R/C	235	229	26	11053	88500	423.63	0.03	33.33	75.99	15.38	50.33
Steel structure	39	30	9	998	29250	775.59	0.01	61.03	23.80	7.51	38.11
Wall	42	35	5	872.5	14250	360.06	0.01	28.33	38.04	4.82	32.83
Foundation	37	28	7	1064	21000	596.32	0.01	46.92	22.16	7.24	32.24
Plastering	39	31	4	3205.5	9000	312.96	0.01	24.63	36.46	4.40	29.96
Temporary	33	29	4	3475.5	7500	332.59	0.01	26.17	23.09	6.55	24.58
Watertight	15	17	1	243	2250	166.20	0.01	13.08	34.09	2.42	21.11
Dismantling	19	18	1	2841	750	189.00	0.01	14.87	27.13	3.21	20.09
Painting	12	11	1	310.5	3750	338.38	0.00	26.62	13.41	4.10	18.90
Earth	16	14	3	210	6750	435.00	0.00	34.23	10.13	7.69	18.62
Tile	5	4	1	187.5	2250	487.50	0.00	38.36	8.62	2.66	18.18
Etc.	22	20	2	550	6000	297.73	0.00	23.43	13.25	7.61	17.62
Brick	9	8	1	85	2250	259.44	0.00	20.41	10.71	3.85	14.79
Stone	12	11	1	157.5	750	75.63	0.01	5.95	25.70	2.14	12.37
Window & Door	5	4	1	300	750	210.00	0.00	16.52	6.44	3.56	10.31
Metal	8	8	0	649	0	81.13	0.00	6.38	11.42	3.21	8.54
Finish	9	9	0	642	0	71.33	0.00	5.61	8.03	5.14	6.71
Isolation	7	7	0	88.5	0	12.64	0.01	0.99	25.07	1.28	4.99
Wood	7	7	0	131	0	18.71	0.00	1.47	12.06	2.66	4.21
Total	596	536	76	30599.5	203250					Avg. Risk by trade	27.47

Assessing Site Risk

Formula 4 shows the method for integrating the weight of an influence risk factor and risk for a given trade. Influence factors index (RIF index) is calculated using formula 4 that shows the method for integrating the weight of an influence risk factor and relative risk for a given trade.

$$RIF = RR\sum_{i=1}^{9}(f_{is} \times f_{iw}) \quad (4)$$

where fs = site weight; fw = influence risk factor weight;

To apply formula 4 above mentioned, a case must be considered. The case that many workers are in same trade is very frequently. In the construction site, a team which consists of workers performs an activity or trade under ordinary circumstances. So, fs can represent site weights of many workers.

In the process of weighting influence factors related to workers, summing risk influence factors weights of the every worker and then it is divided by the number of workers in a trade. Formula 5 shows methods that calculate risk influence factors weights of age, type of occupation, work days on current site, safety training when number of workers is more than two in same trade.

$$f_s = \{f_s(n_1) + f_s(n_2)f_s(n_3) + \cdots + f_s(n_n)\}/n \quad (5)$$

where fs(n1), fs(n2), fs(n3), …, fs(nn) = individual site weights of n workers; fs = an average of individual site weights of n workers;

RIF index by site is assessed by combining the result of this process and sum of the values multiplying site weight (fs) and influence risk factor weight (fw). Formula 6 represents these process. This index represents how much danger a site is. Also it can be used to compare a site with others.

$$Rt = \left[\sum_{i=1}^{9}(f_{is} \times f_{iw})\right] \times \sqrt{\frac{\left[\frac{\sum_{i=1}^{n} TNF_i}{(NA)\times\sum_{i=1}^{N} R_{iLI}}\right]}{Max(Severity)\times Max(Frequency)}} \quad (6)$$

where TNF = total amount of loss days away from work of nonfatal injuries and fatalities for a given trade; NA = number of accident for a given trade; R_{LI} = labor input ratio:

Conclusion

Construction projects have variable risk factors related to work conditions, worker characteristics, different trades, weather, and etc. To evaluate these risks, this paper proposed a risk assessment methodology that takes construction site characteristics into account. In developing this methodology, 10 influence risk factors were extracted from a literature review and expert surveys. The relative risks of different trades were also calculated. A risk assessment methodology considering construction site

characteristics was introduced by integrating the extracted risk factors and relative risk. Future research needs to develop computerized system. Also, more accident cases should be collected to get reliability of system.

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"SUSTAINABILITY BY…" A SYNTHESIS OF PROCUREMENT APPROACHES FOR HIGH PERFORMANCE BUILDINGS

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ABSTRACT

Sustainable design and construction has experienced significant growth in recent years. The predominant system in the United States for specifying and evaluating sustainable construction practices and materials is the Leadership in Energy and Environmental Design (LEED®) rating system as prescribed by the United States Green Building Council (USGBC®). Currently, research is lacking as to how owners communicate specific sustainability objectives to designers and constructors. Furthermore, it is unclear what approaches owners utilize for differing delivery methods. This study examines 92 recent projects of varying delivery methods, collectively representing over $2.2 billion in vertical construction from 2006-2009. The objective is to determine current delivery and procurement trends specific to sustainability. A content analysis methodology was used to examine and codify specific language and techniques used in procurement documents for each project. This paper presents the resulting framework of four owner approaches for specifying sustainable goals: 1) sustainability by competition; 2) sustainability by specified level; 3) sustainability by qualifications only; and 4) sustainability by reference. Within this framework, trends are discussed across all delivery methods as well as trends specific to individual project delivery methods.

INTRODUCTION

The LEED rating system has become a popular metric for measuring the sustainable aspects of construction practices in the United States. The percentage of new construction projects evaluated by LEED (LEED-NC) has markedly increased throughout the 2000's as agencies and owners recognize the arguments for sustainable construction. This fact may be evidenced by the increased exposure in the design and construction community. Studies have shown that one in five designers have executed design services that have resulted in LEED certification as evaluated by the USGBC in 2006; up from a finding of one in ten designers in 2003 (BDC

2006). Sustainable construction has gained significant market share and shows no signs of slowing from this trend.

Current literature often suggests that the successful delivery of sustainable projects is largely dependent on design integration (Yudelson 2009, et al.). However, a relationship between project success and the use of integrated project delivery methods has yet to be established. In efforts to investigate this potential relationship, an understanding of current procurement practices specific to differing project delivery methods must first be established. The question remains, how do owners currently articulate sustainable objectives and on what merit do they acquire design and construction teams in relation to project delivery method? This study addresses this question through the development of a concise communication categorization system. Specifically, the study establishes commonalities and differences that exist in the current new construction sector for communicating sustainable objectives and selecting architects, engineers, and contractors in relation to project delivery methods.

BACKGROUND

The LEED rating system was developed by the USGBC in 1998 as an assessment tool for evaluating the performance of construction and design from a standpoint of sustainability. Specifically, the system focuses on the use of durable or recycled materials, reduction of energy consumption, reuse of land resources, and cooperation with other sustainable infrastructure goals. The current levels of certification include (in ascending order) Certified, Silver, Gold, and Platinum and are based on the number of points that are acquired in meeting the aforementioned focuses of the system (USGBC 2007). Currently, the LEED rating system is an accepted high performance rating system that is used to evaluate a significant portion of new construction within the United States.

A project delivery method defines the sequence of events, contractual obligations, participant relationships, and specific mechanisms for overseeing time, cost, and quality (Dorsey 1997). The three primary project delivery methods include Design-Bid-Build (DBB), Design-Build (DB), and Construction Manager at Risk (CMR). While there are variations and combinations of these delivery methods, this study addresses only these three major methods. DBB is considered to be the traditional method within the modern construction industry. In the DBB method, the owner acquires a design team that designs the project in its entirety prior to competitive bidding by prospective contractors. This method is most effective for projects in which "the design professional does not require the detailed knowledge of the means and methods of construction" (ASCE 2000). The DB process strongly differs from traditional delivery methods in that the owner selects a single entity that will be responsible for both the design and construction of the project. Design-build procurement methods vary greatly, but owners typically include qualifications, technical proposals, and cost in the selection. CMR shares some characteristics of both the DBB and DB methods. The owner holds individual contracts with the designer and the construction manager. The construction manager's contract has two

phases: preconstruction and construction. The owner selects the construction manager at risk early in the design process so that they may provide preconstruction services at a fee and then serve as the constructor upon negotiation of a reasonable price with the owner (ASCE 2000).

The influence of project delivery method on budget, schedule, and construction quality metrics in construction has been well established. In comparison of project delivery methods, researchers have shown that significant differences in the degree to which schedule, cost, and quality goals are met were heavily influenced by the level of team integration and the selected delivery method (Konchar and Sanvido 1998, Pocock, et al. 1996, Ling, et al. 2004). Specifically, these studies showed that integrated delivery methods that can facilitate a greater degree of early team integration were superior in meeting cost, schedule, and quality goals.

Similarly, several studies on designer and contractor integration were also performed with direct reference to their capabilities of better delivering projects in which sustainability was an objective. Initial studies showed that traditional delivery method strategies may not address the nuances of high performance buildings and may limit the ability of the contractor to contribute to the sustainable objectives (Lapinski, et al. 2006). Furthermore, increased lines of communication between the design team and the contractor, specifically in the areas of mechanical systems and energy modeling, were factors linked with successful high performance building projects (Riley, et al. 2005). A study on the performance metrics used to measure the success of project delivery methods in sustainable construction found that the time at which the contractor became involved was the key factor affecting all performance outcomes (Korkmaz 2007). Collectively, these studies are in consensus that early team integration is necessary for achieving high level sustainable objectives.

Conversely, studies have also shown that project delivery methods may not have as much to do with sustainable construction performance or cost efficiency as originally suggested, especially at lower LEED certification levels. One study found that the ability of integrated delivery systems, specifically the DB method, was no more capable of delivering LEED points or sustainable objectives than the traditional DBB delivery method for public jobs with lower certification levels (Carpenter 2005). Other studies found mixed results when comparing the project delivery methods as related to high performance construction. In one study comparing project delivery methods to high performance project success, DB was found to have attributes strongly associated with success but it was concluded that “a relationship between DB and green design did not explicitly emerge” (Bilec 2008). Furthermore, a significant amount of data variation existed regarding which delivery method was most appropriate and in what situation. While it is postulated by some that integrated delivery methods may be able to better deliver high performance building through their holistic approach, it appears that a consensus has yet to be established.

Multiple studies have produced divergent conclusions regarding the effects of project delivery methods on meeting sustainable construction objectives. As a precursor to

establishing the effects of project delivery method on sustainable delivery, current practices must first be defined. Knowledge of the common procurement procedures and language relating to project delivery methods will amplify the sustainable building body of knowledge regarding the current state of practice. Current trends in procurement documents can show how owners and designers articulate sustainable objectives both qualitatively and contractually. Furthermore, a study of procurement document language will provide owners, architects, engineers, and constructors with a greater understanding of common trends, potential advantages, and pitfalls to avoid when authoring procurement documents for future buildings.

RESEARCH APPROACH

The primary objective of this study was to identify current trends in procurement documents for projects in which sustainability was a goal; specifically, the identification of these trends in relation to delivery methods. To objectively identify trends in the language and techniques used to select project teams, a content analysis of solicitation document for which sustainability was a goal was chosen. A content analysis is defined as, "any technique for making inferences by objectively and systematically identifying specified characteristics of messages" (Holsti 1969). The documents used in the study were acquired from industry contacts, mass e-mailing efforts, public construction solicitation websites, and from internet search engines. The documents acquired were representative of the wide variety of high performance projects within the construction market from 2006 to 2009. Both public and private sector procurement documents were included, with public documents forming the majority of the sample due to the proprietary nature that is common with private documents. Representative documents were acquired for DBB, DB, and CMR projects. The DBB and CMR categories were then delineated further into procurement documents intended to acquire design services and those intended to acquire contractor services. The delivery method and LEED certification level demographics of the procurement documents analyzed are shown in Table 1. Analyzed projects are presented by owner classification in Table 2. The analyzed projects are approximately equally divided between the DBB, DB, and CMR delivery methods. Collectively they represent over $2.2 billion dollars in vertical construction work from 32 different states.

Table 1: Analyzed Projects by Delivery Method and LEED Certification Level

PDM / LEED Cert. Level	***Unspecified***	***Certified***	***Silver***	***Gold***	***Total***
DB	10	3	12	2	27
DBB (A/E)	10	1	7	1	19
DBB (GC)	0	3	9	1	13
CMR (A/E)	5	2	5	1	13
CMR (GC)	8	0	12	0	20
Total	33	9	45	5	92

Notes: Platinum level projects were included. The minimum level required in the documents is shown. "Unspecified" projects seek LEED certification but do not specify the desired level of certification.

Table 2: Analyzed Projects by Delivery Method and Owner Classification

PDM / Sector	Educ. (K-12)	Educ. (Univ.)	Gov't (Muni.)	Gov't (State/Fed)	Military	Other	Total
DB	2	6	4	2	11	2	27
DBB(A/E)	2	5	12	0	0	0	19
DBB (GC)	2	4	2	1	2	2	13
CMR(A/E)	1	6	4	0	0	2	13
CMR (GC)	0	8	8	4	0	0	20
Total	7	29	30	7	13	6	92

Traditional project demographics (location, size, cost, LEED level sought, etc.) were acquired from each set of documents. In addition to the demographics, two specific categories of interest were found in a pilot study. The time in the procurement process at which a certification level is decided upon was found to be a delineating factor in how owners communicate sustainable objectives. Some owners were found to reward designers and/or builders in a scored procurement process for higher LEED levels while others were found to communicate sustainable objectives by a set LEED level. Still others communicated that LEED certification was a goal, but indicated no desired magnitude of sustainability as measured by a certification level. Another delineating factor was found to be the manner in which owners communicate the desired level of experience of the designer and/or builder with LEED buildings. Some owners were found to require and/or score the experience level of designers and/or builders while others were found to require no experience. The required experience with LEED was further delineated into experience of the company, experience of specific personnel, or both. Subcategories and a coding system were developed to quantify the language differences addressing these issues. Per accepted content analysis protocol, each subcategory that is coded must be both "exclusive and exhaustive" (GAO 1996).

A hierarchy of categories for simplifying and presenting the content analysis results was established to emphasize the broad differences between differing project delivery methods. The first and highest category in the hierarchy is "sustainability by competition". Within this category, only projects that weight or score higher LEED certification levels within the procurement are included. This implies that owners utilizing this procurement style view the sustainable objectives of their projects with the utmost importance. The second category is "sustainability by specified level". Projects that are included in this category specify their sustainable objectives by a specific performance level (i.e. project shall achieve a LEED Gold certification…). The third category is "sustainability by quality". For projects to fall in this category they must not specify a specific LEED level to be met (whether mandated or evaluated) and must evaluate the designer and/or builder based on their experience or credentials for sustainable construction. The last and lowest category is "sustainability by reference". Projects within this category must not have specified a specific LEED level (whether mandated or evaluated) and not have evaluated the designer and/or builder based on their experience or credentials with sustainable

construction. This is the lowest category as it is implied that owners utilizing this procurement style value the sustainable building aspects of the project the least. Figure 1 depicts the coding categories, subcategories, and the filtering process.

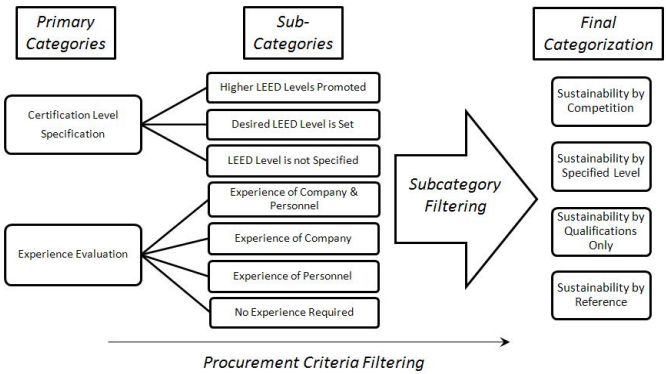


Figure 1: Procurement Document Categories and Filtering Process

This categorization and filtering system was used to delineate and classify key differences in how owners procure designers and/or builders with regards to different delivery methods. The results from this analysis are presented in the next section.

RESULTS AND DISCUSSION

Ninety-two procurement documents were analyzed through the content analysis approach. The content analysis examined each solicitation document through the coding system described in Figure 1. The results of this analysis describe the trends in communicating sustainability for each of the three delivery methods. Table 3 shows the results by sustainability communication category and by delivery method (results given in percentages). A discussion of the results by sustainability communication category follows.

Table 3: Study Results by PDM and Sustainability Communication Category

PDM / SC Category	***DB***	***DBB (A/E)***	***DBB (GC)***	***CMR (A/E)***	***CMR (GC)***	***ALL PDM***
Sustainability by Competition	14.8%	0.0%	0.0%	0.0%	0.0%	4.3%
Sustainability by Specified Level	55.5%	47.4%	100.0%	61.5%	60.0%	62.0%
Sustainability by Qualifications	14.8%	42.1%	0.0%	30.8%	40.0%	26.1%
Sustainability by Reference	14.8%	10.5%	0.0%	7.7%	0.0%	7.6%

Sustainability by Competition

As previously discussed, sustainability by competition most emphasizes the sustainable aspects of a project above the other categories as higher LEED certification levels are encouraged through a scored procurement system. The results show that sustainability by competition was the least used method for communicating sustainable project goals (4.3 percent of the sample population). It is also of interest that all data points in the "sustainability by competition" category (and representing 14.8 percent of the total DB study population) are DB projects. Given that the best value procurement process is quite common within DB projects and that integration between the design and construction entities is inherent within this delivery method, this finding is not remarkable. However, this finding presents a significant missed opportunity for the CMR delivery method as higher LEED levels could easily be implemented in a best value procurement method; a method often used in conjunction with the CMR delivery method. The practice of rewarding higher LEED levels in a design competition (qualifications based or best value procurement) could be implemented within the traditional DBB delivery method at the acquisition of the design team (the DBB A/E category) as well.

The absence of data points in this category representing the DBB delivery method at the acquisition of a contractor (the DBB G/C) is unsurprising. Given the design and construction differences needed for higher LEED levels and the clear separation of the design entity and the construction entity inherent with this PDM, a best-value bidding system for acquiring a contractor would likely require separate sets of bidding documents for each LEED level or extremely comprehensive plans for "add-alternate" pricing. This would likely increase error and omission exposure for the design entities through the need for more designs. This may also increase the likelihood for potential contract dispute for the owner for the same reasons.

Sustainability by Specified Level

The "sustainability by specified level" communication category was the most popular method for communicating sustainability goals across all of the project delivery methods (62 percent of the sample population). This category was also the most common method for communication within each individual project delivery method. This finding indicates that owners usually have well defined sustainability goals when acquiring designers and/or builders, regardless of the delivery method to be used. This practice for communicating goals is most profound for projects utilizing the DB delivery method, with 56 percent of the DB sample population using this method. Projects using the CMR delivery method specified a certification level to be sought for approximately 60 percent of the projects analyzed when acquiring the design or the constructing entity.

For the traditional DBB delivery method, a clear consensus was found in that owners only use a specified level when acquiring a contractor (the DBB GC category). As previously discussed, this finding is unremarkable as a method for seeking different certification levels is inherently difficult with this delivery method, due to the requirement for clear, error-free contract documents at the time of contractor bidding.

However, when owners acquire the design entity with this delivery method (the DBB A/E category), owners communicate sustainability goals by a specific level approximately as often as they acquire designers based on their experience alone (sustainability by qualifications only).

Sustainability by Qualifications Only

Acquiring designers and/or builders solely by their previous experience with LEED certified buildings was the second most used method. Twenty-six (26) percent of the total sample population vet designers and constructors by this method. Owners utilizing the DB delivery method use this form of communication for vetting design-builders as often as by competition (the highest form sustainability communication) and as by reference (the lowest form of sustainability communication).

Owners using the traditional DBB delivery method use previous experience as the qualification for hiring a design team as often approximately as often as they specify a specific certification level to be attained. However, when acquiring a contractor, owners do not appear to require any form of experience pertaining to LEED certified buildings. This represents a missed opportunity as previous experience requirements could be easily implemented in a prequalification process or a best value procurement process.

Owners utilizing the CMR delivery method when acquiring a designer or a contractor (the CMR A/E and GC categories) use previous experience with LEED buildings less than by a specified level in both categories, but more often than any of the remaining categories. Owners using the CMR delivery method appear to use this method for vetting potential contractors more often than when vetting designers.

Sustainability by Reference

As previously discussed, the sustainability by reference category is the lowest form of communicating sustainable aspects of a project. Procurement documents that use this strategy do not reward higher certification levels, do not specify a desired LEED certification level, and do not require previous LEED design or construction experience. Projects that fall in this category discuss the desire for LEED certification within the procurement documents but provide no indication for what the sustainable goals are or how they are to be met. While this method of communicating sustainable goals and ensuring sustainable goals was not common, it was not the least used method either. Eight (8) percent of the sample population, regardless of delivery method, was found to utilize this communication method. While performance of these methods for communicating and ensuring sustainability are beyond the scope of this study, it is hypothesized that this method may not allow the designer and/or builder to properly allocate personnel or budget resources for meeting the resulting certification level as the requirements for lower certification levels are much different than the requirements for the highest certification levels.

Examples of this communication method were only found when owners were acquiring design entities (assuming the DB projects leave significant design tasks to

be performed). No examples of this communication method were found when acquiring a contractor specifically (the DBB and CMR GC categories). This indicates that owners do not acquire a contractor without clear definition of the sustainable aspects of the project. It may also indicate that owners more often develop specific sustainability goals with the designer rather than the contractor. Projects that fell into this category occurred more often within the DB delivery method than with the other delivery methods.

CONCLUSIONS

This study investigated procurement documents to establish the current practices for articulating sustainable goals in current design and construction. Several trends were found for both the industry as a whole as well as within specific project delivery methods. The paragraphs that follow highlight the conclusions from this study regarding those trends. This study is ongoing and validation techniques are still in process.

Communicating sustainability goals by a specific LEED level ("sustainability by specified level") is the most common practice across all delivery methods. Sixty-two (62) percent of the analyzed projects were found to specify their sustainable goals by a set LEED level. This indicates that owners usually have well defined sustainability goals when acquiring designers and/or builders, regardless of the delivery method used. This finding is most profound within the DB delivery method with 56 percent of the DB sample population using this specification method. This was the sole form of articulation used by owners using the DBB delivery method when acquiring contractors, showing inflexibility for this delivery method with regards to sustainable construction. The popularity of this method of specification may be due to the increasing number of mandates for a specific LEED level to be achieved.

When creating procurement documents, some owners were found to set a base LEED certification level for the project but reward higher LEED levels through a scored procurement system ("sustainability by competition"). While this method for meeting sustainable objectives is best suited to integrated delivery methods, the only examples of this were found in DB projects. This finding represents a significant missed opportunity as it could be easily implemented in the DBB delivery method for the procurement of designers and the CMR delivery method for the procurement of both designers and constructors.

The vetting of designers and/or constructors solely through previous LEED building experience occurred in approximately one fourth of the projects analyzed. While this practice is somewhat common it could easily be used in addition to the other communication processes outlined in this study. One of the best candidates for implementation of this practice is the traditional DBB delivery method when acquiring a contractor. This practice could be easily applied through a prequalification or a best-value procurement process.

The communication of the desire for sustainable aspects of a project without clear definition of those goals or experience requirements ("sustainability by reference") occurred in approximately one out of every ten projects analyzed. While this study does not measure delivery effectiveness or performance, it is probable that this practice does not provide designers and/or constructors with adequate information to properly allocate personnel and financial resources for meeting the sustainable objectives of the project. For this reason, this method of communicating sustainable objectives would not appear to be prudent.

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A Unified Process Approach to Healthcare Project Delivery: Synergies between Greening Strategies, Lean Principles and BIM

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Abstract:
The healthcare industry is one of the most significant built environment markets today with over 120,000 buildings in the United States. In spite of the recent decrease in construction spending, it is estimated that healthcare construction will rise dramatically in the next 10 years. Therefore, there is a great opportunity for improvements to be made in this market segment. Healthcare facilities are amongst the most complex facilities to design, construct and operate. Green healthcare can enable improved clinical outcomes, lower operating costs, energy consumption and water use. Lean principles emphasize whole process optimization through collaboration, continuous improvement, elimination of waste and a focus on delivering the value desired by the end-user (patients). Patients are a very special category of end-users, and their needs and health are the highest priority. The complicated healthcare building delivery system can benefit from focusing on the value adding activities and eliminating the wasteful ones. Building Information Modeling (BIM) can be very beneficial for healthcare projects because of the complexity within the building systems in terms of indoor environmental quality, cooling and heating loads, and also the large quantity of medical equipment. This paper examines the synergies existent in the healthcare construction market segment in terms of greening strategies, lean principles and BIM during the programming and early design stages of a project to provide a combined benefit greater than the sum of their individual benefits. A conceptual model is presented to improve healthcare facility delivery. Additionally, a research plan for future work is outlined and explained, and conclusions are drawn.

Keywords:
Sustainability; healthcare design and construction; process; lean principles, BIM

1. Background

In the United States, the healthcare industry accounts for 15.2 % of the gross domestic product (GDP) with projected growth based on historical trends to 20% by 2018 (CMS Office of Public Affairs, 2008). The economic recession has slowed the healthcare construction boom, but it is projected to rise by 25% in the next five years(CMS Office of Public Affairs, 2008). In the United States, healthcare construction is a $17 billion market. The tremendous size and growth provide great opportunities to impact how the built environment affects human health and wellbeing.

1.1 Sustainability in Healthcare

In the last few decades, the idea of **sustainability** has been associated with the integration of economic, social and environmental principles. In terms of healthcare, the "greening" and sustainability of healthcare facilities can provide numerous benefits. It can provide (Ulrich et al, 2004):

- health benefits by improving clinical outcomes
- economic benefits by decreasing energy and water usage
- environmental benefits by using natural materials instead of chemical choices.

Most important of these, however, are the benefits that lead to clinical outcomes. For these reasons, it is crucial that our healthcare facilities are designed, constructed and operated appropriately to assure dependable performance.

1.2 Lean Principles

In the building industry, many green buildings fail to fulfill their initial goals due to wasteful approaches that are used to design, construct and operate them. A focus on the whole building delivery process looking at value added activities and waste, facilitates an opportunity to enhance the building delivery process (Horman 2006).
The main **principles of lean** construction are:

- Whole process optimization through collaboration and systematic learning
- Continual improvement/pursuit of perfection involving everyone in the system
- A focus on delivering the value desired by the end-user /owner/client/
- Allowing value to flow by systematically eliminating obstacles to value creation and those parts of the process that create no value
- Creating pull production (Lean Construction Institute, 2008)

The complex healthcare construction market segment can greatly benefit from the adoption of lean principles throughout their design, construction and also operations long after the facility has been built. Patients and a very special category of end-users of the facility, and their needs, health and value desired are the highest priority.

1.3 Building Information Modeling in Healthcare

Building Information Modeling (BIM) is the process of generating and managing building data during its life cycle (Lee 2006). The National Building Information Modeling Standards (NBIMS) Committee defines BIM as "*a digital representation of*

physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder (NIBS, 2007)."

2. Hypothesis and Scope

Healthcare projects that integrate BIM and lean methods during the planning and design stages of a green healthcare facility will have better project outcomes in terms of cost, schedule, project stakeholder satisfaction. The full potential of lean principles, BIM and sustainability are achieved only when used together.

This research is focusing on the planning and early design stages of a project due to decisions being made during these stages having the highest effect and value on project performance later as seen in Figure 1 below.

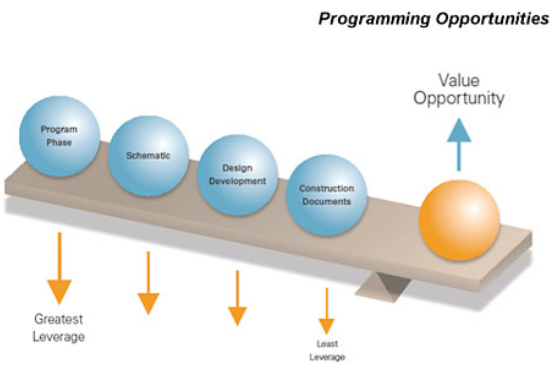


Figure 1: Leverage of Building Delivery Phases (WBDG, 2009)

3. Objectives

The main objective of this paper is to examine the existing strategies and principles within the healthcare construction market segment in terms of greening strategies, lean principles and BIM and to provide a conceptual model for incorporating them as a unified process approach to healthcare. The following will also be explored:

1. Examine relationships between lean and green and BIM during the programming/ early design stages of healthcare facilities.
2. Determine factors that drive the use of green strategies, BIM, and lean strategies
3. Develop a conceptual model for healthcare delivery, and validate and test it using the case studies available and experts in the field

4. Conceptual Model

The following figure depicts an overview of the principles investigated for this research and an individual focus for each. Assumptions and definitions in terms of the main topics of this study are outlined below.

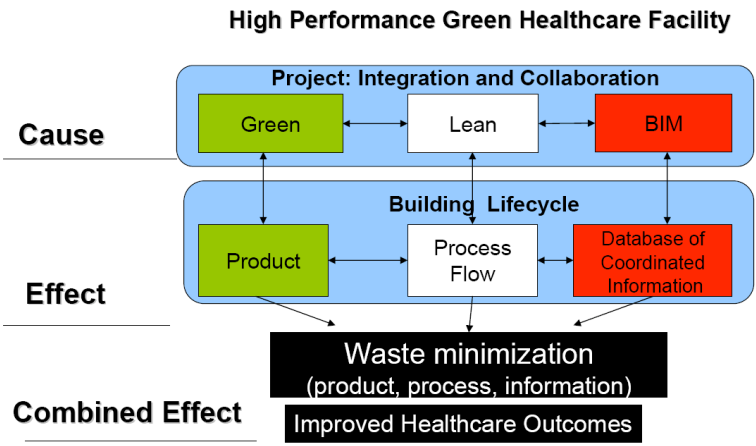


Figure 2: High Performance Green Healthcare Model

4.1 Greening Strategies

Green for this research is defined by the following aspects that focus on **products/ systems:**

- Energy efficiency: healthcare facilities operate 24 h throughout the year and use tremendous amounts of energy. Every $1 a non-profit hospital saves on energy is equivalent to generating $20 in new revenue, according to the Department of Energy. (Wood 2008)
- Indoor environmental quality: daylighting and views, thermal comfort, ventilation
- Sustainable site: orientation, geometry, natural habitat
- Water Efficiency: reduction in potable water usage and innovative wastewater technologies.
- Green materials: use of healthy, durable and renewable materials

4.2 Lean Principles

Lean is defined by the elimination of waste in **processes**:

Design process waste (adapted from Womack 2003):

• Rework: correcting any errors or doing the same work multiple times
• Processing: over-processing, unnecessary steps, reviews
• Waiting for signatures, for meetings
• Overproduction: Producing too much or producing too soon
• Intellect: any failure to fully utilize the time and talents of the people
• Motion: any motion that does not add value; e.g. re-entering the same information more than once
• Inventory: any more than the minimum to get the job done
• Transportation: any non essential transport is waste

The processes stated above should be applied during all the stages in the delivery of a building, from programming, design to construction and operations. These processes become crucial in a healthcare facility in terms of the operational procedures. Some of them are noted below:

Operational Processes

• Workflow of spaces – patient flow within and between departments
• Emergency room work throughput
• Workplace organization
• Inventory control
• Scheduling processes and systems
• Surgical flow improvements and organization
• Admitting/ discharge

Consideration and implementation from the project teams for the following issues should be given during the programming and early design stages of the project.

4.3 Building Information Modeling

Building Information Modeling is defined for this project as **a tool** used to generate and manage building **information** during its life cycle..It can aid with information regarding:

- Repetitive functions that can lead to creating prototypical design solutions.
- Precision required in meeting the functional requirements of a healthcare facility, including expensive medical equipment
- Constant flow of people, materials and information during the use phase which can be simulated and studied during design phase through BIM.
- A single information model of the facility can support teamwork and collaboration during design and construction phases of the facility.
- Integration of architectural design and engineering design for new facilities as well as for remodeling of and additions to existing healthcare facilities.

- 3-D models of the facility as built can support facility operations and management team, a critical component of BIM use by healthcare industry.

Figure 2 below shows a graphical representation of the important factors investigated in this research. An optimum facility is achieved if the three main areas, greening strategies, lean principles and BIM are integrated in the programming and planning stages of the building delivery process. An optimum healthcare facility is a facility that is delivered fast, accurately, effectively and aids the healing of patients.

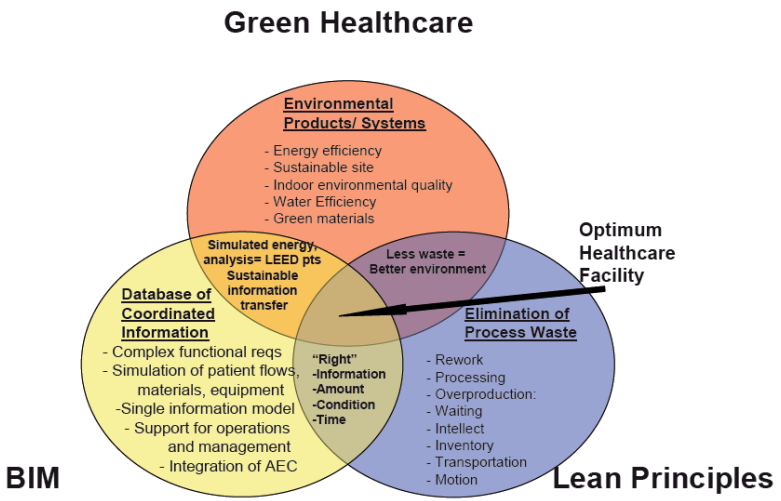


Figure 3: Integration of Green, Lean and BIM

5. Why do Hospitals need "Green", "Lean" and BIM?

Many hospitals are struggling. Healthcare facilities are the most challenging types of facilities to plan, design, construct and operate. These facilities usually support very sensitive and costly activities such as patient treatment, laboratory and research testing, waste treatment (incineration and autoclaving), and food preparation. Hospitals house distribution facilities, and support spaces for healthcare professionals, and need extremely sophisticated and large building equipment to ensure these activities and facilities run reliably and without cross contamination.

The cost of care is going up. Patient injuries and deaths due to preventable errors are happening far too often in hospitals. Hospital employees, nurses and doctors are often frustrated with the problems they face every day. Lean is a methodology that allows

hospitals to improve quality of care by reducing errors and waiting times. Lean helps eliminate roadblocks to allow a focus on providing care. Lean has the potential to reduce costs and risks but also facilitating growth and expansion (Graban, 2009). Most of the lean principles are incorporated in the planning and programming stages of a facility. The design team has an important role in facilitating the upkeep of these strategies. Healthcare facilities need to be designed with a focus on what matters most, which is the health, and well being of patients and staff and clinical outcomes. As an example, time that nurses get to spend with a patient can be greatly increased if the time a nurse walks throughout the day in the facility can be reduced. It is estimated that a nurse walks 4-6 miles in a 10 h daily shift (Harvey 2009). Using lean principles in the physical design solutions of the building could reduce this time, and therefore nurses could spend more time at the patients' bedside. The facility should be designed with scenario simulations, and layout design that improves operational processes within the hospital. Flow space, storage space, work space (process space) and utilities (bathrooms, staff lounges) should all be taken into account. Research shows that with improved processes, a new facility could be built with 25% fewer OR rooms, representing significant reduction in design and construction costs (Benner 2009).

A lot of green building processes have great amounts of wasteful rework, delays, changes and overproduction due to inappropriate delivery processes. Process waste can undermine sustainable outcomes and limit the business case for sustainability (Lapinki 2005). If process waste is decreased in the delivery of green buildings, then sustainable strategies could be used without the higher first costs.

The build environment has a vast impact on the healthcare and well being of patients and staff. Healthcare facilities are places where people are treated and healed. In some cases though, healthcare facilities are responsible for inducing health problems. One example is hospital acquired infections or nosocomial infections. Hospital-acquired infections can be caused by bacteria, viruses, fungi, or parasites. These microorganisms may already be present in the patient's body or may come from the environment, contaminated hospital equipment, health care workers, or other patients. (Frampton 2003) The alarming fact is that hospital acquired-infections are one of the leading causes of death in the United States, killing more people than car accidents, AIDS and breast cancer combined. It's been estimated that patients who contract an infection in the hospital stay an average of 20.6 days compared with 4.5 days for other patients, and their hospital stays cost six times more. The estimates for society as a whole range from $5 to $30.5 billion every year. (Frampton 2003) Other research and case studies show that poor ventilation and indoor environmental quality are major causes of nosocomial infections. Improper lighting is correlated with patient depression and medication errors (Bendetti 2001). Similarly, noise upsets patients and causes increased stress and lack of sleep (Johnson 2001). These examples show the great impact greening strategies and the built environment can have on the operations of a healthcare facility.

BIM seems most beneficial for the healthcare industry because of the complexity within the building systems in terms of indoor environmental quality, cooling and heating loads, and also the countless medical equipment. Cost and schedule are crucial in the delivery of healthcare facilities and also quality control can make a difference between life and death. Other benefits of BIM stated by industry professionals include the ability to simulate process and material distribution, patient and staff flow, M/E/P activities, ability to manipulate a room in front of a user group and how all these activities interrelate (Barista 2007).

In addition to its complexity in terms of systems, a hospital is the only type of building constantly under construction, "with ongoing renovation and expansion to accommodate new modalities, new protocols, new technologies". (Cooper 2007) In addition to the design and construction benefits, BIM aids with the facility management in order to control risk, errors and maintaining patient safety by anticipating problems that need to be solved ahead of time so it becomes a living "repository" of information.

6. Research Methodology and Future Work

This initial conceptual model will be investigated and validated further with a case study research methodology. A **multiple case study approach** is the main research strategy for this study. Three case studies representing healthcare facilities in the design phases will be used. The case studies investigated are exploratory because they are one of the very few LEED Gold certified hospitals in the nation, and also incorporating BIM and lean strategies, and therefore this study allows us to gain more insight into their building delivery process. All three case studies are LEED Gold certified, and they have different areas (green, BIM or lean) as their main focus.

The results of this multiple case study exploratory design will provide insight into the delivery of high performance green healthcare facilities. The three case studies are used for multi-perspective analyses. This indicates that this research considers not just the voice and perspective of the stakeholders involved in the delivery of the projects, but also of the relevant groups of stakeholders and the interaction between them.

Further objectives of this study include:

1. Identify specific examples of synergies and patterns of the synergistic benefits for projects that are adopting this framework through the case study research.
    - Identify roles in the planning/ design process of stakeholders involved with greening/ lean/ BIM issues in the case studies investigated
        - Which stakeholder is responsible for what aspect?
        - Who is the driver within the process?
    - Determine factors that drive the use of green strategies/ BIM/ lean within the case studies investigated?
        - Why are these projects using these strategies?
        - Is it decreased cost, improved health outcomes, increased productivity, increased collaboration, increased quality?

   - To validate the conceptual model and test it using the case studies available and experts in the field
2. Capture strategies for implementation through the case study research and convey them through the use of a process map
   - Develop a planning/ design process model - planning guide that defines "when, who, why, where" decisions regarding green attributes, lean principles and BIM should be incorporated.

The data will be collected by performing interviews with the following stakeholders: owner, architect, engineering firm, construction manager, LEED champion, BIM expertand lean consultant. Other strategies for data collection include observational studies during meetings, using vignettes to uncover the synergies and document analysis such as the LEED checklist, lean audit and BIM model.

The main methods used to analyze the findings in this research study will involve content analysis, comparative analysis based on pattern-matching and cross case analysis. Process maps will be used to analyze "when" and "what" critical issues happened during the building delivery of the facilities. The critical processes and events in the programming and early design stages for each hospital will be modeled and compared. Process modeling is the critical step in analyzing and understanding the delivery processes.
The final product of this research includes the patterns of the synergistic benefits in terms of the three aspects, and a process map that conveys when key decisions regarding green attributes, lean principles and BIM should be incorporated, "how" and "who" ahould be performing them.

7. Conclusions

This paper has presented an initial conceptual model for the building delivery of healthcare facilities by integrating greening strategies, lean principles and Building Information Modeling. From a whole-building approach perspective it is necessary that these issues be integrated throughout the delivery of a healthcare facility in order to ensure optimum performance. The programming and early design stages are crucial in making decisions. Healthcare facilities run 24 hours, using tremendous amounts of energy, and they are some of the most complex facilities to plan, design, construct and operate. By incorporating these strategies, we can deliver healthcare facilities fast, effectively and efficiently to enhance healing.

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Dedication: In loving memory of my late advisor Dr. Michael Horman. I will always be grateful for his guidance, friendship, dedication and expertise throughout my work here at Penn State, and for encouraging me to pursue my PhD.

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AN INTEGRATED CONDITION ASSESSMENT MODEL FOR BUILDINGS

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ABSTRACT

Building facilities are a major part of urban infrastructure, as they provide shelter, living space, and service areas to accommodate human activity. Despite their great economic, cultural and historical importance, many studies have shown that buildings are sick, deteriorating and considered to be a major source of pollution. Lack of funds and mismanagement are the principle reasons for the unsatisfactory performance of building facilities. Maintaining a building is essential to keep it performing and functioning for a longer period of time. Despite the importance of the condition assessment (CA) stage in the asset management process, a literature review reveals that there is no building assessment framework that considers both physical and environmental conditions. The objective of this paper is to develop an integrated CA model that integrates both the physical and environmental aspects of buildings. This model provides an accurate, reliable, and sustainable framework capable of assessing a building from both physical and environmental perspectives. The framework is to be implemented and tested using data collected from experts as well as from operation systems for existing office buildings in North America. Details of the proposed framework and its implementation are presented. The research work in this paper assists facility managers and owner's organizations in administrating such buildings.

INTRODUCTION

Building facilities play a major role in any country's urban infrastructure, as they provide physical support services, shelter, and accommodation for human activity. Despite the great historical, cultural and economic importance of these buildings, there is mounting evidence that they are deteriorating and are in an unsatisfactory situation due to lack of funds and poor or mismanagement (Hudson et al. 1997). The estimated maintenance and repair expenditure requirements, when

added to the capital renewal budget in Canada are about CDN$ 196.5 billion per year, which is almost double the current value of new construction at approximately CDN$ 100 billion (Vanier, 2000).

Unfortunately, more emphasis has been placed on new construction for the past three decades, without adequate attention to the cost of maintenance and operation of existing buildings (Johnson and Clayton, 1998), and as a result, many organizations will have more facilities than they can afford to maintain. Existing buildings should provide high-quality and comfortable indoor environments in order to fulfill the occupant's needs. Furthermore, a building's indoor environmental quality (IEQ), which includes thermal, light, acoustics, and air quality factors, is considered to be one of the most important factors affecting occupant's assessment of their quality of life. Indoor air quality has been ranked among the top four environmental risks posing a significant threat to public health in the United States. It has been reported that indoor environments are more sensitive than outdoor air, even in the most industrialized areas (Godish, 1995). In addition to the evidence that people spend most of their time in indoor environments, poor Indoor Air Quality (IAQ) costs tens of billions of dollars every year. The cost of absenteeism in the workplace in the U.S. is estimated to be $12.4 to 24.8 billion/year, while the cost of the reduced productivity of the non-absent workers at work is estimated to be $1.5 to 3.1 billion/year (Levin, 1999).

Facility managers, in their day-to-day management and operation of buildings, contribute significantly to the creation of a healthy working and living environment for building users. Lack of funds, poor and mismanagement are the main reasons for the unsatisfactory performance of building facilities. Maintaining a building is essential to keep it performing and functioning for a longer period of time. Condition assessment is the most important stage during the asset management process. It is the starting point for the other stages – determining where it will be necessary to decide when to repair, rehabilitate or replace any component in the building.

Not much research in the area of building condition assessment has been reported in the literature; moreover, no study has conducted a combined study of both the physical and environmental factors. There is a need to develop a model that combines the physical and the environmental aspects of buildings. The scope of the present study is to investigate the various building systems and components, as well as the different indoor environmental quality factors. The objective of this paper is to develop an integrated condition assessment model that considers buildings' physical and environmental aspects. The results of the research presented in this paper will assist facility managers and owner's organizations in administrating their buildings.

BACKGROUND

Infrastructure deterioration can be the result of many factors interacting together and affecting the infrastructure itself. In the literature these factors are classified as physical, environmental, and operational, and they are responsible for infrastructure interaction (Al-Barqawi and zayed, 2006). Condition assessment is the way to determine the state of existing infrastructure facilities, which is a necessary step for facility managers to then plan for future maintenance, repair, rehabilitation, or replacement. It can be defined in different ways; it was defined by the NCES (2003) as the basis for determining the level of preventive maintenance needed for a

building's systems and components. According to Elhakeem (2005), the four main aspects needed to make a CA for any asset are asset hierarchy, evaluation mechanism, field inspection, and condition analysis. Several researchers have developed deficiency lists for inspection either by paper or electronic formats; however, visual inspection is most appropriate for buildings (Ahluwalia, 2008). Elhakeem and Hegazy (2005) developed a system for the CA of building infrastructure using a visual guidance approach to make the process faster, less subjective, and suitable for less experienced people. Ahluwalia (2008) proposed a framework that predicts the condition based on the available maintenance records combined with a visual guidance system, as well as location-based inspection with standardized building hierarchy. The framework focused on process automation to meet the needs of large organizations with limited resources. Langevine (2002) applied the AHP technique to the building hierarchy and several criteria were used to determine the relative importance of each building system/component in terms of each criterion. All of these models, systems and processes were applied only on the physical elements inside the buildings and didn't include the quality of indoor environment.

The concept of environmental quality involves both human and physical factors, which operate at different spatial scales (Hoon Yoon, 2008). The human-environment interaction is complex and affects many aspects of our daily activities. Different means of the environmental conditions interpretations has led to the development of different concepts, such as the "sick building syndrome" as well as the various studies undertaken in the field of indoor environmental quality (IEQ). Indoor environmental quality has been defined in different ways; it was defined as an essential part of the broader concept of "quality of life" --the basic qualities such as health and safety in combination with aspects such as coziness and attractiveness (RIVM, 2002). The environmental quality of buildings refers to "the provision of comfortable lighting, acoustics, thermal and indoor air quality for occupants, improving the residential quality for building occupants" (Davis, 1986). There has not been much work done in modeling the different environmental factors and studying the relationships between them. Campbell (1976) developed a model in which life satisfaction is viewed as the sum of the satisfaction with different environmental domains. The results of the satisfaction degrees were from a process of appraisal, perception, evaluation, and copying behavior. However, most approaches to environmental quality assessment do not comprehensively consider the various environmental quality factors. Hoon Yoon (2008) developed models that provide an integration of all the environmental quality factors in buildings. He suggested weighting factors for the integrative evaluation of all the physical environmental factors based on the responses to his survey conducted to measure respondents' environmental quality priorities. Ahmed (1994) developed an expert system that evaluates the environmental quality of office buildings as an integrated approach. He conducted a survey in the academic and industrial sectors to assign weights for the different environmental quality factors. The developed models and systems focused only on the environmental, personal and social aspects for the occupants inside a building, and do not address the relationship between building systems and the indoor environmental quality. This is an important issue that needs to be addressed.

RESEARCH OBJECTIVES AND METHODOLOGY

The objective of the research presented is to develop an integrated condition assessment model that considers the physical and the environmental aspects of buildings. It will assist facility managers and owner's organizations in their administration of buildings. In order to develop an integrated condition assessment model that considers both the physical and environmental aspects of buildings, the research methodology was divided into 3 main parts which are integrated at the end to give the final combined condition rating. The methodology is based on managing a building according to its spaces; where space is the principle evaluated element, according to its internal physical elements as well as its indoor environmental quality. Figure 1 illustrates the methodology's concept and shows the main component as highlighted below:

1- Spaces inside the building and their ranking
2- Physical Assessment
3- Environmental Assessment

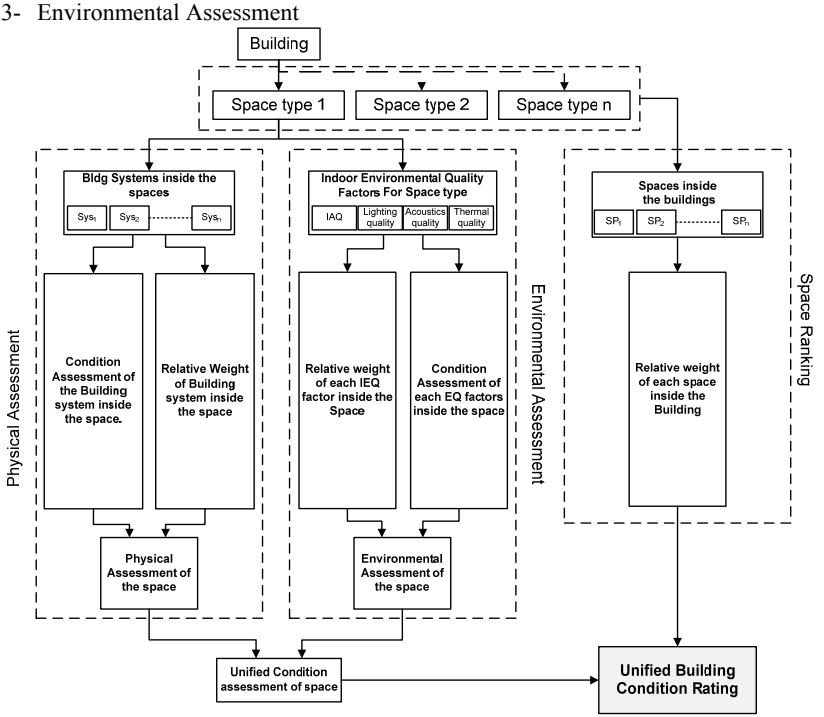


Figure 1: The methodology of developing the condition assessment

MODEL DATA ACQUISITION

It was found, from the literature, that there is no standardized data for all the different weights of the spaces, as well as for the systems and IEQF inside the spaces. In order to overcome this problem, this study adopts an expert subjective system based on Saaty's (1991) analytical hierarchy process (AHP) approach. The weights of

each space inside the building, weights of each system inside the space type, and the weight of each indoor environmental quality factor (IEQF) inside the space are estimated using the Eigen Vector method (EV). The Analytical hierarchy process (AHP) and the Simple Multi Attribute Rating Technique (SMART) will be combined to develop the integrated condition rating model

1- Spaces in the building and their ranking

Each building type consists of a certain number of spaces which represents the different functions held inside the building; B = {SP1, SP2…..SPn}. Each space type has its own characteristics and requirements; moreover each space has its own relative importance compared to others in a specific building type and according to many factors; for example the function of the space, the number of occupants, the frequency and the duration of usage, etc. The study identifies the relative importance of each space type inside a building. The data is collected in the form of a survey sent to experts. The data is analyzed using the AHP technique, in which the relative importance weight of each space type is calculated using the Eigenvector approach. Figure 2 shows the process of prioritizing the spaces and having a relative importance for each space with respect to the others inside the building type.

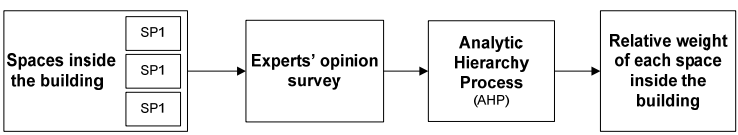


Figure 2: The process of prioritizing spaces inside a building

2- Condition assessment of physical elements (Physical Assessment)

The definition of physical assessment, within this research, is the inspection and evaluation of the physical elements inside each space (SP); represented by the different building systems; SP_i = {Sys_1, Sys_2…..Sys_m}. Assessing the physical condition of each system in a way that can evaluate building components can provide very useful information to an asset manager. In order to assess the physical condition of a building space, both the identification of the different building systems in each space and the asset hierarchy must be determined at the outset. The objective of asset hierarchy is to classify and cluster these components under different categories. For example, a building can be classified into different systems (HVAC, superstructure, finishing, etc.) at the primary level and then to a subsystem level, eventually reaching the component level. Direct condition rating is the approach selected for evaluating the condition of any component inside a building. Finally, weights are formulated for each subsystem and component, based on their functional importance to the overall condition of the system. Figure 3 shows the process of assessing the physical elements inside a building.

Condition assessment

i. Identify the list of deficiencies that should be assessed in each building system inside the space type.
ii. Set a condition index scale which is used to assign a value that represents the system condition. This scale is used to represent the numeric values related to the linguistic representation. The scale is from 0 to 100; where 0 is failure and 100 is excellent condition.

iii. Calculate a CA of each building system inside the space ($C.Sys_{ji}$.)

Relative weight

iv. Make a pair wise comparison as a questionnaire; the expert should identify the weight of each building system with respect to the other inside of a particular space type.

v. Apply the Analytical hierarchy process (AHP) to obtain the relative importance weight of each building system inside the space type ($W.Sys_{ji}$) using the Eigen-vector approach.

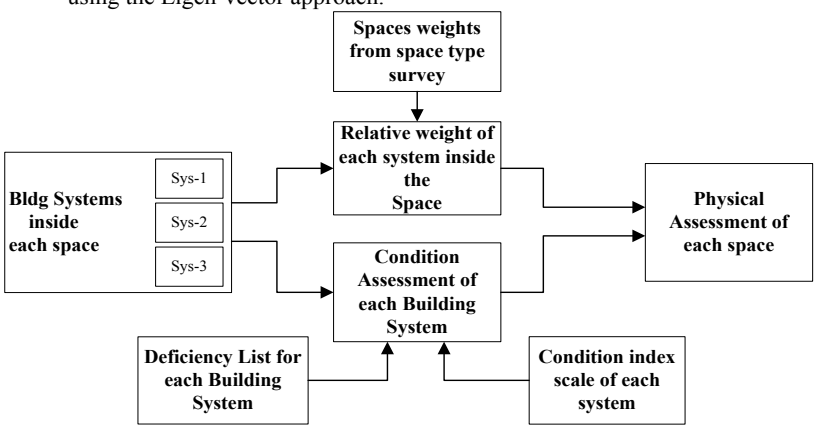


Figure 3: The process of assessing the physical elements inside a space

By multiplying the condition of the system inside the space by its weight a physical condition assessment of the space can be calculated, as shown below in equation 1:

$$\boldsymbol{PC\ (SP_i) = \sum_{j=1}^{m} C.Sys_{ji} \times W.Sys_{ji}} \qquad \textbf{[1]}$$

Where:

PC (SPi) is the physical condition inside the space,
C. Sys_{ji} is the condition of each building system inside the space, and
W. Sys_{ji} is the relative weight of the system inside the space.

3. Condition assessment of environmental quality (Environmental Assessment)

The environmental assessment as performed within this research is to measure and inspect the indoor environmental quality of the building. The Indoor Environmental Quality (IEQ) of a building is divided into four main categories, each of which is an indoor environmental quality factor (IEQF): (1) indoor air quality, (2) thermal quality, (3) lighting quality, and (4) acoustics quality. In other words, each space has four different IEQFs to be measured and they are represented as follows: SPi = {$IEQF_1$, $IEQF_2$…..$IEQF_l$. Figure 4 shows the process of assessing the physical elements inside a building.

Condition assessment

i. Identify the different measurement variables of each IEQF in the space type. For example, the indoor air quality should measure the different air pollutants that

affect health; such as the amounts of carbon dioxide, carbon monoxide, ozone, radon, etc.

ii. Set the benchmarks and the acceptable ranges of each IEQF. Develop a scale which represents the critical and the acceptable regions.

iii. Calculate the condition assessment of each IEQF inside the space type.

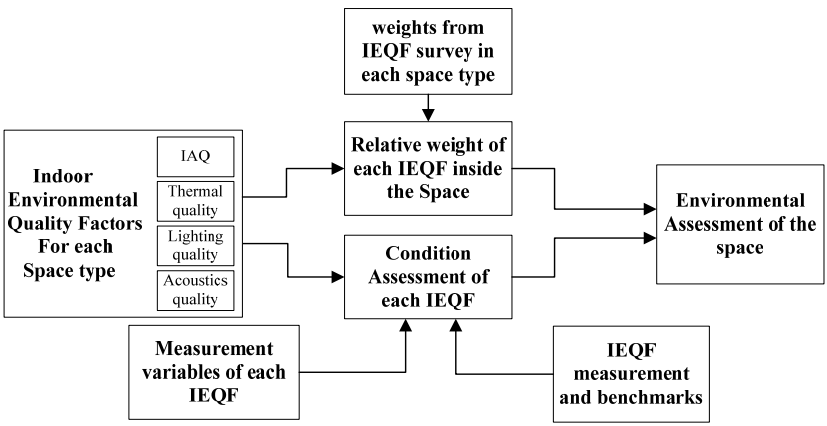


Figure 4: The the process of assessing the physical elements inside a building

Relative weight

i. Make a pair wise comparison as a questionnaire; experts should identify the weight of each IEQF with respect to other factors inside the space type.

ii. Apply the analytical hierarchy process (AHP) to obtain the relative weight of each IEQF inside the space type.

The environmental assessment of the space is calculated by multiplying the relative weight of each indoor environmental quality factor by its own weight, as shown in equation 2.

$$\boldsymbol{EC\ (SP_i) = \sum_{K=1}^{l} C.EQF_{Ki} \times W.EQF_{Ki}} \quad \textbf{[2]}$$

Where:

$EC\ (SP_i)$ is the environmental condition inside the space,

$C.\ EQF_{Ki}$ is the condition of each environmental quality factor inside the space, and

$W.\ EQF_{Ki}$ is the relative weight of the environmental quality factor inside the space.

4- Unified condition model of space

The unified condition of the space [C (SPi)] is composed of both the physical [PC (SPi)] and the environmental [EC (SPi] conditions inside the space. A questionnaire survey is made in order to find the relative importance between the physical and the environmental conditions inside each space.

Finally, by multiplying the physical or the environmental conditions by their relative weight in each space, the unified condition of the space is calculated as shown below in equation 3:

$$\boldsymbol{C(SP_i) = PC\ (SPi) \times W_p + EC\ (SPi) \times W_E} \quad \textbf{[3]}$$

Where:

$C(SP_i)$ is the unified condition inside the space,
W_p is the relative weight of the physical assessment inside the space, and
W_E is the relative weight of the environmental assessment inside the space.

5. Condition assessment of a building

The condition assessment of a building is the integration of the unified condition assessment of its spaces. Each space has a unified condition assessment calculated from the unified condition space model as well as the relative weight from the space-ranking questionnaire, as shown the following equation.

$$\boldsymbol{C\ (B) = \sum_{i=1}^{n} C(SP_i) \times W.(SP_i)} \quad \textbf{[4]}$$

Where:
$C(B)$ is the unified condition of the whole building, and
$W.(SP_i)$ is the weight of each space inside the building.

ILLUSTRATIVE EXAMPLE

The following is a hypothetical example to present and demonstrate the application of the developed model for buildings. In order to apply the previous methodology for a small office building, it should be identified first via experts' opinions survey the relative weights of all the spaces compared to others inside the building, the relative weights of the indoor environmental quality factors inside the space, as well as the relative weights of each building system inside the space. The office is a one floor building which hosts the following spaces inside: office work space, meeting room, reception, storage and wet area. Tables 1 and 2 represent the relative importance for the previous elements, which can be got by the Eigen Vector method (EV) from the experts' survey.

Table 1: The relative importance of spaces inside the building

Space code	Spaces SP_i	Priority Weights	Priority Ranking
Sp_1	Office space	0.30	1
Sp_2	Meeting space	0.22	2
Sp_3	Wet area	0.18	3
Sp_4	Reception	0.22	2
Sp_5	Storage	0.8	4
Total :		1.00	

Table 2: The relative importance of IEQFs and Building Systems inside each space

Spaces SP_i	Weights of each IEQF $W.EQF_{Ki}$				Weights of each Building System $W.EQF_{Ki}$			
	IAQ	Interior	Elec.	Plumbing	HVAC	Acoustics	Thermal	Light
Office space	0.30	0.20	0.20	0.30	0.20	0.35	0.0	0.45
Meeting space	0.30	0.15	0.25	0.30	0.25	0.30	0.0	0.45
Wet area	0.45	0.15	0.20	0.20	0.10	0.20	0.50	0.25
Reception	0.35	0.10	0.20	0.35	0.40	0.30	0.0	0.30
Storage	0.20	0.0	0.20	0.60	0.15	0.60	0.0	0.25

The next step is to make the condition assessment for both the building systems and the indoor environmental quality factors (IEQFs) inside each space. The building systems will be assessed by the direct condition rating technique through the building

inspection process, while the IEQFs will be assessed using their special measurement devices and sensors.

Each Building system and indoor environmental quality factor has its own evaluation scheme; those evaluation schemes are based on either physical or environmental rational. Based on the Simple Multi Attribute Rating Technique (SMART) the condition rating of each individual is based on one generic 5 points scale with 0 represent "very bad" and 1 represents "very good" conditions. Table 3; represents the condition rating based on the building inspection process.

Table 3: Condition rating of IEQFs and Building Systems inside each space

Spaces SP_i	Condition Rating of each IEQF $C.EQF_{Ki}$				Condition Rating of each Building System $C.Sys_{ji}$			
	IAQ	Interior	Elec.	Plumbing	HVAC	Acoustics	Thermal	Light
Office space	0.25	0.5	0.25	0.5	0.75	0.5	0.75	0.5
Meeting space	0.25	0.75	0.25	1.0	0.5	1.0	0.5	0.75
Wet area	0.5	0.75	0.75	0.25	1.0	0.25	1.0	0.75
Reception	1.0	0.25	1.0	0.5	0.75	0.5	0.5	0.25
Storage	0.75	0.5	0.75	0.5	0.5	0.5	0.5	0.5

Physical condition [*PC (SPi)*] is to be calculated using equation 1, while the environmental condition [*EC (SPi)*] is to be calculated using equation 2.The Unified Condition of the space [*C (SPi)*] is to be calculated using equation 3. This equation combines both, the physical and environmental conditions together by multiplying them by their relative weights found by the questionnaire survey conducted. The overall condition assessment of the building [*C (B)*] is calculated as shown below using equation 4. It is calculated by multiplying the unified condition assessment of each space inside the building by its relative weight from the spaces' priorities.

DISCUSSION AND CONCLUSION

This research addresses the importance of studying the indoor environmental quality of buildings (IEQ) and how it affects the user's quality of life. The appropriate levels of these indoor environmental quality factors (IEQF) can increase occupants' satisfaction, increase employees' productivity, and decrease the rate of absence in working environments. However, there is a significant problem due to the deterioration, inadequacy, and insufficiency of the existing infrastructures in North America. Since the scope of this paper is limited to buildings, the research methodology is based on inspecting and evaluating buildings according to both the physical and the environmental aspects. The methodology is based on managing a building according to its spaces; where space is the research major element, evaluated according to its internal physical elements as well as its indoor environmental quality.

The proposed integrated condition assessment methodology is based on the AHP and SMART techniques. They are used to calculate the condition assessment at every stage. The proposed CR model is flexible and can be easily adopted to suit all building types. It can serve as the backbone for larger decision support system for the sustainable maintenance management of buildings. The developed condition rating outputs can be used as the first step for deciding what, where, and when to maintain, repair, rehabilitate, or replace.

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The Application of Visualization for Construction Emission Monitoring

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Abstract

Excessive amount of human-made Green House Gas (GHG) emission in recent years has caused a major global warming problem; yet in the past two decades or so, their adversarial effects are better sensed and reported. The construction industry and its related activities are major producers of these emissions. Despite their contribution, there have been minimal efforts in effective and proactive sensing and visualization of these emissions. This paper presents a system for visualization of GHG emissions from construction equipments during the construction phase and its application in a real-life case study. A metamorphic representation of trees is used to further demonstrate the required number of trees to neutralize released GHG emissions. To that extent, a system for visualization of construction emission is implemented, and the perceived benefits and further developments are discussed. The paper concludes that visualization can be used as an effective tool to assist stakeholders and managers in monitoring and controlling the environmental impacts of construction activities.

1. Introduction

Climate change refers to long-term fluctuations in the climate system. Changes in climate are driven by changes in the amount of radiation present in the Earth's atmosphere. The earth's surface absorbs radiation from the sun and this energy is redistributed by the atmospheric and oceanic circulation and radiated back to space. Some of the gases existing in the earth's atmosphere help the process of keeping the radiations from the sun by reflecting solar radiations back toward the Earth. These gases are known as Green House Gases (GHGs), since they have an effect similar to greenhouses (California Energy Commission 2002). The greenhouse effect keeps the Earth warm. Without this effect, earth's surface would be about 60 degrees Fahrenheit colder than average Earth's temperature i.e 45ºF. However, the excessive human-made GHGs are altering the process in which naturally occurring GHG trap the Sun's heat before it can be released back into space. Altering the distribution of

radiant energy is likely to affect climate (PEW Center on global climate change, 2002). The greenhouse effect has been taking place for billions of years, yet over the last 50 years excessive emissions (i.e. human-induced emissions) are believed to be responsible for most of the observed earth's warming known as global warming. According to the EPA (2009), the Earth's atmosphere average temperature has increased about 1.3ºF over the last century. In addition to this, if the current trend of GHG emission continues, the increase would reach more than 5ºF by the end of this century (EPA 2009). The United States produces more than 7 billion metric tons of GHG (CO_2 Equivalent) yearly which places this country as one of the leading GHG producers of the world next to China. Among all the GHGs, CO_2 accounts for the largest percentage (83%) and thus requires prompt action for reduction (California Energy Commission 2002). The transportation sector is the second largest contributor of GHG emissions accounting for approximately 30% emissions, which is slightly lower than the highest share from the Electric Power sector (EPA 2009). The construction industry is responsible for more than 16% of the total transportation emissions. Considering its share of building operation and maintenance in the total GHG emission, there is a great potential for controlling and minimizing GHG emissions produced by the construction sector (Junnila *et al*. 2006).

Visualization has proved itself as one of the most effective tools in fast decision making and has potential in minimizing the time required to describe and explain situations and alternatives in coordination meetings (Golparvar-Fard *et al*. 2006). 3D presentation of data allows display of multiple different parameters simultaneously and over a single figure which significantly reduces the time required to build mental relationship between different figures at the time of decision making (Russell *et al.* 2009). The authors propose 3D visualization of the GHG emissions resulting from construction activities in order to provide owners, construction managers and other key project stakeholders with a representation of the amount of GHG emitted by their projects. In addition to project participants, there is a general assumption among the public especially those living in close proximity of construction sites that construction is one of the most polluting industries and their daily lives are being affected adversely due to construction emissions. The proposed visualization system can provide a representation of construction emissions, probably leading to a more realistic assessment of environmental impact of construction operations.

Despite all the efforts to reduce GHG emissions, current emission levels are much higher than Earth can tolerate. Planting a tree is known as the cheapest and the most effective mean of drawing excessive GHG emissions from the atmosphere (Prow 1999). Plants and specifically trees absorb GHG from the atmosphere during photosynthesis and release oxygen as the output. This phenomenon is one of the most natural ways of absorbing GHG from the air and thus can be used by construction project managers as a way to neutralize GHGs produced as a result of construction activities. This concept is used as the basis for the implemented system which converts the amount of GHG emission to the number of trees required to compensate for the loss. Furthermore, it creates a metaphor that visualizes how sustainable construction may operate. Since metaphors can easily become misleading (Adar *et al.* 2006), special attention is made describing the metaphor and its limitations.

2. Objective

The goal of this study is to visualize the share of a specific construction site's GHG emissions. In order reach this, a visualization system has been implemented rendering estimated values for a specific construction site. This visualization of a real construction site enabled authors to study the applicability of the system for further real-world applications. The system supplies users with a number of trees that can be planted to compensate for the loss caused by the generated GHG. It allows control decisions to be made easily and quickly, in turn potentially reducing the amount of GHG emission and bringing awareness to the stakeholders and affected public.

3. Research Background

Recently, there has been significant growth in visualizing of GHG emissions. In early effort, the Australian government introduced black balloons that represented emissions and the results could be visualized. Each of the balloons held roughly 50 grams of GHG. TV commercial were created to inform viewers that every Victorian household annually produced over 12 tones (240,000 balloons) of GHG (Sustainability Victoria 2009). The results of this visualization were significant in making the public aware of the importance of proper control of household apparatuses. However, the result was primarily in the form of story-telling and did not study the reduction solutions. NASA (2009) has also funded a research project, known as "Carbon dioxide map of U.S.", which was released as an extension to Google Earth. It provided detailed CO_2 emissions from fossil fuel combustion and displayed fossil fuel emissions by hour, geographic region, and fuel type. Ceip (2009) prepared a visualization of GHG emission for each region of the world. Their effort visualized gridded data in Google Earth based on each country with selected gasses shown on top of the current existing geographical maps. Their visualization had grids of relatively large size which covered large areas such as cities. Later, White and Feiner (2009) proposed a visualization technique for urban site visits and the generated CO in the nearby environment. Their efforts lead to a novel visualization of sensor-based CO data in an Augmented Reality environment. However, main focus of this system was on creating a visualization toolkit for CO gas emission data. Their system was mainly used by ordinary people to choose the healthiest route to walk.

A review of related research on visualization of GHG emissions has focused on either GHG emissions from fossil fuels and combustion engines or GHG emissions during operation and the maintenance life cycle of buildings and infrastructure. As discussed before, construction of these building and infrastructure, and activities related to them contribute to the overall GHG emission. Therefore the emphasis of this research is on the visualization of GHG emissions during the construction phase of a project. In this paper, we looked at a conceptual simulation of GHG emission during a construction project on the campus of the University of Illinois. Estimated values of GHG emissions for the first year of the construction are visualized and the applicability of the resulted visualization system for in-time decision making is investigated. In the meantime, a metaphoric representation of the number of trees required to compensate for the loss due to CO_2 emissions is also visualized. It is expected that this metamorphic presentation of the result can magnify the importance of reducing emission to stakeholders and support construction managers in their decisions by considering operational alternatives to reduce emission. The remainder of the paper is organized as follows: Section 4 describes the development of the proposed system.

We discuss the specific goals of the project, its potential users, and how the system could later be used. Section 5 looks into how the inputs, outputs of the system, and emissions should be visualized. Finally, in section 6, the results of the system are presented; usability and innovative components of the system are discussed in addition to discovered patterns in the visualized data.

4. System Development

In order to visualize GHG emissions during construction phase of a project, several visualization alternatives were reviewed and a-similar-to Geographical Information System (GIS) representation of the site with the GHG emission data presented as layers was selected. Not only a map representation has the ability of visualizing construction site level activities, but also allows the logistics operations to and from the construction site to be visualized. Visualization of site logistics operations helps to expand the visualization idea beyond the construction site in order to include many other activities resulting from construction. For instance, trucks bringing ready-to-pour concrete to the construction site or trucks taking away excavated soils must also be considered as construction equipments. Without the above mentioned model, such logistics activities will not be considered and the results will not truly reflect the actual GHG emissions resulting from construction site activities. However, the scope of this paper is only limited to activities directly resulting from construction (i.e., excavation, pouring concrete) and no other activity beyond this scope is considered.

Since the system can be used for all type of emissions beyond GHG, additional required parameters are also added to the visualization. It is noted that beside hazardous part of emission such as CO, NO_2, *etc.* the rest of GHGs are not locally important and their effect should be studied from global point of view. However, local effects of hazardous GHGs in addition to dust and smoke should also be visualized. In order to help decision makers better understand the local effect of these gases, additional environmental parameters might be needed. These parameters range from precipitation and temperature to wind direction. However, in the implemented system, only wind is considered for this part as the effect of other parameters is not as significant as wind direction. There have been many debates regarding the effect of emission from construction activities on the people living in the neighborhood. The case is much more important in case of having a hospital, school, kindergarten, or nursing house close to the construction site. In the past, typical strategy used in such cases was to limit the size of equipments used in part of the construction site close to these facilities. In addition, in order to minimize exposure to harmful emissions, work schedules were limited to times when school is closed or elder people or patients are inside the building (such as lunch time). Based on this, having wind direction visualized in addition to emission will help in predicting the direction in which emissions will be moved and to recognition of the neighborhood area that will be affected. Thus, combination of wind direction and real-time emission is of primary important and needs to be visually presented. Subsequently such a system can be beneficial for studying construction alternatives and inform both project participants as well as local communities about the adversarial effects of emissions. In the following sections, specific goals, potential applications, usability of the system as well as inputs and outputs are thoroughly discussed. Finally the efficiencies and innovative aspects of the system are presented.

Goals: The following outlines the specific goals of design and implementation of our visualization system for representation of sustainable construction operations:
1. Bring awareness to owners, construction companies and other project stakeholders on the importance of controlling excessive construction emissions;
2. Visualize construction activities that generate GHG and related emissions in real-time over the construction area and bring focus and awareness to those activities or equipments that have high rate of emission generation;
3. Visualize equivalent no. of trees required to compensate the loss due to emissions;
4. Bring awareness to project stakeholders as well as local community interested in the adversarial effects of a construction project in the neighborhood areas;
5. Provide construction contractors with an effective tool to study construction operation alternatives in reducing GHG emission which indeed could be used as a metric of how green the contractor is.

Visualization System Inputs: In order to study realistic nature of emission for our case study, we looked into construction plans. These plans along with construction schedule outline construction activities, types and number of equipments and machinery required for each activity. Based on these information, emissions from equipment can be estimated according to manufacturer's provided emission information. Subsequently, to simulate the emission source of each machine, a two dimensional Gaussian distribution is modeled and simulated [Eq.(0)]. For each construction activity outlined in the construction plan, all machineries used are listed. Later, for each of these equipments within a construction activity, a 2-dimensional discrete Gaussian distribution is estimated based on the following formulation:

$$f(x,y) = A\exp[-(\frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2})] \quad (0)$$

Where x and y represent local proximity to the source of emission. The main reason for having Gaussian distribution is to emphasize distribution of the emission in the local area around the equipment. Once this distribution is modeled, GHG emissions are simulated based on construction operations and resulting values are visualized as a layer over the construction plan. Fig. 1 further demonstrates the distribution function of GHG emissions. In addition, the average meteorological distribution of wind can be measured in real-time on a construction site. This information allows concentration and local effects of PMs and hazardous gases to be further studied.

Visualization System Outputs: The outputs of the system are categorized as below:
1. Visualization of GHG and PM and its real-time distribution over the construction site; this component of is further categorized into following subcategories:
   a. Visualization of daily GHG emissions;
   b. Visualization of the summation of GHG emitted prior to current study time;
   c. The expected project's emissions in the remainder period of construction;
   d. Representation of wind flow and its potential effect on concentration

2. Visualization of trees required to be planted to compensate the CO_2 emission resulting from construction activities. Prow (1999) reported that a single mature tree can absorb CO_2 at a rate of 48 lbs/year and release enough oxygen back into the atmosphere to support 2 human beings. Based on this ratio and the results of the conducted simulations, two tree representations were generated:

a. The numbers of trees required to compensate the carbon dioxide generated from the start of the project until the specific visualized day;
b. The estimated number of trees required to be further planted to neutralize the adversarial effects of carbon dioxide emissions till the end of the project.

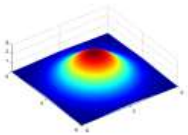


Figure 1.2D Gaussian distribution used to illustrate the emission source.

The required number of trees required to neutralize the CO_2 emission could be considered from two different perspectives: number of trees needed to be planted, and number of existing trees whose activities are neutralized due to the generated emission. Since from the emission point of view, neutralization of trees is equal to destroying, if last perspective is considered, part (a) shows number of trees destroyed so far and part (b) presents number of trees that can be saved. In fact, this concept is used in the visualization and trees already destroyed are shown with darker reddish color to present the fact that they are already destroyed and the number of trees that can be saved are shown by green to present the fact that they are still alive and thus can still be saved. In the "s*ystem usability"* section, usability, understandability, efficiency and innovative components of the system are further discussed in detail.

System Components : The system was designed to have three major components:
Visualization of emission over a map representation of the construction site and its close neighborhood: In order to ensure that the system would be effectively used by the target user groups, the authors decided to further augment the visualization system with a representation of its data value. For example in order to visualize GHG emissions, a grid structure was generated and over each node, a bar representation of the emissions generated from the beginning of the project was utilized. Consequently another bar representation was utilized to further visualize the estimated remainder of the GHG emissions. The height of these bars was proportionally distributed between the aforementioned emissions. It should be mentioned that the remainder of GHG emission refers to the difference between total estimated GHG for the construction project and the amount released so far which is available through summation of measured values. In addition, discrete Gaussian distribution of the emissions was visualized using a color spectrum. Color spectrum allows different values of emissions to be visualized simultaneously. Finally the wind visualization was represented using streamlines in addition to arrow heads.
Visualization of trees: Two categories for visualization of trees were designed:
1. Designing visualization for the numbers of trees required to compensate the CO_2 generated from the start of the project till the day of measurement. These trees are visualized using a red color in order to highlight the fact that they have already been destroyed and emphasize current negative effect of the construction.
2. Designing visualization for the number of trees estimated to be required for compensating the remaining CO_2 emissions in future. The authors made this

representation based on the concept that tree visualization brings large attention towards the actual or potential damage caused by these excessive CO_2 emissions.

User Interface (UI): UI is designed to allow different alternatives to be switched on and off and allow user groups to study different configurations both over map as well as its metaphoric tree representation. Map interface will be designed in a fashion to allow users to use projective transformations on the visual representation and modify vantage point to find the most effective perspective. Simplicity was a key concept in design of this part in order to allow users to start using the system with minimal training. Further study is needed to ensure that this aspect of the system is satisfied.

5. System Architecture

The proposed system is implemented using Java and the Visualization Toolkit (VTK) library. The following further elaborate on each component of the system:

***User Interface*:** Fig. 2.a shows a snapshot of the implemented control panel for the visualization interface. The user has the option of studying different emission features independently or in an integrated fashion.



Figure 2. (a) Layout of the user interface (b) (c) Symbolic tree visualization

Tree Visualization: Fig. 2.b and 2.c illustrates the symbolic representation of trees. In this particular case, three mature trees (color coded in red) are required to be planted to compensate for the CO_2 emission generated till the visualization date. On the other hand, it is also estimated that there will be 5 other trees required to compensate the remainder of the expected emission till the end of the project. Any decision that is made to reduce emissions can minimize the need for further planting of trees and the user has the ability to change current visualization date to see the history of required tree over lifetime of the construction.

The Emission Site Visualization: The main component of the system contains the geo-spatial configuration of the site with selected emission measurements and other environmental parameters at a particular time. It visualizes emissions generated from operation of the equipment using color coded Gaussian distributions (See Fig 3.a.). The visualization renders emissions over the map by highlighting key areas where construction operations were over a working day. In Fig.3a, 5 construction equipments with same emissions have been used. The Gaussian distribution shown on the upper right corner of this figure represents more concentrated distribution of GHG. This is because 2 machines are operating in close proximity to each other. By comparing the location of emission generation with real area, it can be observed that the three upper emission distributions are being generated in close proximity to the student residence facilities. Thus, if visualization showed that this emission will have negative effect on the people living in the neighborhood, the activities at this part of site can be rescheduled to a time when most of the residents are away attending

classes or even on vacation. Based on average class schedules, times around morning and noon are not appropriate construction because many students are present at resident halls during these times. Simple re-scheduling of construction activities leads to significant improvement in public health in neighborhood and it is much less expensive to re-schedule than to replace equipments with less GHG emitting equipment or adding expensive filtering systems.

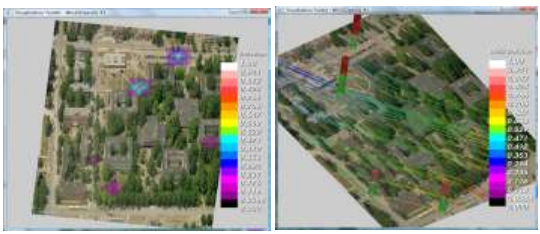


Figure 3.(a) Daily emission visualization projected at equipment's spatial locations (b) Visualization of total released/remained emission together with wind streamlines.

Furthermore, as seen in Figs. 3.b and 4.c, the overall estimated emission is also visualized using a bar presentation. This type of presentation enables project stakeholders to study operational paths and come up with alternatives that potentially have less effect on the neighborhood areas which in this case is the student residence hall and dormitory area. In other words, visualization of total released emission can help better manage or schedule construction activities to minimize the local effect of emission. One of the main points of interest in implementation of the system is to provide users with the ability to study the concentration of simulated generated emissions in real-time from both local and global point of view. Wind streams and wind glyphs are presented on a daily basis to allow the study from local point of view (Figs. 3-b, 4.a and 4.b). It should be mentioned that wind direction can be obtained from local measuring devices or from weather prediction stations.

6. Discussion

The proposed system enables the study of GHG emissions resulting from different construction schedules for a specific project and helps in selecting the best schedule. The current method of scheduling construction activities is primarily based on minimizing the cost and time. Alternatively, the proposed visualization helps in selecting the best schedules with minimal local and global environmental impact. This will also enable project stakeholders to study different construction operation alternatives to minimize the impact of these emissions, visualize and understand how potential GHGs can be sequestrated in the close proximity of emission sources. The tree visualization allows key decision makers of a project including the owners to be aware of the adverse effects of their projects and provides an opportunity to better and more sustainable construction practices to minimize their impact. This may ultimately lead to the formation of legislative guidelines specifically targeted to the operational stages of construction. Currently with the increasing support and funding for sustainable infrastructures, many projects follow LEED guidelines (US Green Building Council 2009). Although one of the targeted goals in LEED certification is

to reduce energy consumption that leads to less GHG emissions, most of the attention is focused on the maintenance and operation phase of the buildings and less attention is paid to the construction phase itself. In fact, there exists limited regulations regarding the amount of emission during construction and no quantitative system exists for controlling real emissions. We must also consider that construction sites are harsh environments and might change emission values from those values mentioned in the equipment's specification manual (Shiftehfar and Boukamp 2008). This becomes more damaging if the equipments are not maintained properly which is often the case. Our hypothesis is that an informative visualization of sustainable construction practices can ultimately lead to better awareness for all project stakeholders. If implemented as a set of guidelines and requirements, the system can lead to minimization of GHG emissions at large. This research experiment raises further questions: How can the emissions generated from construction operations be less adversarial? Is there a need to change construction machinery or are there ways for which we can modify our existing plans and strategies without affecting the work productivity? Are there incentives that can be used to require contractors to plant an equivalent number of trees to compensate for the environmental damage resulting from their activities? Does emission from construction activities have a significant effect on neighborhood areas, and, if yes, how can the construction schedule be modified to minimize such negative effect. In order to adequately respond to these questions, our system needs to include tools (such as real-time sensors) that monitor emissions so they may be compared to estimated values from simulations. As a short term solution, planting trees to compensate for the loss due to emissions may be reasonable solution to neutralize CO_2 emission; however, in long term, further studies are needed to investigate optimal operations and to understand the benefits of implementing such a system for sustainable construction practices.

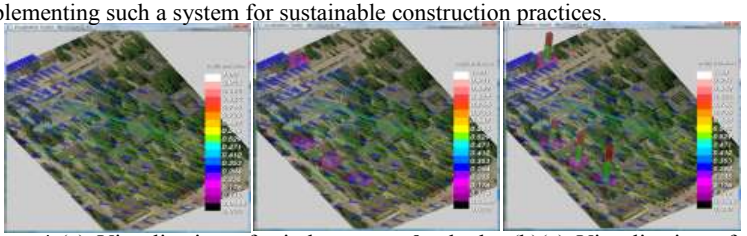


Figure 4-(a) Visualization of wind streams & glyphs (b)(c) Visualization of wind streamlines with the potential local effect on emission dispersion

Another bottleneck associated with the implementation of such visualization is the lack of availability of proper guidelines. Currently LEED, the most dominant guideline system in the US, does not have specific procedures for contractors to track their GHG emissions in order to control and reduce the impact on the environment. Besides, contractors are historically not in favor of these changes. This is because there is a perception that such guidelines result in reduction in profit margins by lowering workforce productivity. If these visualization systems are further prototyped and implemented, it can bring awareness of emissions and allow contractors to create innovative solutions for changing their work plans without affecting productivity.

7. Conclusions and Summary

Although historically GHGs have been a natural source of warming in the atmosphere, in the past two decade or so, their adverse effects have attracted more attention. The construction industry and its related activities are major producers of these emissions. Despite this contribution, there has been minimal effort in effective sensing, analyzing and visualizing these emissions. In this paper, we describe a system for visualizing simulated GHG emissions from construction equipments during the construction phase of a project. Based on the results of simulation, we calculated and displayed the required number of trees for neutralizing the emitted GHGs. The proposed visualization system seems to have the required potential to enable project stakeholders to study different construction operation alternatives and further revise operations to minimize overall GHG emissions (Global effects) and distribution of GHG during the lifetime of the project (local effects). Further research needs to be conducted in several areas. First, we need to explore several visualization schemes to see which are most legible. We also need more case studies to determine how such a visualization system could be effectively implemented and used in practice. Also, further studies are required to see if the results of this work can inform guidelines and protocols for construction regulations.

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CALCULATION OF GREENHOUSE GAS EMISSIONS ASSOCIATED WITH HIGHWAY CONSTRUCTION PROJECTS USING AN INTEGRATED LIFE CYCLE ASSESSMENT APPROACH

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ABSTRACT

Large quantities of greenhouse gases are emitted in producing and acquiring, materials and equipment for the construction, maintenance and rehabilitation of highways. The objective of this research is to quantify the life cycle emissions associated with different pavement designs, by applying existing life cycle assessment (LCA) methods that integrate process-level construction data. The research is based on two pavement rehabilitation and re-construction projects across the State of Michigan. Field inspector's daily reports and direct site observation were used to collect data pertaining to daily material and equipment usage, construction processes used, and site characteristics. The paper describes the collection and organization of the data, and the calculation of life cycle greenhouse gas emissions associated with each project. This is part of a broader research effort to integrate process-level construction data, and long-term performance of each pavement type in the life cycle assessment of environmental impacts associated with highway infrastructure. It will support decision-makers in public agencies such as a Department of Transportation in assessing and reducing the environmental impacts associated with highway construction.

INTRODUCTION

The challenge posed by global climate change is motivating state and local transportation agencies to investigate strategies that reduce the life cycle greenhouse gas emissions associated with construction and rehabilitation of highway infrastructure. Existing life cycle impact assessment metrics and methods (Hendrickson et al. 1998, Cicas et al. 2007, Bilec et al. 2006, Zhang et al. 2006, Consultants Pr´E 2009, NREL 2009) supporting such strategies are dependent on estimates of construction inventories (materials installed and equipment used in

construction). In this paper, we describe a method to collect and organize such data, directly from pavement construction sites for the calculation of carbon emissions associated with various highway construction and rehabilitation operations. Specifically, this paper illustrates the application of the method to calculate the carbon emissions from a Hot-Mix Asphalt re-construction project and a Concrete rehabilitation and reconstruction project in the State of Michigan. This is part of a research project supported by a grant from Michigan Department of Transportation (MDOT) that aims to calculate the carbon footprints for different pavement designs.

The significance of this research is that it develops inventories to calculate carbon emissions using data *directly* collected from construction sites in real time. This is a departure from current methods that compare carbon emissions using *estimated inventories* (Horvath and Hendrickson 1998, Muga et al. 2009). Prescribed results from estimated inventories can be misleading, as the assumptions used in the estimates do not always apply generally across diverse contexts. Instead, the proposed method identifies driving materials, equipment, and construction operation metrics for calculating carbon emissions. When applied to individual projects this method will enable decision-makers to monitor the exact emissions for each highway construction and rehabilitation operation – a critical step towards implementing future cap-and-trade policies. The research takes advantage of existing methods for calculating greenhouse gas emissions, while furthering the goals of pavement life cycle cost analysis and environmental impact assessment. In this paper, we report the emissions associated with material acquisition and construction phases of two highway construction projects. This includes the emissions from the manufacturing of the materials, and the emissions from the equipment use on-site. The maintenance and end-of-life phases are not included. Also, emissions associated with transporting materials, equipment, and workers to the site are not included. This will be reported in future research.

PROJECTS STUDIED

The two projects that have been used in this study are:

- A HMA reconstruction project involving approximately three miles of road reconstruction, ramps, and culverts for northbound and southbound lanes of a four-lane freeway located north of the Indiana border in southwest Michigan. Prior to the reconstruction, the highway section had a concrete pavement. The State DOT invited bids for the reconstruction on two alternative pavement designs: one using HMA and the other using concrete. The project was awarded to a bid that had the lowest life cycle cost, which in the competitive bidding process was the HMA design. At the time of data collection for this study, the project was approximately 50% complete. The complete northbound section was finished and the contractor was preparing to reconstruct the southbound section.
- The second project was a concrete pavement rehabilitation project, approximately seven miles long, on a major Interstate in southwest Michigan. The study focused primarily on concrete overlay rehabilitation, pavement removal, concrete pavement reconstruction, and culvert. At the time of data collection for this study, the project was approximately 50% complete in

which the southbound section was complete and rehabilitation had just begun on the northbound section.

It is important to note that these construction projects were used to illustrate the method of data collection and calculation of the associated carbon emissions. The intention of this study is *not* to compare the two projects.

DATA COLLECTION

Two types of data were collected – *construction data* and *site characteristics data*. The former was collected from construction management software, while the latter was collected directly by the researchers from the construction sites.

Construction Data

Construction data collection lead to the development of material and equipment inventories used during the reconstruction and rehabilitation processes. The primary challenge in collecting this data was eliciting co-operation and collaboration from project engineers, contractors and sub-contractors on site. Given their existing responsibilities, there was a natural reluctance on their behalf. Hence, it was imperative to take advantage of existing reporting methods, without increasing the burden of reporting. This was also critical to ensure that the proposed method can be practically implemented.

Data Collection Using FieldManager™

MDOT requires the use of software called FieldManager™ developed by InfoTech Inc, (InfoTech 2009) on all their construction and rehabilitation contracts. It is a Microsoft Windows based interface designed for use by state transportation agencies, local governments, engineering consultants, and large contractors. Inspectors (on behalf of MDOT) record general site information, contractor personnel and equipment on-site, and quantities of material used on a daily basis, using the Inspectors' Daily Report (IDR) interface in FieldManager™. The following three fields of the IDR were used to accurately account for the materials and equipment usage inventories for each of the projects surveyed.

General Site Information: As the name indicates, this field defines the context within which the construction operations for the day were conducted. It includes the day and times work was performed, prevailing weather and site conditions, and site-specific location (expressed using station information) of the work being performed. For future studies, this information can be used to record the impacts of weather and site conditions on productivity of equipment and resource allocation. For example on a hot day more water may be used to maintain base density. This may be very relevant in places where water is scarce, thus influencing water usage. Site layout may also impact equipment travel times.

Contractor Personnel and Equipment: The contractor personnel and equipment inputs of the IDR are critical to quantifying project emissions. Recent studies have shown that energy use and emissions of construction processes are primarily due to construction equipment use, which can account for 50% of most types of emissions. Also, equipment larger than 175 hp made prior to 1996 tend to have greater emissions than more recent models (Guggemos and Horvath 2006). The observed and recorded equipment data, in the IDR is subject to the inspector's discretion on how he/she reports what is being used on-site. Often different inspectors use different

descriptions for the same equipment. While this does not necessarily corrupt the collected data, it does create a burden on the researchers to appropriately present and clean the data for analysis. As explained in a latter section, there may be a need for a standardized reporting procedure in Field Manager™.

Inspectors also recorded the contractor personnel working on-site, including information describing the crews and how long they worked on a particular day. This information can relevant when studying socioeconomic impacts of a project on workforce and labor.

Material Posting: Material used on the construction site was recorded using the IDR, by tracking progress made on each pay item as specified in the construction contract. The location, station information and quantities of materials associated with each item installed were stored. In doing so, an as-built record of procured and installed material is maintained. Actual productivity and schedule of the construction project can also be monitored. Once the project is completed and the total amount of materials has been billed, the material wastage or excess usage can be calculated by comparing the as-planned items in the bid-tab to the actual installed materials. Using as-built quantities in the calculation of life cycle impacts and emissions leads to significantly more accurate project impacts compared to similar calculations done with estimated quantities.

Site Characteristics Data

As with any project, to accurately calculate the emissions, it was necessary for the researchers to perform actual site visits in order to determine the following:

- Location of plant site, material stockpiles, water source, and disposal site to determine haul distances associated with transportation/hauling equipment.
- Equipment checks to ensure that equipment posted in IDR matches equipment actually being used on-site.

While the data collected from the IDRs were crucial to developing material and equipment inventories, the site specific data served two purposes: (i) to validate and support the data collected through FieldManager™ and (ii) allowed researchers to evaluate the construction site and consider impacts of location on construction operations.

DATA ORGANIZATION

In this section we discuss the development and implementation of a database that organizes and integrates the different categories of data described in the previous section. A coherent schema that centrally organizes the information collected was developed and a database has been implemented in PostgreSQL and is being hosted on a server at Michigan Tech. This makes the data easily query-able for different environmental impact assessment. In addition, in future MDOT can use this as a repository for collecting construction information that can be easily available to researchers. At this point in the research, the following data has been (and is continuously being) uploaded:

- IDRs and on-site data collected from a number of construction projects – including the two described in this paper.

- General descriptions of relevant equipment and materials typically used in highway construction – these tables are effectively the duplication free, super set of all the materials and equipment used in the projects surveyed.

The construction contract, IDR, material and equipment information integration provides a bottom-up detailed record of materials installed and equipment used during each construction process. Together this integration allows the tracking of the resource usage (both material and equipment) throughout the construction stage of the pavement life cycle. The database also includes pavement history records to allow integration of impact analysis across the entire pavement life cycle – however a discussion of that is beyond the scope of this paper.

MATERIAL AND EQUIPMENT INVENTORY

In creating an inventory of the total materials used for each project, a report was generated from the database containing the description, the total sum of material placed to date, and the units associated with each material. For the purpose of this study, only the driving materials placed were considered in the analysis. These materials account for the principal materials defining the project items. For example materials associated with rest area construction, guard rail installation and bridge-deck construction were excluded – not because they are unimportant, but because they merit separate collation rather than being clubbed together with concrete and HMA reconstruction. Table 1., shows the critical materials used in the analysis of both projects.

EIO-LCA Sector	Material Description
331111	Steel Reinf., Lane Ties, Dowels, Mesh, Fence, Load Transfer Assy.
21232	RipRap and Aggregates
313210	Geotextile Liner and Blanket
324121	HMA
325998	Curing Compund
325510	Pavement Paint
32612	Pipe Underdrain
21232	Granular Material Cl II & III
327211	Pavementt Marking Glass Beads
324121	Asphalt Emusion (Bond Coat)
327310	Cement
21232	Coarse Aggregate (For Concrete)
21232	Fine Aggregate (For Concrete)
325211	Joint Sealer and Filler

Table 1: Driving Materials

In acquiring an inventory to represent the equipment being used on the construction site, a report was generated from the database containing the description of all equipment posted by the inspector in each day's IDR along with the total quantity and hours associated with each description. In the absence of reporting standards used by the inspector's, each inspector usually has their own way of recording and naming the equipment in the IDR. A critical challenge in collating the equipment data was to manually categorize and classify all the raw equipment data. In doing so, equipment was classified into three categories; Hauling, Stationary, and Other. The 'Other' category contained miscellaneous and specialty equipment which are not representative of typical highway construction equipment - such as a foreman's pick-up truck. As with driving material classification, inclusion of this

equipment category is not critical to the construction processes at hand. The Hauling Equipment was then further classified into off-road or on-highway hauling equipment. The Stationary equipment was further classified into the 14 types of construction equipment as listed in Table 2.

After all equipment was categorized into their respective categories, a total quantity and total number of hours used was determined. These totals are also highlighted in Table 2.

Table 2: Equipment Specifics and Total Hours Used

Stationary Equipment Specifics							
Name	Make	Model	Year	HP	Tier	Hours Used1	Hours Used2
UtilityTractor	John Deere	6100D	2008	100	1	144	276
SkidSteer	CAT	299C	2008	90	3	627	253
Excavator	CAT	345D L	2008	380	3	1230	826
Dozer	CAT	D6T	2008	200	3	1892	1591
Front End Loader	CAT	980H	2008	349	3	1102	373
Grader	CAT	140M	2008	183	3	494	625
Broom	Broce Broom	RCT350	2008	85	3	156	64
Roller*	CAT	CB-534D	2008	125	2	1562	1369
Scraper	CAT	623G	2008	330	3	258	374
Backhoe	CAT	450E	2008	124	3	390	251
Cold Planer	CAT	PM-201	2008	650	3	164	111
Road Reclaimer	CAT	RM-300	2008	350	3	NA	42
Paver	CAT	AP-1000D	2008	224	3	552	288
Road Widener	Weiler	W530	2008	114	3	NA	6
MTV	Roadtec	MTV-1500D	2008	300	3	NA	96
Trencher	Vermeer	T455	2008	125	1	120	16
Conc. Paver	G&Z	S850	2008	275	3	400	NA
Texture Cure Machine	G&Z	TC800	2008	85	3	400	NA
Off-Road Hauling Truck	CAT	740	2008	453	3	10	1042

1 Concrete Rehabilitation Project
2 HMA Reconstruct Project
*Compares to PS-360C Tire Roller

DATA ANALYSIS

In this section we discuss the analytical capabilities that the implemented database provides. Specifically, we queried the data to calculate the associated carbon emissions.

Economic Input-Output Life Cycle Assessment (EIO-LCA)

The prevalent approach to studying the environmental effects of products or processes is to systematically account for the different stages through the life cycle, consisting of the materials extraction phase, manufacturing/production stage, the use phase and the ultimate end of-life/disposal phase. The Economic Input Output-Life Cycle Assessment (EIO-LCA) is an analysis model that defines the scope and number of environmental effects quantified in an assessment. It also provides an analytical tool that includes templates and data libraries. (Hendrickson et al. 1998, Cicas et al. 2007) The model attempts to capture all the requirements to produce a product, service, or activity, only for the life cycle stages of extraction/mining, transportation, and manufacturing.

The usefulness of the EIO-LCA model is dependent on the accuracy of the material inventories developed for each pavement design and construction operation

type. In addition, the outputs are reliant on the economic input of the identified materials in US$ and based on the 1997 US Economy (the 2002 model could not be accessed). Average cost for each material or item varies by region and the costs reported in the contracts are agency costs (cost to the DOT rather than cost of material production) which are inapplicable to EIO-LCA studies. In this study, RS Means (RS Means 2009) was used to determine the bare material price of each material used in the construction process. In addition, cost indexes were used to convert the 2009 prices from RS Means into 1997 US Economy prices to account for the 1997 US Economy model used in EIO-LCA.

GHG Emission Calculator (e-Calc)

To quantify the emissions of the construction equipment an emission calculator tool, e-Calc was used. E-Calc, a Visual Basic plug-in in MS Excel, allows the estimation of carbon emissions of construction equipment using EPA approved formulae and test data. It provides an inventory of typical equipments used to support typical inputs to calculation (Sihabuddin and Ariaratnam 2009). To use this tool, the equipment inputs need to be concise and contain information such as; make, model, year, rated hp, useful life hours, cumulative hours used, and % power used. Hauling equipment information like Gross Vehicular Weight (GVW) and mileage is needed. Although Field Manager™ is capable of doing so, many times IDR's fail to report this information. For this study, and since a lot of this information was unavailable from the IDRs, assumptions were made to represent the equipment being used. In future work, the sensitivity of the calculated emissions will be investigated by relaxing the assumptions. For this study, these assumptions included:

- The power used was assumed to be 50% considering average and moderate working conditions as outlined in Caterpillar Performance Handbook (CAT 1999).
- For those useful life hours of equipment not listed in Caterpillar Performance Handbook the useful life was assumed to be 10,000 hrs.
- The cumulative hours used was considered to be half the life of the equipment.
- All construction equipment was considered to be fairly new, although this may not be the case, recent reports show that older equipment emits significantly more emissions (Guggemos and Horvath 2006).
- For the hauling equipment, GVW was considered to be in the range of 33,001 – 60,000lbs.
- The useful life associated with the diesel engines was considered to be 1,000,000 miles of which the current mileage was half the useful life.
- In cases where equipment had no hourly usage assigned to it, a default value was used.

The travel distances and number of trips for the hauling equipment also had to be calculated using the on-site observation data collected to use the tool. The number of trips was determined from the total amount of material placed on-site and the capacity of the hauling equipment. HMA hauling trucks were assumed to have a hauling capacity of 28 tons of HMA and Concrete hauling trucks had a hauling capacity of 10 cubic yards of concrete. The travel distances were calculated from the known batch plant locations to locations where material was being placed (this

formulates to an arithmetic progression). The sulfur content of the fuel also plays an important role in emissions from the equipment. As reported by the EPA the sulfur content of the construction equipment was found to be 0.005% and the on-highway equipment was found to be 0.0015% (Diesel Net 2009). E-Calc was implemented using this information along with the information provided to us in the IDRs to calculate the total emissions due to the construction and hauling equipment being used on each project.

RESULTS AND CONCLUSION

Two Highway construction projects were monitored and studied to investigate the emissions associated with the material and equipment usage throughout the construction phase. The results from each data type and project are outlined in Tables 3-6. Figure 1 provides an integrated view of the emissions per lane mile.

Table 3: Material GHG Emission (Concrete Rehabilitation Project)

GHG Emissions	MT CO_2 EQ	MT CO_2 EQ/Lane Mi
Total GWP	14200	1023
Carbon Dioxide (CO_2)	13600	980
Methane (CH_4)	453	32.6
Nitrous Oxide (N_2O)	49.2	3.5
CFCs	84.1	6.1

Table 4: Material GHG Emission (HMA Reconstruct Project)

GHG Emissions	MT CO2 EQ	MT CO_2 EQ/Lane Mi
Total GWP	3700	566
Carbon Dioxide (CO_2)	3090	472
Methane (CH_4)	552	84.4
Nitrous Oxide (N_2O)	21.2	3.2
CFCs	29.5	4.5

Table 5: Equipment GHG Emissions (Concrete Rehabilitation Project)

GHG Emissions	Units	Units/Lane Mi
Hydrocarbon (HC)	524.3 lbs	37.8 lbs
Carbon Monoxide (CO)	3651.31 lbs	263.1 lbs
Carbon Dioxide (CO_2)	650.78 Ton	46.9 Ton
Nitrogen Oxide (NO_x)	6726.34 lbs	484.6 lbs
Particulate Matter (PM)	476.8 lbs	34.4 lbs
Sulfur Oxide (SO_x)	391.2 lbs	28.2 lbs

Table 6: Equipment GHG Emissions (HMA Reconstruct Project)

GHG Emissions	Units	Units/Lane Mi
Hydrocarbon (HC)	474.9 lbs	72.6 lbs
Carbon Monoxide (CO)	3127.3 lbs	487.2 lbs
Carbon Dioxide (CO_2)	586.8 Ton	89.7 Ton
Nitrogen Oxide (NO_x)	6040.9 lbs	923.7 lbs
Particulate Matter (PM)	409.7 lbs	62.7 lbs
Sulfur Oxide (SO_x)	350.1 lbs	53.5 lbs

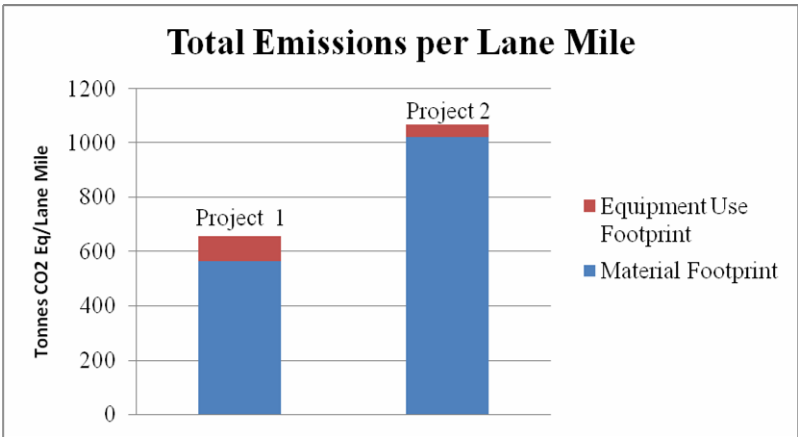


Figure 1: Total Emissions per Lane Mile for Principle Components through the Material Acquisition and Construction Phases

The concrete rehabilitation project results in significantly more emissions than the HMA reconstruct. One reason for this may be the context. The concrete rehabilitation project is located in an urban area making work zones more constricted than that of the HMA reconstruct which is located in a rural area. Although, it is important to note that the HMA reconstruct project had a start date for construction approximately 30 days before the concrete rehabilitation project.

In reviewing the total resulting equipment GHG emissions associated with each project, it can be seen that the equipment usage in both projects are comparable. This may result from experienced contractors monitoring the productivity and efficiency of their equipment. When the emissions are compared per lane mile, the HMA reconstruct has considerably more emissions from equipment than that of the concrete rehabilitation project. This can be a result of the paving operation, where HMA paving can only be performed one lane at a time while a concrete paving operation can cover more than two lanes at the same time. Efficiency can be directly related to the amount of GHG emissions resulting from certain construction operations. For future work, the emissions associated with certain construction operations will be assessed.

In conclusion, this paper introduces a method describing the collection, organization and integration of two types of construction data; material and equipment. The paper discusses the development of a database schema and how its implementation using existing life cycle assessment methods to determine the GHG emissions associated with highway construction projects. The application of this method will enhance calculation of life cycle greenhouse gas emissions because (i) it affords more accuracy as it uses actual on-site data and maintains actual emissions records for each project and (ii) it allows a context sensitive life cycle assessment of highway infrastructure. Such enhanced calculation methods promise to improve construction processes and effectively reduce greenhouse gas emissions.

ACKNOWLEDGEMENT

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DECISION MAKING PROCESSES AND THE ADOPTION OF ENERGY SAVING TECHNIQUES IN SOCIAL HOUSING

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Summary
Many innovative techniques and large policy measures have been introduced to reduce energy consumption. Despite the high ambitions and societal pressures, the adoption rate of energy measures is still low. Using adoption theories this paper provides a framework to analyse the adoption process of energy saving techniques in building processes. The stakeholders in the adoption process of energy measures are analysed during every phase of a building project. This framework is used to analyse four projects of a social housing corporation. The low rate of adoption of energy saving techniques can be explained by the large number and variety of stakeholders involved.

1. Introduction

The energy consumption in the built environment accounts for more than forty per cent of the total energy consumption in Europe (EC, 2002). Improving the energy performance of the built environment has an important impact on the reduction of carbon dioxide emissions and sustainability in general. Many innovative techniques have been introduced to lower the energy consumption or to use renewable energy sources, but not all techniques have been broadly adopted.
There is a large variety of innovative techniques. They differ in terms of complexity and costs. In some cases new techniques can directly replace the conventional product, in other cases large adjustments in the building have to be made. Energy saving techniques can reduce life-cycle costs, but often lead to higher investment costs. Although many measures are widely accepted in society and high ambitions regarding the energy performance of the forthcoming building are often expressed during the initial phase of a building project, these ambitions are not always realised in practice. We are aware that policy-measures might not have the expected impact if there is a lack of social acceptation of those measures (see e.g. Raven 2006). Therefore sustainable energy measures will not be successfully implemented as long as we do not have a clear understanding of the behavior of the users, where we interpret the term 'user' as stakeholders in the construction process: architects, developers, builders, clients and end-users, i.e. consumers. We expect that this is due to the influence of specific stakeholders in the design and construction process of buildings.
Our objective is to make a contribution to the knowledge on decision making processes by developing a framework to analyse the influence on the adoption of energy saving techniques by stakeholders involved in building processes. Our framework is based on innovation adoption theories. We focused on the stakeholders

who are involved in the adoption process of innovative techniques that lower the energy consumption or make use of renewable energy sources. The case studies are building (re)design processes in social housing.
It is expected that the stakeholders involved in the building process are of influence on the adoption process (Cooke et al, 2007), whereby the ambitions stated by the clients before construction and the actual energy performance after construction often do not correspond with each other. In a building process some organisations or persons are only for a limited time path involved and all have different interests and targets. Therefore, many individual reasons to adopt or to reject energy techniques can exist.

2. Developing a framework to analyse adoption in building processes

In this section we will first address the adoption theory as presented by Rogers (2003). Then the context, in which adoption processes take place, will be discussed, before presenting specific characteristics of building processes.

2.1 Adoption theory in general

Many studies have been published on adoption of innovations. Well-known is the work of Rogers that gives insights in which characteristics of energy saving techniques are relevant, how the adoption process can be phased, and which kind of adopters exist. His work is being used to come to a framework on the adoption process of energy saving techniques in the built environment.
Rogers (2003, pp. 12) states that: *an innovation is an idea, practice, or object that is perceived as new by an individual or other unit of adoption*. In this paper the *idea, practice, or object* are techniques that lower the energy consumption or techniques that make it possible to fulfil the need for energy in a renewable way. The *individual or other unit of adoption* in building projects are a variety of stakeholders. A stakeholder is in our case an individual or organisation with an interest or concern in a building project. Not all stakeholders can exert influence on the progress and outcomes of a building project. The group of stakeholders that can exert influence is further referred to in this paper as 'actors'.
Rogers (2003) defines five attribute that strongly influence the rate of adoption of innovations, namely relative advantage, compatibility, complexity, trialability and observability. This means for example that a high level of complexity will more likely result in a lower adoption of an innovative energy saving techniques than a low level of complexity. In the process of adopting or rejecting an innovation five phases are distinguished, namely (ibid., pp. 171-189):

1. Knowledge: in this stage an individual (in our case actor) is exposed to an innovation's existence and gains an understanding of how it functions;
2. Persuasion: the individual forms a favourable or unfavourable attitude toward the innovation. The mentioned perceived attributes are important in this stage;
3. Decision: activities are undertaken that lead to a choice to adopt or reject an innovation;
4. Implementation: this occurs when an individual puts an innovation to use;
5. Confirmation: in this stage the individual seeks to avoid a state of dissonance or to reduce it if it occurs.

2.2 Adoption processes in their context

Dieperink et al. (2004) and Hartmann et al. (2008) stress the importance of studying adoption in its context. The framework of Dieperink et al (2004) expands Roger's model by linking the adoption process with macro developments, technical aspects, economic aspects and the company's context. The specific characteristics of the context have to be understood in order to analyse the decision-making process of innovations.

The integrative model of Dieperink et al. explaining the diffusion of innovations offers a detailed structure to align motivations and arguments of actors for adopting or rejecting energy saving techniques. Vermeulen et al. (2006) elaborates on the model of Dieperink et al. (2004) by specifying first and second level variables, which explain the adoption of energy innovations for new office buildings. They mention that the actor's characteristics and the networks in which the actor participates have impact on the decision making process and therefore on the adoption rate. This network forms the heart of our framework.

Research of Hartmann et al (2008) focuses on the adoption of innovations by professional public clients, in which four conflicting factors were strongly affecting the innovation perception of this actor. Hartmann et al. (2008) offer a model of the adoption process that links the public dimension and professional dimension of the client with the innovation perception. These scholars see *risk* as an important additional innovation attribute. Their model describes the deliberation process underlying the adoption process.

Based on these studies we distinguish four contextual dimensions, namely: the characteristics of the actors, the context of the project, the macro developments, and the state of technology. The last one is based on Dieperink's "technical aspects" and Hartmann's attribute "risk". By specifying which techniques are in which stage of the innovation life cycle, risks can partially be assessed.

2.3 Adoption processes in the construction industry

Building projects can be characterised as inter-organisational projects. In building projects, where organisational connections exist adjacent to inter-organisational connections, decisions are taken in a complex context. In every phase of the building process actors and stakeholders join or leave. The different phases of building processes can be profoundly explained by using the process protocol of the University of Salford as specified in Table 1.

Table 1: Phases in the design and construction process (Kagioglou, et al., 1998).

Group	Phases
Pre-project phases	0. Demonstrating the need
	I. Conception of need
	II. Outline feasibility
	III. Substantive feasibility study & outline financial authority
Pre-construction phases	IV. Outline conceptual design
	V. Full conceptual design
	VI. Production design procurement & full financial authority
Construction phases	VII. Production information
	VIII. Construction
Post completion phase	IX. Operation & maintenance

This arrangement shows from a certain perspective some similarities compared to the innovation decision process of Rogers. The awareness of a certain necessity and generating an attitude are prevailing in the first phases (phase 1 and 2). In the final drawings and documents, before setting a price for construction, adoption or rejection decisions need to be taken (phase 3). The construction process needs to cope with the installation procedure for the specific energy techniques (phase 4). In the end the user of the building will experience if the techniques perform and really can save energy (phase 5).
In the building process we consider ten actors to have direct influence in the adoption or rejection of energy saving techniques (see Table 2). The actors are involved in different stages of the building process. The trajectory to come from an energy saving concept to specific energy saving techniques, the contextual factors influencing the process, and the roles of the actors are included in our framework (see Figure 1). The five phases of Rogers are expected to be only partially in line with the phases of the general design and construction process. Individual actors are persuaded and are taking decisions on energy saving measures at different stages in the process. In other words, the overall diffusion process consists of various personal adoption cycli which vary per actor.

Table 2: Descriptions of the ten actors regarded in this research

	Actor	Description
Granters	Client – Principal (Cl)	Person or organisation requesting the constructive service of a professional person or organisation. In some cases a client can be a property developer.
	Customer- User (Cu)	Person or organisation making use of the provided building
	Warden (W)	Person or organisation responsible for the supervision of and maintenance on the building and its location
	Property developer (PD)	Person or organisation that converts land to a new purpose, especially by constructing buildings
	Project manager (PM)	Person that plans, organizes, and allocates resources to come to a successful completion of a specific project (as specified by the client)
	Municipality (Mu)	A town or district having a local government that enforces building regulations
Takers	Architect (A)	Person who designs buildings and in most cases supervises their construction
	Consultant (Cs)	Person or organisation that provides expert advice professionally
	Contractor (Co)	Organisation or person that undertakes a contract to provide materials and/or labour for a construction project
	Subcontractor (Sc)	Organisation or person that carries out work for a company as part of a larger project
	Manufacturer (Ma)	Firm that fabricates construction components and/or materials

3. Using the framework for social housing processes

In this section we will operationalise the framework in order to analyse social housing projects by specifying the context in more detail. There are multiple reasons to study social housing projects. First, by the end of 2003 the total number of houses owned by social housing corporations was 2,420,500 being more than one third of the Dutch houses (Dekker, 2004). Secondly, the development of social housing seems to experience financial problems in achieving an improved energy performance. Thirdly, social housing corporations are considered to be highly experienced principals or property developers regarding real estate, but based on the investments costs less experience is expected to exist on the adoption of innovative techniques that go

beyond the regulations in the Building Code. In this section we will further explain the context based on the four factors described in Figure 1.

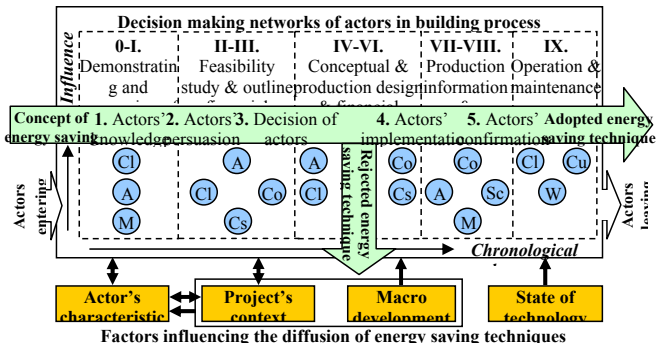


Fig. 1: Framework to analyse the adoption process in building processes.

3.1 Macro development

The context issue called "macro development" is mainly referring to the society at large (Dieperink et al, 2004). We clustered the developments in political, juridical and economic events within the construction industry in the Netherlands during the time-period 2003-2009.

Political developments: Starting from 2003 the government tried to encourage housing corporations to develop more houses to rent and to sell. Although, the number of houses developed by housing corporations increased, the government announced in 2006 that the corporations need to spend money on improving complete neighbourhoods. By 2010 the corporations will spend € 2.5 billion per year for improving neighbourhoods. At this moment it is estimated that housing corporations own houses with a value of € 380 billion (by means of the Valuation of Immovable Property Act), according to CBS the total VIPA-value of houses was approximately € 1,633 billion in 2008.

Legal developments: In the time period 2003-2009 the national Building Code of 2003 applied for new buildings. Regarding the energy use of buildings, a minimum insulation value of 2.5 $(m^2 \cdot K)/W$, a minimum value for ventilation of 0.7 $dm^3/(s \cdot m^2)$, a maximum value for air infiltration of 0.2 dm^3/s per dwelling and an Energy Performance Coefficient (EPC) for dwellings of 1.0. The minimum floor height of 2.6 m and the height and width of door openings (2.3 m x 0.9 m), also incorporated in the Building Code, influence the energy use indirectly. The EPC is based on an equation that relates forecasted and permissible energy use, incorporating the installed systems for heat production, heat resistance of the building shell and the size of the house, etc. By the beginning of 2006 the EPC was reduced to 0.8.

Economic developments: Regarding the economic developments in this time period, it is important to address that in 2002 and 2003 there were small increases in the Gross Domestic Product (GDP) of only 0.1% and 0.3%. After 2003 the GDP increased every year from 2.2% to 3.6%, until the crisis started in the second half of 2008. On average the house prices increased from January 2003 to January 2009 by 23.8%. The price to construct a new house for a housing corporation rose from € 90,000.- in 2003 for 383 m^3 to € 99,000.- in 2008 for 385 m^3. Prices of houses developed by private ownership or by project developers rose from € 126,000.- for 542 m^3 to € 147.000,- for 563 m^3.

3.2 State of technology

One can argue if the state of technology is a macro development. Nevertheless, technical developments are highly important in the field of energy saving techniques and the authors would like to address that for every building project the current state of available energy techniques should be regarded. However, stakeholders might attempt to rely on traditional techniques that are known to them by means of former projects. Last decade many new technologies were introduced in the housing market to save energy. At this moment the high efficiency natural gas boiler and insulation packages with a heat resistance of 3.0 $m^2 \cdot K/W$ are common in the Netherlands. The adoption rates of solar collectors, photovoltaic panels, and heat pumps are still rather low, although the techniques are already available for many years. The adoption rate of heat exchangers for waste water of showers is on the other hand relatively high. This technique has low investments costs, is easy to implement in new houses and has a high impact on the EPC. New techniques recently introduced in residential real estate are Phase Change Materials and LED-lighting for example. The availability of techniques will in the nearby future increase, because of growing environmental awareness and higher energy prices. Techniques that are already available will be improved and will probably become cheaper.

3.3 Project's context

Dutch social housing corporations have agreed to lower the energy consumption of their houses. Starting by October 2008, the natural gas consumption needs to be lowered by at least 20% within 10 years. Therefore, an energy performance certificate, which were introduced all around Europe in line with the Energy Performance Building Directive (EC, 2001), with classification B is desirable for existing houses or the performance should at least be improved by two steps in this A to G classification method. For new houses the energy consumption should be decreased by 25%, starting from the first of January 2011. In 2015 the reduction should increase to 50%.

Our main interest in this paper is the energy target. From the corporation's point of view the most important issue and "raison d'être" is to offer housing to all persons in society that are not able to obtain housing by themselves. These persons are most often restrained by financial means, but it is also possible that tenants have a physical or mental handicap.

3.4 Actor's characteristics

The objective of social housing corporations is to provide affordable housing of a proper quality for households with a minimum income. It is hard to achieve this

objective in a market with relatively high land prices of € 341.- /m^2 on average. Besides, the average building costs of a rented house are € 86,000.- (excluding VAT) (Bouwend Nederland, 2007) and the adoption of energy saving techniques makes even higher investments necessary.
A subsidy on the rent is provided for the tenants of this type of residential real estate, when their income -minus the costs of renting- are below certain thresholds. These thresholds are solely based on the basic costs of hiring without service costs or energy costs. On average the basic costs are € 402.- per month (Bouwend Nederland, 2007). This means that extra energy investments (that go beyond the basic regulations of the Building Code) can not be earned back by raising the monthly rent, because an increase will result in a subsidy stop for the tenant. However, the tenant does receive a lower energy bill and therefore will benefit from the investment done by the housing corporation.

4. Results of the case study research

After describing the context, this section presents four cases to gain insights in the influence of stakeholders in adopting energy saving techniques. These cases are provided by one social housing corporation in the Dutch municipality of Almelo. We analysed internal documents (like investment reports, specifications and drawings) and held interviews to specify the role of different actors and to fill in our framework. The corporation owns approximately 6,700 houses. Within the corporation different departments can be distinguished. One department has the obligation to initiate projects (client), another department manages the project (project manager), and a third department maintains and rents houses (customer). In some housing corporations these departments even form stand-alone firms, which only share one corporate identity for outsiders. By interviewing stakeholders and by studying written documents we were able to study the role and influence of every actor with the use of our framework.

4.1 Case 1: The design and construction process of new social houses

The first case (see Figure 2) studied is a project in which 73 new social houses were developed, of which 35 houses were commissioned by the client (Cl 1) described in the previous section. The other 38 houses were commissioned by another social housing corporation in the same municipality (Cl2). In January 2005 a first proposal to develop the 35 houses shows that the houses are expected to be built with a standard EPC of 1.0 or less. Although the municipality requested to develop houses with a 10% lower EPC from the very first beginning, it took the social housing corporation more than eight months for incorporating this policy into their design process.
In November 2005, under pressure of the municipality (Mu), the social housing corporations improved in het investment proposal the EPC ambition to 0.9. This mainly meant that the architect improved the heat resistance of floors, walls and roofs in the designs of the houses, resulting in EPC's with values of 0.81 to 0.95 with an average of 0.90. In this case the municipality was the most important stakeholder in coming to a better energy performance than obliged by the National Building Code. This improved energy performance was commissioned by the client to the architect.

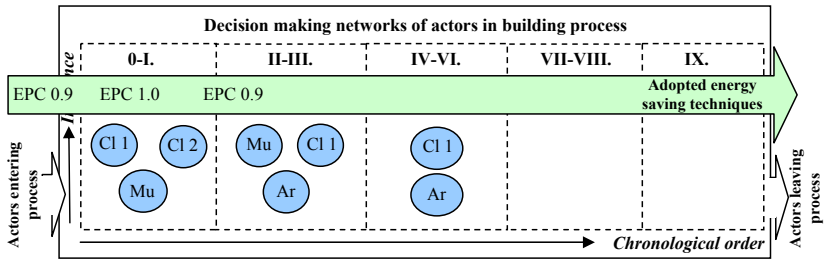


Fig. 2: Stakeholders in achieving an improved energy performance in case 1

4.2 Case 2: The design and construction process of new condos for seniors

The second project is a housing project for elderly. In this project the social housing corporation (Cl 1) collaborated with a local living and healthcare centre (Cl 2), as shown in Figure 3. The social housing corporation developed a high-rise apartment building containing 41 apartments and three penthouses. The initiation took place in December 2002 and the construction was completed in June 2009. In September 2003 the ambition was expressed to come to an improvement EPC of 0.9. Nevertheless, in 2005 an EPC of 0.98 was mentioned in the request for the building permit. The property developer, an internal department of the social housing corporation, used his influence to come to an improved EPC within the designs of the building. Although the client (Cl1), property developer (PD) and project manager (PM) belong to the same organisation, the project manager did not share the ambition in contrast with the property developer. In the next phase the EPC was therefore adjusted to 0.98.

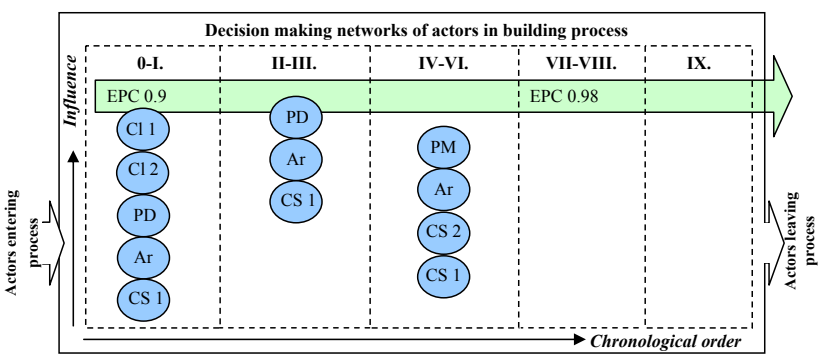


Fig. 3: Stakeholders influence in achieving an energy performance in case 2

4.3 Case 3: The design and refurbishment of duplex houses

The third case, that started in 2003, is a refurbishment process of 81 duplex houses, which were transformed to 54 dwellings. In this process e no explicit energy saving

ambitions were specified in the project or investment proposal (see Figure 4). Nevertheless, the project manager introduced some measures to improve the energy performance because of the growing awareness that energy performance certification would be introduced for buildings in the whole European Union. Consequently the heat resistance of the roof, windows, walls and floors was improved.

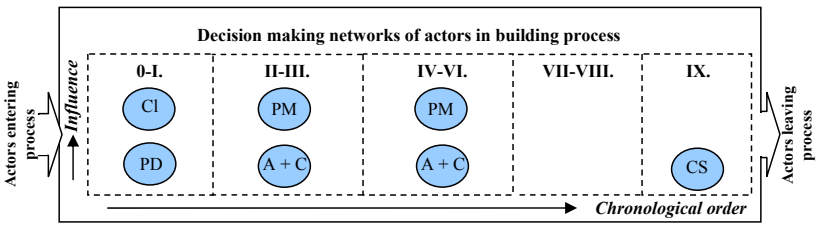


Fig. 4: Stakeholders in coming to an improved energy performance in case 3

Afterwards, on request of the social housing corporation energy performance certificates were obtained for the 54 dwellings, showing so called Energy Indices of 1.13 to 1.21 or in other terms a label B. The energy label was given by an external organisation (CS), when the houses were already constructed and in use.

4.4 Case 4: The design process for refurbishment of condos

In 2004 a process was initiated on how to refurbish 102 condos, which were constructed in 1958 and renovated in 1988. After 45 months in which the plans were initiated, developed and a price was set by a contractor, the plans were not approved by the director, because the project was to expensive (see Figure 5). In 2009 the six buildings encompassing the 102 condos were demolished. The need for refurbishment was given by the fact that in 2008 the buildings would end their second life cycle; twenty years after the renovation of 1988. The plans were based on stripping the complete building to its carcass and adding extra condos with an EPC of 0.8 on top. At first an EPC of 0.95 was set as a target, but the possibility to receive subsidy triggered the project manager to ask for an improved energy performance. A new building shell would provide a better heat resistance for the existing condos.

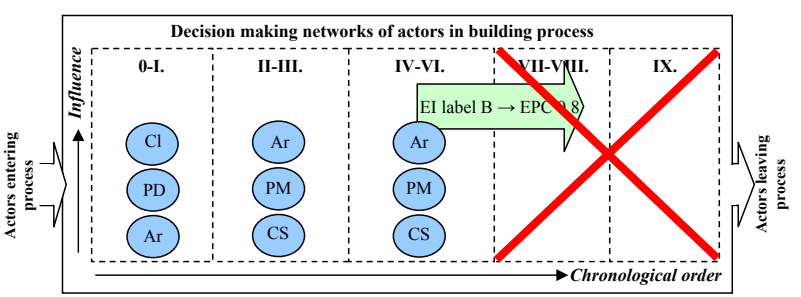


Fig. 5: Stakeholders in coming to an improved energy performance in case 4

5. Discussion and conclusions

Our research aims at improving the understanding of the role and influence of actors in the process of adopting energy techniques. A framework was developed based on the adoption process of innovations. The design processes in our cases show, however, that by using rather traditional technologies the social housing corporation was already able to comply with the compulsory EPC of the Building Code or the 10% lower EPC demanded by the municipality. Individual techniques seem not to dominate the discussions between stakeholders, but the EPC as an indicator is a major discussion topic. Rogers' aspect of relative advantage addresses the impact of separate techniques on the EPC and not the possible advantage of energy reduction for the user. On the other hand, the fact that traditional measures are being used in the studied cases shows the great relevance of Rogers' attribute of compatibility.

The influence of stakeholders differs strongly per project. Although the client, project manager, and project developer belong to the same organisation, they seem not to share one common vision regarding the energy performance. The municipality was able to force an improved EPC for the new buildings and ambitious project managers played an important role in the renovation projects. The impact of the architect may certainly not be neglected but his influence was only prevalent in the last case.

We can conclude that our framework helps to depict the transformations in relations between stakeholders during the design process. A clear analysis of the specific interests of stakeholders is needed to develop and implement successful energy savings measures. The paper further revealed the importance of studying adoption in its specific context, in this case the social housing setting.

Further research should take place on the roles of energy saving techniques and stakeholders in the building processes of offices.

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Exploring the Validity of Qualitative Methods to Analyze Project Delivery of Sustainable, High Performance Buildings

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ABSTRACT

Construction management and project delivery literature is dominated by quantitative methods. However, recent research suggests that its project based and people centric nature requires adoption of additional qualitative methods. Owing to the mounting complexity in sustainable, high performance building projects and consequent increase in the requirements for optimized solutions achieved by interdisciplinary integration of project teams; an on-going research aims to determine the relation between project delivery methods and level of integration in the delivery process and their further effects on sustainable goals. The preliminary findings of this study show that qualitative methods lead to a deeper understanding of sustainable building project delivery. In the conducted structured interviews and surveys for data collection mainly from three project participants (i.e. owner, designer, and contractor) for each case study, disjunctions were seen within inter-participant responses and between the survey and interview of the same participant. The affected metrics in this process, which include owner's commitment, project delivery method, and integration in the delivery process, are presented in this paper.

KEYWORDS: High performance green buildings, integrated design, project delivery methods, performance metrics, qualitative methods.

1. INTRODUCTION

Construction management is highly dominated by numerical data. Predominance of such data historically has resulted in quantitative research. Recent research shows that the construction industry's highly dynamic and people centric character includes

variables challenging to quantify such as owner commitment (Beheiry, 2006), project team characteristics, and team communication and chemistry (Korkmaz, 2007) that influence construction projects. Therefore, the adoption of qualitative methods should also be considered for the analysis of construction projects. An on-going research effort focusing on project delivery of sustainable, high performance buildings verified the importance of utilizing qualitative methods in data collection and analysis for capturing vital information on project delivery attributes. The main goal of this research is to: "*determine the extent to which project delivery methods and practices affect levels of project team integration and whether this has an effect on project performance outcomes with a priority on achieving sustainable goals."*

Sustainable, high performance buildings are defined as *"buildings that integrate and optimize all major high performance building attributes, including energy efficiency, durability, lifecycle performance, and occupant productivity"* (The Energy Policy Act, 2005). The emphasis on both environmental protection and value addition to the quality of occupant life have made the process of sustainable, high performance buildings construction more complex than the traditional ones (Du Plessis, 2007). Delivery of these buildings requires integrative project delivery practices including early participant involvement and high interaction for a collaborative process that focuses on design, construction, operation and occupancy phases of projects (7Group, 2004; Pommer and Horman, 2009). Although the sustainable industry and literature points towards integration and close relationships among project participants, a dearth of literature was found when rigorous guidelines to achieve the same were researched upon.

In pursuit of this endeavor, a background study conducted on project delivery of traditional projects revealed the dominance of quantitative studies (Pocock, 1996; Konchar and Sanvido, 1998; Molenaar and Songer, 1998). Alternatively, recent studies focusing on project delivery of sustainable buildings underline a rising trend in the use of qualitative data for the search of various phenomena (Lapinski, 2006; Korkmaz, 2007; Pommer and Horman, 2009). Keeping the goal of the study in mind and the inherent subjectivity in the perspectives of project participants towards events in construction projects, this research adopted qualitative methods of data collection and analysis. The preliminary findings of the study lucidly illustrate that qualitative methods are essential to truly understand the project delivery attributes of a sustainable, high performance building. More specifically the methods utilized assisted the research effort to: 1) build consensus and eliminate the discrepancies within inter-participant responses; 2) generate a deeper understanding of the events that is not possible from only survey responses; and 3) discover the hard to quantify but significant types of variables. The study variables in this research effort, for which the use of qualitative methods lead to a greater understanding, include owner's commitment to sustainability, project delivery method (PDM), and integration in the design process.

2. BACKGROUND

Quantitative data analysis generates numerical data through large-scale surveys, where qualitative research explores attitudes, behavior and experiences through methods such as interviews and focus groups (Dabbs, 1982). Due to its nature of

relating to numbers and measures - therefore, *implied* precision, quantitative methodology is *impulsively* considered to be more scientific than qualitative (Berg, 2006). The limitations of the quantitative methodology includes: 1) its extent being bounded to the development and utilization of mathematical models, theories and / or hypotheses pertaining to natural phenomena (Silverman, 2001); and 2) its limited potential to examine, analyze and interpret observations for the purpose of discovering underlying meanings and patterns of relationships, including classifications of types of phenomena and entities (Patton, 2002). Also, qualitative methodology is comparatively unpopular because the research takes longer period of time and requires greater clarity of goals during design stages (Berg, 2006).

In the construction industry many phenomena are often too large to be tested in a traditional, quantitative, and statistical fashion. Taylor et al. (2009) suggests that in the field of construction research, case studies allow researchers to study phenomenon set in reality; thereby, allowing the researcher to witness decisions made about real issues impacting factors such as a time, cost, quality, and safety. Case study approach to research, being one of the most adopted qualitative methodology across disciplines, as defined by Yin (2003), is: *"an empirical inquiry that investigates a contemporary phenomenon within its real life context, especially when the boundaries between the phenomenon and context are not clearly evident."* This approach has been critiqued on generating non-generalizable results due to limited sample size (Yin, 2003; Taylor et al. 2009). Taylor et al (2009), also reports that many manuscripts based on case study research are executed with insufficient precision, quantification, and/or objectivity where investigators have allowed a biased view to influence the direction of the findings. However, such bias can occur and be controlled with any research method (Taylor et al. 2009).

In project delivery studies too, researchers have followed quantitative methods traditionally; however, recently qualitative methods has gained attention as a valid approach for the research project delivery especially for sustainable building projects. A snapshot of this transition i.e., from quantitative to qualitative research given in Table 1 where various project delivery methods such as DB (design-build), DBB (design-bid-build), and CMR (construction management at risk) were investigated.

For data collection in quantitative studies, the use of archival records and survey applications are the most common methodologies. In qualitative studies, superiority of no method (e.g., observations, survey application, structured, semi-structured, unstructured interviews) has been observed. However, Sandelowski (2000) suggests that data collection tool can be used in a combination to fulfill a variety of objectives to provide a fuller description of cases such as interviews and/or observations. For example, the discrepancies found in a survey can be resolved by conducting follow-up interviews.

3. RESEARCH APPROACH

The data collection tool utilized in this study was based on the research conducted by Korkmaz (2007). This survey was developed on previous research focusing on comparison of PDM's (Konchar and Sanvido, 1998) and procurement methods in design-build projects (El Wardani et al., 2006). After adopting this verified data collection tool, it was adjusted according to the research specific criteria and verified by an industry panel associated with this research. Finally, the tool was tested through

Table 1: Review of the methods utilized in project delivery literature

Reference & Description	METHODS		LIMITATIONS
	Quantitative	Qualitative	
Pocock (1996): Compared the performance of traditional projects to those using alternative delivery.	- Regression analysis		
Konchar and Sanvido (1998): Empirically compared the cost, schedule and, quality of the U.S. building projects under CMR, DB and DBB.	- Univariate and - Multivariate regression models		Quality performance was based on the perception of the owner.
Molenaar and Songer (1998): The study provides a selection model for public sector DB projects.	- Regression models		The model cannot produce accurate predictions a 100% of the time.
Pulaski (2005): Develop a process-based model for detailed project decisions concerning sustainability on high performance building projects	- Categorize and Plot (+) and(–) rated data, Sign Test and, Null hypothesis testing	- Content analysis - Comparative analysis - Document review	- Short period of time to effectively gauge any continuous improvement. - Limited number of case studies.
Magent (2005): Evaluate the value, relationship, and timing of decisions in the design process of high performance buildings.		- Pattern matching - Cross case synthesis - Explanation building	- Researcher bias - Limited number of case studies as validation
Beheiry et al. (2006): Investigate the impact of corporate commitment to sustainability on capital project planning.	Regression analysis		- Small sample size - Low level of significance in the findings
Lapinski et al. (2006): Empirically identify the critical activities that led to the success of Toyota's South Campus project.		Process mapping	
Korkmaz (2007): Define meaningful evaluation metrics for HPG building project delivery.	- Univariate and - Multivariate regression Models	- Pattern matching - Cross case synthesis	- Limited number of studies - Handpicking case study threatens the external validity
Pommer and Horman (2009): Understand the key practices those are most critical for the delivery of health care facilities.		- Process mapping - Pattern matching - Cross case synthesis	- Limited number of case studies

a pilot study. The final survey includes questions that are a mix of multiple choice, Likert scale, and open ended questions under the following sections: owner commitment, PDM, contract conditions, project team procurement, integration in the design process, project team characteristics, cost and schedule performance, safety, levels of high performance and sustainability, quality, owner's post-occupancy

evaluation, and lessons learned. A combination of survey application and structured interviews (i.e., based on the GAO (1991) methodology) were utilized for data collection.

The case study selection criteria employed in this study required that the case study projects are: 1) under the new construction category (i.e., the *new construction* and *core and shell category* of USGBC's LEED® certified projects is prioritized in the search of projects); 2) delivered under one of the major project delivery systems in the U.S.: design-bid-build (DBB), design-build (DB), and construction management at risk (CMR); and 3) certified under one of the four categories of USGBC's LEED® certification (i.e., platinum, gold, silver, certified). A location variety in the sample was preferred to eliminate bias towards any city, region, or state. Also, to eliminate functional and major construction systems differences that could lead to high variability in the performance outcomes, the type of buildings in the study sample were limited to office buildings. A list of potential projects to collect data on was generated from the USGBC's LEED® certified project directory which was also verified by the research industry panel. The researchers planned for including three main project participants (i.e., owner, designer, and contractor) from each case study to the data collection process. Potential respondents were contacted via telephone or e-mail to request participation in the study.

The resulting sample consists of 12 case studies ranging from 7000sqft to 190,000sqft. Of these case studies, five of them were delivered under CMR, four under DB and three under DBB. In terms of LEED® certification achievement, three of the case studies were certified, while other three received silver, two gold and, four platinum certifications. The final collected data was in the form of survey and interview recordings. The interview recordings were transcribed verbatim and coded for themes with commercial software.

The case study tactics based on Yin (2003) to comply with the data quality addressed in this research are classified under: construct validity, internal validity, external validity, and reliability. The tactics employed under construct validity (i.e., use of multiple sources of evidence and establishment of chain of evidence) helped the researchers to see the discrepancies between various responses (i.e., among respondents' from the same case studies and between the survey and structured interview of the same participant). The analysis of the data were conducted through: 1) Pattern matching: to identify recurring phenomenon in the data which can also assist generalizability; and 2) Cross case synthesis: to compare similar projects in terms of size and scope that are at the opposite ends of performance scale in terms of their performance outcomes and emphasize on the differences within project characteristics to understand the do's and don'ts for the process followed.

4. FINDINGS

The findings of this study strengthened the view of adopting qualitative methodologies in project delivery research. The metrics identified as being directly affected by the methodology utilized in this research include: owner commitment, PDM, and integration in the design process. The findings of this study affected by the qualitative methodologies are described below under data collection, data analysis, and additional lessons learned.

Data Collection: Yin (2003) suggests the use of multiple sources of evidence and establishment of a chain of evidence to construct validity. Therefore, this study interviewed multiple respondents from a single project to understand the whole picture. Also, the data collection tool included survey application and structured interviews. Although the respondents first filled out the survey (via e-mail or phone), during the structured interviews they again went through the whole questionnaire elaborating on their survey responses. The structured interviews revealed discrepancies in the collected data as described below. Examples of such discrepancies are given in Table 2.

Table 2: Examples of discrepancies within responses

Variables Tested	Survey Responses	QUOTES from Structured Interviews			VERIFIED DATA
		OWNER	DESIGNER	CONTRACTOR	
Primary reason to pursue green	O: Energy Use/ Cost D: No response C: Energy Use/ Cost, State Rebates	*"we were very proactive on cutting edge technology and it seemed like the way to go.. we wanted to save money in the future ...* ***there were some grants we were looking at as well"***	*"what we sold the owner on was the energy reduction in energy consumption and the productivity of the occupants"*	*"……. gave owners* ***funds*** *as an incentive if they met the green objectives"*	Suggested from all quotes was that **'financial incentives'** was the primary reason to pursue green.
Timing of inclusion of green strategies	O: Conceptual Phase D: No response C: Schematic Phase		*"I think it was not till* ***the end of schematic phase*** *that the owner committed to go forward with LEED®"*		Designer response to be conclusive: **Design Development**
Project delivery method	O: DBB D: DBB C: CMR	Analyzed based on contractual conditions			DBB
Importance of green goals for the team	O:very important D: no response C:very important	*"they were very important."*	*"for us they were very important, for the owner they were important but not nearly as important… for the contractor I'd say not important"*		Designer response to be conclusive: **Fairly Important**

*O= Owner, D= Designer C= Contractor

1. Discrepancies between the responses of the same project participants through survey application and structured interviews:

As the survey and the interview responses of the same participants were compared, it was observed that many responses did not align with each other. This was seen in the following variables: reason to pursue green objectives, selected project delivery and procurement methods, and project team procurement. These discrepancies can be based mainly on two reasons; a) absence of the apt response option in the survey; and b) lack of understanding of the terminology of the response options.

a) Absence of the apt response option in the survey: Scholastic categorization of responses is different from the industry understanding of the same. For example, the survey gave only three options for the 'selection of the PDM', namely: DBB, CMR, and DB. However some projects were hybrids. For example, by definition some of the projects were delivered by the DBB method but they had the contractor on board informally earlier than the bidding process. Another observation was that, a couple projects were a combination of CMR and DBB because the contractors were on board to conduct pre-construction services; however, they also ended up winning the final bid. Due to the lack of understanding of the exact scholastic definition, the respondents chose the best option according to their understanding. Under PDM, it was also seen that many respondents could not differentiate CMR and DB. It was only after they explained their project processes and their contractual relationships in the structured interviews; the exact PDMs could be inferred. Therefore, structured interviews were critical in understanding the actual PDM adopted in these cases.

This discrepancy also occurred in the answers to 'primary reason to pursue green'. The survey responses for this question mainly belonged to one of the three answers: 1) owner driven factor/vision statement; 2) mandated by the client; and 3) energy and cost savings. However, the open ended answers revealed other reasons, such as LEED® certification and positive market image. It seems that in most cases, the main reason to pursue green objectives was: achieving LEED® certification, which eventually translated not only to a positive market image (i.e., boosting business interests), but also in some cases financial motivations such as tax breaks, state grants, and permission for higher building square feet ratio per area.

b) Lack of understanding of the terminology of the response options: Scholastic definitions and terminologies are slightly different from the industry. Although definition of various terminologies was provided in the survey, it was observed that the respondents did not necessarily clearly understand those and therefore, responded to the survey questions according to their best understanding. However, during the structured interviews when they verbally explained their survey response, the right answer was centered upon. For example, many respondents marked low bid on the survey when the procurement method for the contractor was asked for. However, during the open ended answers they suggested that it was also qualification based, thereby making the method best value selection.

2. Discrepancies among the responses to the same questions by various respondents: In some projects disjunctions were seen within inter-participant responses i.e., responses of various participants from the same project towards the same questions. These discrepancies occurred mainly due to three reasons; a) absence of the apt response option in the survey; b) lack of understanding of the terminology of the response option; and c) respondents' desire to project a positive image. The main metrics observed to be affected in this category are: owner commitment, PDM, and level of integration in the project delivery achieved. The first two reasons have been previously explained, reason c has been explained in detail below.

c) Respondents' desire to project a positive image: It must be considered that the projects chosen for this study had LEED® certification as one of their primary characteristics. LEED® not only confirmed their sustainability but also authenticated the project teams' commitment towards environmentally friendly building design and

construction practices. Therefore, many times it seemed that the received responses were tailored around being environmentally responsible. The participants seemed to choose the survey responses that projected a positive image of themselves. However, at many points of cross-referencing multiple sources of evidence, the collected data did not align with each other. In these cases, to come to a single response for each case study, the project had to be seen in its entirety, and then based on the validity of the responses, decisions had to be made. For example, some of the respondents reported under 'importance of green goals' that, they were very important; while their team members reported it to be only fairly or not important. Based on the responses to other relevant questions (i.e., reason to pursue green and the timing of inclusion of green strategies) a single consensus had to be defined.

Similar conflict was also visible in 'the timing of inclusion of green'. In the majority of the cases, the participants instinctively suggested that 'green' notion was included in the project at conceptual design phase; however, for conclusive responses, designers' answers were prioritized. This is because in actuality, projects don't go through explicitly defined phases and amongst all the respondents, designers have the maximum potential to understand these phases. Moreover, in all of the project delivery methods, designer is the project party that is available and working on the project starting from the early phases, while other parties might not get involved directly with projects until after the bidding phase (i.e., in DBB projects).

Data Analysis: Low sample size reduces the chances of getting statistically significant results. On the other hand, in qualitative studies, minimal number of cases selected through preset criteria can help enable the achievement of considerable findings. By analyzing data through *pattern matching,* trends can be seen within projects that play an important role in the success and failure of a project. For example, in this study while examining 'the timing of inclusion of green strategies to a project' under owner commitment, a trend was seen that projects are more successful if green strategies are included early in the design process. Also, chances of exceeding the intended target increases if the project is highly integrated i.e., all the participants are on board contractually and working towards a common goal. *Cross case synthesis,* as another method utilized in this research, facilitates comparison of similar projects in terms of size and complexity, which are on the extreme scale of the project performance spectrum. This method allows in achieving comparative findings in terms of project delivery attributes between projects that perform high and low in all outcomes categories (i.e., cost, schedule, sustainability, quality, post occupancy). While it would be impossible to come to a statistically significant conclusion with data points from only twelve projects, careful selection of a small sample of case studies reveals findings through the observation of patterns in qualitative data analyses and allows for many insightful lessons learned.

Additional Lessons Learned: The use of qualitative data collection and analysis methodologies in this study also revealed additional lessons learned towards achieving the goals of the research:

1. *Lower success projects displayed more discrepancies:* Project success/outcomes was based upon the following metrics: cost, schedule, project quality, and level of sustainability and high performance achieved. It was seen that projects displaying

low success in the overall included more discrepancies within responses than the projects show high success.

2. *Lower certified projects displayed more discrepancy:* A trend was observed within the selected case studies that, projects that are silver or certified in LEED® had more discrepancies within their responses compared to others.
3. *The ratio of failure in low certified projects was higher than in high certified projects:* Out of the 12 projects, six are low certified in LEED® (i.e., certified and silver) and the other six are higher rated projects (i.e., gold and platinum). Two of the low certified projects scored very low and two scored medium in their outcomes metrics, while under high certification only one scored very low and one scored medium for outcomes.
4. *DBB projects prone to maximum discrepancy:* There are three projects in the sample that were delivered under the DBB method. Compared to other projects, maximum discrepancy within responses was seen in these projects. This discrepancy can be owed to the timing of the contractors' involvement in the project team. Due to the late entry to the project, the contractors were found to be not necessarily fully informed about the details of all project information and/or the exact information of the process, especially prior to their entry.

5. DISCUSSIONS

This paper shows that construction research also requires qualitative methodologies in addition to quantitative methods. Due to the small green building population that includes many variations, generating significant statistical lessons learnt for project delivery of sustainable, high performance buildings is not possible. However, by handpicking case studies and looking at the data in various ways (i.e., pairing them according to success and various project delivery attributes) we can achieve meaningful results to improve our understanding about their project delivery processes. However, there are various limitations of this methodology that can be overcome by careful attention to the data collection and analysis procedure. One of the primary drawbacks is that the time lag skews the memory of the events and experiences in the minds of the team members resulting in inaccurate responses. Also, many respondents tend to tailor their answers to project a positive image. Careful attention has to be paid to remove such respondent bias by conducting comparative analyses within the interviews of the other participants from the same project. Finally both handpicking case studies and conducting structured interviews can accommodate bias from the researcher to suggest predetermined results. However, these can be eliminated by following a standard data collection procedure and analysis methods. Finally, researchers should consider the potential longer periods of time qualitative methodology might require. Improved clarity of goals during research design stages and crafting a well thought case study selection criteria can help overcoming this drawback and improve research results.

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IDENTIFYING FACTORS THAT AFFECT THE ENERGY CONSUMPTION OF RESIDENTIAL BUILDINGS

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ABSTRACT

The reduction of energy consumption is one of the economic necessities in the United States due to the depletion of fossil fuel energy sources in the world. Renewable energy, such as solar energy, has been increasing in use in residential buildings to lower homeowner energy costs. The construction industry is also contributing to the reduction of energy consumption of buildings by producing designs that are energy efficient and by constructing buildings with energy efficient materials, and mechanical and electrical equipment.

This study collected data on energy consumption (electricity and natural gas), building characteristics, and energy use practices of 30 homeowners and their residences in Henderson, Nevada. Statistical analysis was performed to determine electricity and natural gas consumption for theses homes. The results showed that the annual electricity and natural gas consumption of these homes was close to that of the national energy audit record. The study also identified six factors that affected the annual electricity consumption of the homes. Additionally, it determined three factors that affected the annual natural gas consumption of the home. The findings of this research will be beneficial to homebuilders and homeowners interested in reducing energy consumption through design, construction and homeowner practices.

KEY WORDS: Energy Consumption, Construction Industry, Residential Buildings.

INTRODUCTION

The United States (US) is one of the largest energy users in the world. In 2007, the electricity consumption of US was 3,817 billion Kwh, which is equivalent to 23.3% of the world consumption (EIA 2009). The world electricity consumption increased 4% from 2006 to 2007, while the US consumption increased by 2% during this period.

Similarly the US ranked first in natural gas consumption. The natural gas consumption in the US in 2007 was 23,058 billion cubic feet, which is 26 % of the total world consumption. The US consumption increased by 6.5% from 2006 to 2007. In 2007, the US residential sector used about 4.7 billion cubic feet of natural gas, which is 20% of the total US consumption. In 2007, the residential natural gas consumption in Nevada was 3,808 million cubic feet, an increase of 0.4% from 2006.

Due to an increasing consumption and depletion of energy sources, the US government has formulated various policies for reducing electricity and natural gas consumption. These policies help not only to reduce the energy consumption but also help to reduce greenhouse gas emissions. In addition to this, home designers, homebuilders, and homeowners need to be aware of homeowner practices that affect the energy consumption of residential buildings. Some of these are: use of energy-efficient appliances, energy efficient home designs and remodels that use good ventilation and insulation, and use of solar-powered appliances. This study focused on determining the efficacy of the above mentioned factors. The main objectives of this study are:

- Determine the annual electricity and natural gas consumption of homes in Henderson, NV
- Determine the factors that affect the electricity and natural gas consumption of these homes.

LITERATURE REVIEW

Ugursal and Fung (1996) studied the interrelationship between energy consumption of buildings and appliance efficiency, and fuel substitution for space and domestic water heating. They conducted simulation studies using data from 937 homes located in different regions of Canada. The results of the study showed that appliance efficiency and fuel substitution could reduce energy consumption of the buildings. Energy savings from replacing old appliances with high efficiency appliances was found to be less significant in comparison to that of fuel substitution. Another finding was that appliance efficiency coupled with improved home envelopes and heating/cooling systems could significantly save energy consumption.

Resencrantz et al. (2004) conducted a simulation study to determine the effect of anti-reflective (AR) coated low-emissivity (low-e) glass on the daylight factor, solar factor, and annual heating demand of homes. The study's results showed that the monthly average solar factor for AR coated low-e glass increased by 7% compared to the low-e glass without AR coating. In addition to this, the annual heating demand decreased by 4% due to high solar transmittance through the windows. The simulation also showed that the day light factor increased by 21%.

Feuermann and Novoplansky (1997) conducted a study using simulations to determine the effect of windows with low solar heat gain coefficients (SHGC) on the reduction of energy consumption in the summer and winter. The SHGC windows were double glazed with the exterior pane tinted. Summer energy savings were determined with the SHGC window's tinted pane facing the exterior. Similarly, winter energy savings were determined by reversing the window such that tinted pane faced the interior. The results showed that significant energy savings in summer and

winter could be achieved with the reversible windows. Guliermetti and Bisegna (2007) studied positions of the reversible windows and concluded that the yearly savings obtained with reversible windows were strictly linked to the method used to control indoor air temperature to avoid overheating. Their study also found that windows facing west and east increased the yearly energy saving from 10% to 15% compared to southward facing windows.

Aydinalp et al. (2002) proposed the neural network (NN) method to model the appliances, lighting, and space-cooling component of residential energy consumption in Canada. The NN model determined causal relationships between energy consumption of homes and different factors. Some of the factors were household income, dwelling type, ownership, size of the homes, and number of adults and children living in the homes. The findings of this study were electricity consumption: increased as income increased; was higher for single detached houses than single attached houses; higher for owner-occupied houses than renter-occupied houses; and increased as number of children and adults in the house increased.

Heldin and Orr (1978) conducted a study to determine the effect of heating-degree days on the energy consumption of residential buildings. They collected data for 1,000 homes located in Saskatchewan, Canada and analyzed the relationship between these two factors. The results showed that there was a linear positive relationship between number of heating-degree days and the energy consumption of the homes.

RESEARCH METHODOLOGY

The factors affecting the electricity and natural gas consumption of the homes were first examined and identified through a relevant literature review and by conducting a pilot study. Ten home owners' data were collected in the pilot study to determine the availability of the data. Using the results of the pilot study, the final survey instrument was designed which consisted of five sections. Section 1 contained questions related to home ownership, number of people living in the home, and square footage of the home. Section 2 contained questions related to age and frequency of use of the home appliances. Section 3 contained questions on fuel usage for heating equipment, equipment age, and frequency of use of the equipment. The room temperature setting the homeowner used during the winter was also collected. Section 4 contained questions related on air conditioner age and frequency of use. The room temperature setting the homeowner used during the summer was collected. Section 5 consisted of questions related to electricity and natural gas consumption data for 12 months.

The questions in Section 1 were selected to determine whether ownership, number of people living in the home, and home's area have a correlation with energy consumption. Aydinalp et al. (2002) showed that there is a positive correlation between the area of a home and energy consumption.

Section 2 questions were designed to determine the relationship between the use of appliances with the energy consumption of a home. Ugursal and Fung (1996) showed that the use of TV, computers, and other home appliances have linear correlation with the electricity consumption of the homes.

Section 3 and 4 questions were designed to determine the relationship between the use of air conditioners and heaters with electricity and natural gas consumption of the home. Heldin and Orr (1978) showed that the number of heating-degree days is the main source leading to natural gas consumption in homes with natural gas heating.

Familiar non-technical terminology was used in order that homeowners would easily understand the questions. The authors also made a home visit or telephone call during data collection to verify that the homeowners understood the questions correctly. Data were collected for 30 homes constructed in 2001, 2005, and 2008 in Henderson, NV.

FINDINGS

The data was analyzed to determine mean, maximum, minimum, and standard deviation of the electricity and natural gas consumption. These statistics and correlation coefficients were used to determine the factors affecting the energy consumption of the 30 homes. The results are described below.

SUMMARY STATISTICS OF ELECTRICITY CONSUMPTION METRICS

Table 1 shows descriptive statistics of electricity and natural gas consumption of the homes. The table shows the annual consumption per household, annual consumption per square foot (SF), and annual consumption per capita. The average annual electricity consumption per household was 9,240 Kilowatt-hour (kWh). The annual electricity consumption per SF was 5.05 kWh. The average annual electricity consumption per capita was 4,831 kWh. The average annual electricity consumption per capita had a maximum variation of about 11,000 kWh. The annual electricity consumption per SF had the minimum variation. The greatest variation was approximately 20,000 kWh and it was for annual consumption per household.

Table 1: Descriptive Statistics of Electricity and Natural Gas Consumption

Statistics	Annual Consumption per Household		Annual Consumption per SF		Annual Consumption per Capita	
	Electricity (kWh)	Natural Gas (MJ)	Electricity (kWh)	Natural Gas (MJ)	Electricity (kWh)	Natural Gas (MJ)
Mean	9,240	46,537	5.05	25.90	4,831	24,013
Maximum	24,181	83,942	8.64	49.18	12,090	76,259
Minimum	4,476	19,497	2.96	8.82	1,080	7,348
Standard Deviation	3,656	16,950	1.72	10.11	2,615	14,560

The table shows the annual consumption per household, annual consumption per SF, and annual consumption per capita. The average annual natural gas consumption per household was 46,537 mega joules (MJ). The average annual natural gas consumption per SF was 25.90 MJ. The average annual natural gas consumption per capita was 24,013 MJ. The annual natural gas consumption per

capita had a maximum variation of about 69,000 MJ. The annual natural gas consumption per SF had the minimum variation.

RELATIONSHIP ANALYSIS

Analyses were performed to determine the relationship of energy consumption with characteristics of the homes and use of home appliances. Two separate analyses were conducted to determine factors affecting electricity and natural gas consumption. The findings of these analyses are described below.

Relationship between Annual Energy Consumption and Number of People

The correlation coefficients of number of people living in a home with annual electricity and natural gas consumption were determined. The results showed that there was a weak correlation between these variables. The correlation coefficient between the number of people living in home and annual electricity consumption was .06. Similarly the correlation coefficient between the number of people living in home and annual natural gas consumption was 0.05. These correlation coefficients were not statistically significant at alpha level 0.05.

Relationship between Annual Energy Consumption and Floor Area of Homes

The correlation analysis between the annual electricity consumption and the floor area of the homes showed that the annual electricity consumption was positively correlated with the floor area of the homes. The correlation coefficient was found to be 0.59 and statistically significant at alpha level 0.05. The correlation showed that the electricity consumption of the homes increased as the area increased. Therefore, to determine the relationship with other factors, the electricity consumption data was normalized by dividing the total electricity consumption with the area of the home.

The correlation analysis between the annual natural gas consumption and the floor area of the homes showed that the annual natural gas consumption was also positively correlated with the floor area of the homes. The correlation coefficient was found to be 0.31. The correlation showed that the annual natural gas consumption of the homes increased as the floor area increased. Therefore, to determine the relationship with other factors, the natural gas consumption data was normalized by dividing the total consumption with the area of the home.

Relationship between Annual Energy Consumption per Area and Construction Year of the Homes

The data were collected from the homes which were constructed in 2001, 2005, and 2008. The mean annual electricity consumption of these three different types of homes was compared to determine factors affecting energy consumption. Table 2 shows the mean annual electricity consumption and percentage increase relative to the construction year 2001. The analysis showed that there was no definitive relationship regarding the annual electricity consumption based on construction year. The homes which were built in 2008 consumed less energy than the homes that were built in 2001 and 2005.

Table 2: Annual Electricity Consumption Based on Construction Year

Construction Year	Mean Annual Electricity Consumption (kWh/SF)	Percentage Increase	Relationship
2001	4.84	-	No relationship
2005	5.53	+14.3	
2008	4.72	-2.5	

The mean annual natural gas consumption of these three different types of homes was compared. Table 3 shows the mean annual natural gas consumption per floor area and percentage increase. The analysis showed that the natural gas consumption increased as the year of construction increased. The homes which were built in 2005 and 2008 consumed more natural gas than the homes that were built in 2001. It is not always the case that when two variables are positively correlated then they have a "cause and effect" relationship.

Table 3: Annual Natural Gas Consumption and Construction Year

Construction Year	Mean Annual Natural Gas Consumption (MJ/SF)	Percentage Increase	Relationship
2001	24.58	-	Positive relationship
2005	26.80	+9.01	
2008	26.90	+9.44	

Relationship between Annual Energy Consumption per Area and Type of Window Used in Homes

The mean annual electricity consumption of homes with three different types of window glass used in homes was compared. Table 4 shows the mean annual electricity consumption per floor area and percentage increase relative to the single panel window glass. The analysis showed that the electricity consumption decreased when more panels with low-emissivity (e) glass were used in windows. The homes that used double pane windows with low-e glass had less consumption than the homes that used single or double pane windows.

Table 4: Annual Electricity Consumption and Types of Window Glass

Type of Window Glass	Mean Annual Electricity Consumption (kWh/SF)	Percentage Increase	Relationship
Single Panel	5.34	-	Negative relationship
Double Panel	5.15	-3.68	
Double Panel Low-e	4.61	-13.71	

The mean annual natural gas consumption of homes with different types of window glass was compared. Table 5 shows the result of mean annual natural gas consumption per square foot and percentage increase. The increase in percentage did not show any relationship between these two variables. The natural gas consumption was low for those homes that had glass windows with double pane low-e. However, the homes that had double pane windows consumed more natural gas than those homes that had single pane glass windows. It can be explained from the fact that

when two variables are positively correlated does not mean that they have a "cause and effect" relationship.

Table 5: Mean Annual Natural Gas Consumption and Types of Window Glass

Type of Window Glass	Mean Annual Natural Gas Consumption (MJ/SF)	Percentage Increase	Relationship
Single Pane	25.32	-	No relationship
Double Pane	26.38	+4.17	
Double Pane Low-e	24.27	-4.17	

Relationship between Mean Annual Electricity Consumption per Area and Home Owners Behavior and Appliances Characteristics

The relationships between mean annual electricity consumption per square foot and age of air conditioner, frequency of air conditioner use, and temperature setting for the air conditioner were analyzed. Table 6 shows the mean annual electricity consumption per square foot and percentage increase relative to the baseline parameter. The data showed that all three factors had relationships with mean annual electricity consumption per square foot. The electricity consumption of homes increased as the age of the air conditioner increased. The more frequently the air conditioner was turned on, the electricity consumption of the homes increased. Similarly, the lower the temperature of the air conditioner thermostat is set, the more electricity the homes consumed.

Table 6: Mean Annual Electricity Consumption and Characteristics of Air Conditioner

Factors	Mean Annual Electricity Consumption (kWh/SF)	Percentage Increase	Relationship
Age of Air Conditioner			
Less than 1 year	4.72	-	Positive relationship
1 to 5 years	5.08	+7.78	
6 to 10 years	5.29	+12.14	
Frequency of Air Conditioner Use			
3-4 days a week	4.15	-	Positive relationship
Every day	5.15	+24.10	
Temperature Set During Summer			
68-76 degrees	5.22	-	Negative relationship
77-86 degrees	4.90	-6.18	

Relationship between Mean Annual Electricity Consumption per Area and Clothes Washer Characteristics

The relationships between mean annual electricity consumption per square foot and age of the clothes washer and frequency of clothes washer use were analyzed. Table 7 shows the mean annual electricity consumption per square foot and percentage increase relative to the baseline parameter. The data showed that both of these factors had relationships with annual electricity consumption per square foot. The electricity

consumption of homes increased as the age of the clothes washer increased. The more frequently the clothes washer was used the greater the electricity consumption of the home.

Table 7: Mean Annual Electricity Consumption and Age of Clothes Washer

Factors	Mean Annual Electrical Consumption (kWh/SF)	Percentage Increase	Relationship
Age of Clothes Washer			
Less than 1 year	4.43	-	Positive relationship
1 to 5 years	5.24	+18.37	
6 to 10 years	5.16	+16.56	
Frequency of Clothes Washer Use			
Less than3 days a week	4.05	-	Positive relationship
3-6 days a week	5.36	+32.39	
Every day	5.07	+25.22	

Relationship between Mean Annual Natural Gas Consumption per Area and Heating Equipment Characteristics

The relationships between mean annual natural gas consumption per square foot and age of heating equipment, frequency of heater use, and room temperature setting for winter were analyzed. Table 8 shows the mean annual natural gas consumption per square foot and percentage increase relative to the baseline parameter. The data showed that only room temperature setting during winter had a positive relationship with mean annual natural gas consumption per square foot. The natural gas consumption of homes increased as the temperature of the room was set higher.

Table 8: Annual Natural Gas Consumption and Heating Equipment

Factors	Mean Annual Natural Gas Consumption (MJ/SF)	Percentage Increase	Relationship
Age of Equipment			
Less than 1 year	26.26	-	No relationship
1 to 5 years	25.10	-4.42	
6 to 10 years	26.26	0.0	
Frequency of Heater Use			
Less than3 days a week	30.27	-	No relationship
3-6 days a week	25.00	-21.1	
Every day	25.74	-14.98	
Room Temperature Setting During Winter			
65-70 degrees	23.31	-	Positive relationship
71-79 degrees	27.85	+19.46	

Relationship between Annual Natural Gas Consumption per Area and Clothes Dryer Characteristics

Table 9 shows the mean annual natural gas consumption per square foot and percentage increase relative to the baseline parameter. The data showed that only

frequency of clothes dryer use had a relationship with the mean annual natural gas consumption per square foot. The natural gas consumption of homes increased as the frequency of the clothes dryer use increased.

Table 9: Mean Annual Natural Gas Consumption and Age of Cloth Dryer

Factors	Mean Annual Natural Gas Consumption (MJ/SF)	Percentage Increase	Relationship
Age of Clothes Dryer			
Less than 1 year	26.26	-	No relationship
1 to 5 years	25.21	-4.02	
6 to 10 years	26.26	0.0	
Frequency of Clothes Dryer Use			
Less than 3 days a week	23.52	-	Positive relationship
3-6 days a week	24.47	4.04	
Every day	29.00	23.32	

CONCLUSIONS

The mean annual electricity consumption per household for this sample was about 9,240 kWh. According to the Energy Information Administration (EIA 2009), the average annual electricity consumption per household of the residential sector in Nevada for 2007 was 11,832 kWh. This research's data showed that the annual natural gas consumption per household was 46,537 MJ compared to 59,000 MJ calculated by EIA for Nevada.

Table 10 shows the factors that had relationships with the annual electricity and gas consumption per square foot and some of the factors considered. The study identified nine factors, which had relationship with the annual electricity and natural gas consumption of the homes. The results of this study showed that there are some factors which homeowners can control to reduce the energy consumption of their homes.

Table 10: Relationships between Factors and Annual Electricity and Natural Gas Consumption

Factors	Direction of Relationship	
	Annual Electricity Consumption	Annual Natural Gas Consumption
Construction Year	No relationship	Positive relationship
Type of Widow Glass	Negative relationship	No relationship
Age of Air Conditioner	Positive relationship	NA
Frequency of Air Conditioner Use	Positive relationship	NA
Temperature Set in Summer	Negative relationship	NA
Age of Clothes Washer	Positive relationship	NA
Frequency of Clothes Washer Use	Positive relationship	NA
Room Temperature Set in Winter	NA	Positive relationship
Frequency of Clothes Dryer Used	NA	Positive relationship

LIMITATIONS OF THE FINDINGS

These findings are based on sample size of 30 homes located in Henderson, Nevada. The homes were built in 2001, 2005 or 2008. Therefore, all the homes were of relatively new construction. Natural gas is predominantly used for heating and electricity for cooling. Extreme care should be exercised in the interpretation of this data in other context. The authors recognize that the findings are based on samples of one particular location of US, so generalization of these results would not be possible.

RELEVANCE TO INDUSTRY PRACTIONERS AND RESEARCHERS

The findings of this study provide an indication that designers and constructors can have an impact on whether a home is energy efficient or not based upon their design, materials selected and specified, and quality of construction. Homeowner behavior also appears to be a major factor in the energy consumption of a home. The factors in this study that exhibit a relationship should be used as a guide for target points to attempt to modify homeowner and homebuilder behavior to reduce the overall energy consumption of homes. Although this study was exploratory in nature and the findings based on limited sample size in a particular location, the researchers recommend revision of the survey instrument and an expansion of the study to other areas of the US to determine whether the initial results of this study holds true.

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Impact of Sustainability Perceptions on the Purchasability of Materials in Construction Projects

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Abstract: The construction industry is a constantly-changing market, thereby making suppliers direct their efforts to understanding and meeting owners' requirements. Recently, a significant change in the construction industry has been the increased interest in sustainable materials. Material selection has been identified as an area where designers and contractors can have a significant impact on the environmental performance of a building. This paper illustrates how a tool to measure the user-based assessment of product sustainability can be used to evaluate the contribution of qualitative factors on material selection. The objective is to develop an instrument that validates user's perceptions of product sustainability and evaluate the effect of sustainable characteristics in the purchasability of construction materials. A survey of design and construction students and practitioners is carried out to capture the factors included in the instrument. A Factor Analysis approach is used to validate user's perceptions of sustainability and to demonstrate the effect on purchase intentions due to the factors considered.

1. Introduction

The market for sustainable buildings is increasing since the construction industry has acknowledged they may mitigate the impact on the environment and bring significant social and environmental benefits (Ries et al. 2006, Wang et al. 2005, Thormark 2006). To realize such benefits it is necessary to select materials which conform to sustainable principles (Abeysundara et al. 2009, Wang et al. 2005, Glavic and Lukman 2007). Traditionally, sustainability appraisals are based on life-cycle assessment (LCA) as a tool to quantify the environmental impact (Ljungberg 2007, Abeysundara et al. 2009, Giudice et al. 2005). However, the visual features and the metaphysical aspects of products may influence appraisals and affect decision making

in sustainable materials selection (Ljungberg 2007). Therefore, it would be helpful to create a tool to help suppliers measure the assessment of features from the perspective of users in sustainable materials selection.

A number of studies on properties of sustainable materials have been carried out, indicating the use of objective as well as subjective measures in defining sustainable products. Sustainable materials are materials with high recycled content (Mora 2007, Zhou 2009), low-emitting contaminants (Mora 2007, Glavic and Lukman 2007), rapid renewable periods (Glavic and Lukman 2007), high reused content (Mora 2007, Zhou 2009) and harmful contaminants' free (Zhou 2009). In addition, sustainable materials are characterized as low consuming (Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009), low reparable and highly prolonged (Ljungberg 2007, Mora 2007), easy to build with (Dammann and Elle 2006), safe to use (Zhou 2009, Mora 2007, Ljungberg 2007), highly satisfying to the user (Ljungberg 2007), something the public needs (Glavic and Lukman 2007), do more with less (Glavic and Lukman 2007), and as trend braking (Ljungberg 2007) among others. As a result, if a building has to be built according to sustainable principles, a thorough process of selection of materials has to be performed.

The material selection problem has been tackled with the support of analytical tools (Sirisalee et al. 2004, Ashby 2000), ranking methods (Jee and Kang 2000, Chan and Tong 2007), index-based methods (Holloway 1998, Giudice et al. 2005), and other quantitative methods (Farag 2002). However, the current literature lacks of a method that may simplify and accelerate the decision making process with the support of images. Visual features may broaden decision making capabilities by allowing a process of evaluating more data without overloading the decision maker (Lurie and Mason 2007). Through visual recognition and human's highly developed skills of perceptual senses, decision makers could reduce large data sets to simple visuals.

A number of studies have been developed to assess visuals' qualitative and subjective characteristics that may influence decision making. The scenic views that affect occupants' satisfaction in buildings (Li and Will 2005), the aesthetic of facades which affect perceived quality of buildings (Gifford et al. 2000), environmental aesthetics which influence urban landscape quality (Bernasconi et al. 2009), and product creativity that influences consumer evaluation of products (Horn and Salvendy 2006). However, there is no study of how sustainable features may influence decision making in materials selection. The assessment of sustainability perceptions among construction professionals may help suppliers determine how do users actually perceive a product to be sustainable and what criteria is involved which may affect purchase intentions. Therefore, to help suppliers measure how sustainable features affect the materials selection process, this study carries out a Factor Analysis approach to validate user's specific visual perceptions of sustainability using a modified version of the creativity tool (Horn and Salvendy 2006). A survey of design and construction students and practitioners is carried out to capture the factors included in the instrument. The Factor Analysis determines the number of sustainability dimensions. The analysis can be used to show the purchasability intentions of construction professionals towards sustainable products and the

importance of examining specific visual features as direct predictors of sustainability appraisals.

2. Model of consumer perception of product sustainability

Consumer's perception of product sustainability is examined by developing and testing a measurement instrument of product sustainability based on the creativity measurement instrument developed by Horn and Salvendy 2006. The model shows the process of how consumers retrieve information about a product and compare this information to a set of sustainability criterion in order to determine the level of material sustainability. Sustainability is defined as the subjective judgment of a product to enhance well-being, give satisfaction to the user, and conserve resources in economically viable, safe and healthy ways for consumers (Glavic and Lukman 2007). To be a sustainable product, the product must be judged as socially and creatively rewarding for all stakeholders for the short and long term future (Glavic and Lukman 2007). From this definition, four dimensions of product sustainability were derived and one additional dimension to measure purchase intentions. The quality dimension measures the product's capability to satisfy customer requirements. The functionality dimension measures the usefulness of sustainable materials. The user appeal dimension measures the arousal impact of the product sustainability. The resourcefulness dimension measures the product characteristics associated with sustainability. Finally, the purchasability dimension measures the purchase intentions. The five dimensions of product sustainability are measured using an instrument which includes 14 items (see Table 1).

Table 1. Sustainability measurement instrument

Sustainability dimension	Item number	Product sustainability measurement item
Quality	*P1*	ordinary-extraordinary
	P2	unreliable-reliable
	P3	temporary-durable
Functionality	*P4*	unusable-functional
	P5	impractical-useful
	P6	worthless-helpful
User appeal	*P7*	unattractive-attractive
	P8	detrimental-beneficial
	P9	disappointed-satisfied
Resourcefulness	*P10*	wasteful-resourceful
	P11	inefficient-efficient
	P12	common-innovative
Purchasability	*P13*	not willing to pay for it-willing to pay for it
	P14	not want to purchase it-want to purchase it

The adjective pairs (*P1-P14*) used to measure the quality, functionality, user appeal, resourcefulness and purchasability dimension items deployed for this instrument were based on derived associated wording in subjective characteristics derived from previous studies (Dammann and Elle 2006, Glavic and Lukman 2007, Zhou 2009, Ljungberg 2007, Mora 2007, Horn and Salvendy 2006).

3. Research methodology

In order to test the five-dimensional instrument and to better understand the factors that could influence product sustainability perceptions, a web-based survey was conducted. The use of the survey questionnaire was an approach to capture all the dimensions of product sustainability and was not intended to establish cause-effect relationships (Horn and Salvendy 2006). The results are intended to reveal whether the sustainability perception of design and construction students and practitioners is dependent on the selected variables. Previous to these evaluations, a pilot study was conducted to refine the survey and select the specific material to be used in the study. Since the goal of the survey is to learn about the attitudes of construction professionals toward sustainability, the target population was design and construction students and practitioners involved in decision making of materials selection.

The survey presented a brief definition of sustainable products and a two-dimensional image of a specific construction product. An e-mail was sent to each prospective subject requesting their participation. When the subject opened the Web-based survey (Survey Monkey 2009) by clicking on the link in the e-mail, a brief written introduction and instructions that asked for completion of the measurement instrument was given. The Web-based survey was available for three weeks. The Web site presented a brief definition of sustainable products and a two-dimensional image. The subject was instructed to first examine the product image and description and to think about the product sustainability. Then the subject was asked to mark responses that best describe the specific product shown on the Web site. The subjects were asked to evaluate the overall sustainability of the specific product and mark a sustainability score on a 7-point Likert scale (1=extremely not sustainable, 2=not sustainable, 3=slightly not sustainable, 4= neither not sustainable nor sustainable, 5=slightly sustainable 6=sustainable, 7=extremely sustainable) to the questions asked.

The questions included were each of the adjective pairs in Table 1. For instance, the three item pairs for resourcefulness dimension are resourceful-wasteful, efficient-inefficient and innovative-common. One question asked respondents if the product of the image is inefficient or efficient on the 7-point Likert scale (1=extremely inefficient, 2=inefficient, 3=slightly inefficient, 4= neither inefficient nor efficient, 5=slightly efficient, 6=efficient, 7=extremely efficient). The other dimensions are tested in a similar manner (see Figure 1). Approximately half of the measurement items were reversed to reduce response bias and two questions were repeated to measure data reliability. The subjects' responses were automatically stored anonymously in a database when the subject clicked the "submit" button.

After collecting the responses to the survey, the instrument of consumer perception of product sustainability can be validated and the number of dimensions of product sustainability can be determined. Once the instrument has been validated, a product sustainability score can be given to materials to account for product sustainability and the overall weighting of importance of subjective characteristics. In addition, purchasability can be measured accounting for users' intentions to acquire sustainable construction materials. One type of construction product was selected for

evaluation: bricks. This product was chosen based on the commonality and high usability in the construction industry.



Figure 1. Screenshot of survey regarding sustainable characteristics

4. Data Analysis

The web-based survey was sent to design and construction students and practitioners. The Web site presented a two-dimensional image of the specific product. The subjects were asked to evaluate the overall sustainability of the product and mark a sustainability score on the 7-point Likert scale. A total of 100 surveys were responded and 87 were completed.

Information on important characteristics was obtained from the survey data such as age, gender, highest level of education, experience in construction, type of work performed, usage of sustainable materials, accessibility and willingness to pay for sustainable materials. The information obtained can increase the understanding of issues affecting knowledge in product sustainability and professional awareness of sustainable materials. Learning about these issues can contribute to increase the

accessibility to data sources of sustainable materials and highlight its benefits to the construction industry increasing purchase intentions of sustainable materials.

The minimum age of respondents was 18 years of age with a mean age of 26 years (n=89). Of the total number of subjects (n=89), 48 were female (53.9%) and 41 were male (46.1%). When asked about the highest level of education obtained, 71.9% (n=89) responded to have at least an undergraduate degree. The experience in construction of respondents ranged from 1 to 20 years with a mean of 2.8 years (n=87). Approximately fifty-five percent (54.7%) of the respondents indicated that their work is related to architecture and design, 11.6% related to contracting business and 8.1% related to engineering. In relation to sustainability issues, the data shows that 47.2% of the respondents (n=89) have used or have built a building using a sustainable material, 40.4% (n=89) have been looking for sustainable materials unavailable in their region and 80% (n=89) are willing to pay at least 20% more for a sustainable material in comparison to a common material.

5. Statistical Analysis and Results

Once all the information on important characteristics was retrieved from the survey data, a statistical analysis was performed. Descriptive statistics of the data are provided in Table 2. For instance, it was found that the independent variables *disappointed-satisfied, wasteful-resourceful and not want to purchase it-want to purchase it* have the highest symmetry as compared to the other variables. Furthermore, the descriptive statistics show that most of the variance for the variables *common-innovative* and *impractical-useful* is due to infrequent extreme deviations. In addition, the correlation between the variables is shown in Table 3. Even though the 14 independent variables in the study contain all the sustainability perceptions information and explain all the variance of the sample, some of the variables may have qualitative and quantitative distinctions. Therefore, an analysis that tests the qualitative distinctions and groups variables into factors to determine the dimensions of product sustainability is undertaken.

Table 2. Descriptive statistics of independent variables

Item	sustainability dimension	N	min	max	mean	std. dev	skewness	kurtosis
P1	ordinary-extraordinary	88	1	6	2.7	1.31	0.9	0.0
P2	unreliable-reliable	100	2	7	6.0	0.73	-2.1	9.9
P3	temporary-durable	92	3	7	6.0	0.76	-1.1	2.8
P4	unusable-functional	93	1	7	5.7	0.99	-2.0	6.3
P5	impractical-useful	100	1	7	5.9	1.00	-2.5	9.1
P6	worthless-helpful	92	3	7	5.7	0.87	-0.8	0.6
P7	unattractive-attractive	100	1	7	5.1	1.18	-1.3	1.8
P8	detrimental-beneficial	86	3	7	5.5	0.74	-1.8	3.4
P9	disappointed-satisfied	89	3	7	5.2	1.04	-0.7	-0.7
P10	wasteful-resourceful	91	1	6	4.5	1.26	-0.7	-0.2
P11	inefficient-efficient	93	1	7	5.0	1.19	-1.9	4.1
P12	common-innovative	99	1	7	1.4	0.91	4.0	20.1
P13	not willing to pay for it-willing to pay for it	99	2	7	5.1	1.10	-0.9	0.3
P14	not want to purchase it-want to purchase it	93	2	7	4.9	1.11	-0.6	-0.8

To determine the dimensions of product sustainability an exploratory factor analysis was performed. All data analysis was performed using Statistical Package for the Social Sciences SPSS version 16.0 (2007). Initially the five factors considered a total variance of 71%. However, two of the factors had eigenvalues smaller than one indicating an inappropriate number of factors or dimensions. Furthermore, the factor structure examined with the scree test shows a smooth decrease in the slope after four factors (see Figure 2). Therefore, a refinement and validation of the product sustainability instrument has to be conducted (i.e., three factors seem to be the appropriate number of dimensions to measure product sustainability perceptions).

Table 3. Correlation matrix of independent variables

	P1	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*	*P9*	*P10*	*P11*	*P12*	*P13*	*P14*
P1	1.00	0.02	0.24	0.03	0.13	0.22	0.28	0.14	0.28	0.18	0.17	0.27	0.34	0.28
P2	0.02	1.00	0.38	0.30	0.49	0.43	0.19	0.53	0.28	0.19	0.49	0.06	0.34	0.24
P3	0.24	0.38	1.00	0.12	0.18	0.33	0.30	0.31	0.27	0.25	0.27	0.20	0.31	0.28
P4	0.03	0.30	0.12	1.00	0.36	0.35	0.07	0.45	0.17	0.17	0.49	0.07	0.20	0.19
P5	0.13	0.49	0.18	0.36	1.00	0.44	0.02	0.44	0.26	0.18	0.48	0.02	0.28	0.25
P6	0.22	0.43	0.33	0.35	0.44	1.00	0.23	0.64	0.48	0.19	0.44	0.17	0.46	0.36
P7	0.28	0.19	0.30	0.07	0.02	0.23	1.00	0.26	0.49	0.00	0.10	0.10	0.64	0.53
P8	0.14	0.53	0.31	0.45	0.44	0.64	0.26	1.00	0.44	0.33	0.53	0.14	0.36	0.38
P9	0.28	0.28	0.27	0.17	0.26	0.48	0.49	0.44	1.00	0.13	0.28	0.16	0.73	0.59
P10	0.18	0.19	0.25	0.17	0.18	0.19	0.00	0.33	0.13	1.00	0.44	0.22	0.08	0.19
P11	0.17	0.49	0.27	0.49	0.48	0.44	0.10	0.53	0.28	0.44	1.00	0.15	0.27	0.30
P12	0.27	0.06	0.20	0.07	0.19	0.17	0.10	0.14	0.16	0.22	0.15	1.00	0.16	0.25
P13	0.34	0.34	0.31	0.20	0.28	0.46	0.64	0.36	0.73	0.08	0.27	0.16	1.00	0.67
P14	0.28	0.24	0.28	0.19	0.25	0.36	0.53	0.38	0.59	0.19	0.30	0.25	0.67	1.00

The refinement and validation of the product sustainability instrument would be conducted across different studies (Horn and Salvendy 2009). With this initial study, the model of consumer perception of product sustainability was developed. The model includes the selection of the measurement instruments and the initial structure of the product sustainability perceptions measurement instrument. As indicated by the analysis of the collected data perceptions measures, the instrument has to be evaluated and refined. Therefore, a subsequent study will be performed to reduce the number of dimensions and refine the instrument. The first step of refinement will be to verify the appropriateness and stability of the instrument. The second step of refinement will be to purify the instrument by undertaking a confirmatory factor analysis. In addition to the refinement of the product sustainability perceptions instrument, the instrument's predictive validity will be examined. The validity will be tested by assessing consumer's attitude towards product sustainability measured in the attitudes' instruments (Horn and Salvendy 2006).

With this model of product sustainability and validated instrument, both researchers and practitioners can begin to investigate how various methods, environmental factors, individual or group characteristics, and other variables may influence consumer product sustainability perceptions. Material suppliers can also use this dimensional model to incorporate design considerations, comparisons, and overall evaluations. With the understanding that consumer product sustainability is perceived in the product's level of the instrument's dimensions, suppliers can

concentrate on designing these specific product qualities to enhance consumer satisfaction and purchase intentions.

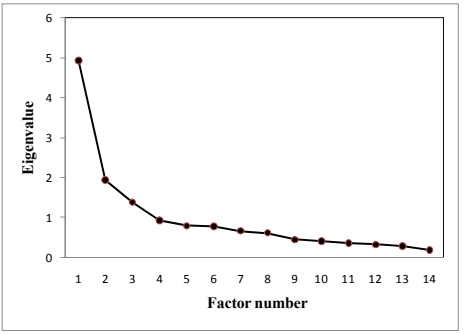


Figure 2. Scree plot

6. Concluding remarks

A number of studies on properties of sustainable materials have been carried out, indicating the use of objective as well as subjective measures in defining sustainable materials. Although the material selection problem has been approached by considering objective factors that may influence the decision-making process, subjective factors need to be considered as well. Visual features of materials may have an emotional impact on the user and on the user's appraisal of sustainability. Therefore, an instrument is needed to assess subjective characteristics in order to improve the current decision-making process by considering subjective measures.

The instrument of consumer perception of product sustainability deployed in this study can help assess subjective characteristics of sustainable materials and bring significant positive changes to the actual process of material selection in sustainable construction. Its usefulness lies in the opportunity to include in the decision-making process subjective characteristics associated with sustainable products. The assessment of subjective characteristics may help capture how users perceive a product to be sustainable and all the factors that may influence product sustainability. Therefore, suppliers can include in the material's image visual features typically associated with sustainable characteristics, reducing large data sets to simple visuals. Through visual recognition and human's highly developed skills of perceptual senses, the benefits of visual information of a product could be realized. As a result, the process of materials selection may be simplified and accelerated. Visual features may broaden the capabilities of the decision-making process by allowing users to evaluate more data without being overloaded with information.

A natural extension of this work could include the evaluation of sustainable buildings. By doing so, a wider scope of decisions can be supported, including ratings of the buildings' emotional impact and global sustainability made by users. Another possible extension to the proposed model is to compare sustainability perceptions among laypersons and construction professionals. This could help determine which variables and factors influence assessments of sustainability in both groups and

differences in awareness of sustainability principles. As a result, these differences may indicate suppliers to concentrate on designing specific product qualities to enhance overall consumer satisfaction and increase purchase intentions according to the target group.

As electronic environments increase, the range of construction materials expands overwhelming users with information and making the information retrieval process effortful. Therefore, it is necessary to understand the market of materials in order to help users benefit from all the information provided. The instrument developed in this study may contribute to benefit the marketing of sustainable materials. By investigating the factors that influence user's perception of material sustainability and predicting user's attitudes, material databases could become valuable tools to assist in purchasability of sustainable materials in an ever-expanding range of options. The understanding of demand within building construction contributes on how to make sustainable practices remain viable for the well-being of present and future generations.

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Leadership in Energy and Environmental Design Certification of a Project in Alachua County: An Analysis of The 2007 Florida Building Code, and the Alachua County Unified Land Development Code for Leed 2009

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Abstract

Contractors, architects, and owners are often unaware of the credits that are achieved under Leadership in Energy and Environmental Design for New Construction (LEED-NC) 2009 by following the local building and land development codes in Alachua County. An analysis of the Alachua County Codes provides were analyzed to evaluate the probability of achieving credit and prerequisite requirements under LEED-NC 2009. Three credits and three prerequisites are achieved through code. Ten credits and three prerequisites share intent and have support for achievement through following the codes. By following the 2007 Florida Building Code and the Alachua County Unified Land Development Code, LEED certification cannot be earned under LEED-NC 2009 without project exceeding code requirements. However, this study provides local construction professionals with a starting point for selecting credits under the LEED-NC 2009 system in Alachua County.

INTRODUCTION

The objective of the study is to show which credits are achieved under LEED-NC 2009 by following the 2007 Florida Building Code and the Alachua County Unified Land Development Code. For each credit and prerequisite in LEED 2009, the 2007 Florida Building Code and the Alachua County Unified Land Development Codes were analyzed to identify similarities. The probability of achievement is given using a four-point scale, see Table 1-1: Achievability Score, which provides a starting point for projects registering under LEED-NC 2009 in Alachua County.

Table 1-1: Achievability Score

Achievability Score	Definition
0	Not addressed by Codes
1	Codes have similar intent to prerequisite or credit
2	Codes have similar intent to prerequisite or credit and have minor support for achievement
3	Codes have similar intent to prerequisite or credit and have major support for achievement
4	Prerequisite or credit achieved through Codes

Leadership in Energy and Environmental Design

The Leadership in Energy and Environmental Design (LEED) Rating System is a high performance green building rating system. LEED for New Construction (NC) is broken down into seven categories: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation in design, and regional priority. Each category has required prerequisites, and credits that are earned for points. Projects must earn all prerequisites and at least 40 points to become certified (USGBC 2009). The most current rating system is LEED Version 3.0 or LEED 2009. The credits with the most weight are those that directly impact energy consumption and greenhouse gas emissions that are associated with building systems, transportation, the embodied energy of water, the embodied energy of materials, and where applicable, solid waste (USGBC 2009).

2007 Florida Building Code

The 2007 Florida Building Code (FBC) represents the minimum standards for buildings in the state of Florida and supersedes all previous codes and all local codes. The FBC is based on national codes and consensus standards, adapted to address Florida's unique environment. The 2007 FBC applies to any construction, alternation, movement, enlargement, replacement, repair, equipment, location, use and occupancy, maintenance, removal and demolition of every structure in the state of Florida (ICC 2008). The intent, as expressed by the ICC the 2007 FBC follows:

> **101.3 Intent.** The purpose of this code is to establish the minimum requirements to safeguard the public health, safety and general welfare through structural strength, means of egress facilities, stability, sanitation, adequate light and ventilation, energy conservation, and safety to life and property from fire and other hazards attributed the built environment and to provide safety to fire fighters and emergency responders during emergency operations.

Unified Land Development Code of Alachua County

The Unified Land Development Code of Alachua County (ULDC) was created to ensure the public health, safety, and welfare of residents and landowners of Alachua County; also promote appropriate land use that is consistent with the policies and goals of the Alachua County Comprehensive Plan (Alachua County 2009). The

ULDC was most recent adopted February 24, 2009 (Ord. 09-01) and is updated as needed (Alachua County 2009). The ULDC applies to all areas within Alachua County and all annexed areas as well. The ULDC looks at development as a whole, including issues such as zoning, parking, and land restrictions.

SUSTAINABLE SITES

The Sustainable Sites (SS) category, in LEED-NC 2009, deals mostly with the physical site and less with the actual structures. Location, heat-island effects, open-space, light pollution, parking, pollution control and storm water are the major areas addressed by the SS Category. For this reason the 2007 FBC plays a minimal role in compliance with LEED SS Credits, unlike the Alachua County. See Table 1-2: Sustainable Sites Findings.

Analysis of 2007 FBC With Regard to LEED 2009 SS

The only similarity between the 2007 FBC and the SS category of LEED-NC 2009 is in Prerequisite 1: Construction Activity Pollution Prevention. The intent of Prerequisite 1 is to reduce construction related pollution caused by soil erosion, airborne particulate generation, and waterway sedimentation (LEED 2009). The 2007 FBC shows similar intent in section 3307.1 which states, "Provisions shall be made to control water runoff and erosion during construction or demolition activities" (ICC 2009). However, this does not meet the requirements of SS Prerequisite 1. The compliance for Sustainable Sites Prerequisite 1 is met by creating an erosion and sedimentation control plan for the site, which conforms to the more stringent of either local standards or the 2003 EPA Construction General Permit (LEED 2009). Additionally, the plan must accomplish the following objectives:

-To prevent loss of soil during construction by stormwater runoff and/or wind erosion, including protecting topsoil by stockpiling for reuse.
-To prevent sedimentation of storm sewers or receiving streams.
-To prevent pollution of the air with dust and particulate matter.

No other similarities can be found between the SS Category of LEED-NC 2009 and the 2007 FBC. Thus, following the 2007 Florida Building Code will not bring a project into compliance with any Sustainable Site Credits or Prerequisites.

Analysis of Alachua County ULDC With Regard to LEED 2009 SS

The Alachua County ULDC deals with development related issues. Section 406.12 of the ULDC requires that construction sites have a stormwater pollution prevention plan that is compliant with the National Pollution Discharge Elimination System (NPDES). The requirement for SS Prerequisite 1: Construction Activity Pollution Plan is to have a pollution prevention plan that is compliant with the more stringent of the EPA 2003 general permit or local standards. In Alachua County, they are one in the same. Thus, by following the ULDC, SS Prerequisite 1 is achieved.

Section 406.26 of the ULDC, partially addresses SS Credit 1: Site Selection, stating that the habitats of all species listed under "50CFR 17.11 and 17.12, Endangered and Threatened Wildlife and Plants, F.A.C. 5B-40.005, Regulated Plant

Index, F.A.C. 68A-27, Rules Relating to Endangered or Threatened Species and those identified as S1, S2, or S3 by the Florida Natural Areas Inventory" be permanently protected. However, the ULDC does allow for development of those lands with a special permit. This is not compliant with SSc1, which requires that areas that are habitats to threatened or endangered species not be built on. Another requirement of SSc1, addressed by the ULDC, is to not develop within 5 feet of elevation of a 100 year flood plain. Section 406.57 of the Alachua County ULDC addresses development in 100 year flood plains and prohibits development in a 100 year flood way. However, a flood way is not the 100 year flood plain and thus the ULDC is not compliant with LEED SSc1 for not developing in the 100 year flood plain

The Alachua County ULDC also addresses SSc1 by restricting development near wetlands and bodies of water. The ULDC has a list of Outstanding Florida Waters (OFWs), which are more protected than non-OFWs waters. In section 406.43 of the ULDC, waters that are non-OFWs and equal to or smaller than half an acre need a 35 foot development buffer, non-OFWs waters greater than half an acre need a 50 foot development buffer, waters within 300 feet of a protected vertebrate habitat dependent on that water need a 75 foot development buffer, and OFWs need a 100 foot development buffer. Most wetlands are considered to be OFWs and thus section 406.43 meets the SSc1 requirement of not developing within 100 feet of a wetland. However, the requirement of not developing within 50 feet of a body of water, is only met on a case-by-case basis. Thus, the ULDC shows support for achieving SSc1: Site Selection, but will not fully bring the project into compliance.

Sustainable Sites Credit 4.2: Alternative Transportation- Bicycle Storage and Changing Rooms is addressed in some regards by the Alachua County ULDC. This credit requires bike racks for 5% of peak building occupants and showers for 0.5% of full time equivalents within 200 yards of the building entrance; residential buildings require covered bike areas for 15% of occupants. The ULDC requires that buildings have one bicycle parking spot for every ten parking spots (based on square footage) or two bicycle spaces for each employee or public entrance to the building. The number of bike racks may be compliant for some buildings, but the ULDC does not require showers or covered bike areas. Therefore by following the ULDC, SSc4.2: Alternative Transportation- Bicycle Storage and Changing Rooms cannot be earned.

The required amount of parking for projects is given in section 407.15 of the Alachua County ULDC and supports the achievement of Sustainable Sites Credit 4.4: Alternative Transportation- Parking Capacity through Option 1. Option 1 requires that minimum parking requirements not exceed local code and preferred carpool and van parking be provided for 5% of total parking. The ULDC does not require carpool preferred parking, but does have a minimum amount of parking required, making Option 1 the only viable option without special permitting.

The Alachua County ULDC supports the achievement of Option 1 of SS Credit 5.2: Site Development Maximize Open Space. Option 1 requires that open space must exceed local open space requirements by 25%. Section 407.52 of the ULDC requires that open space for urban projects be 20% and 50% for rural projects. So to achieve SSc5.2 a project in Alachua County an urban area must have 25% or more open space and in a rural area 62.5% open space. Options 2 & 3 can also be followed through preemptive planning.

Section 496.12 of the Alachua County ULDC requires 20% of the site's canopy remain after development. This is beneficial for achieving SS Credit 7.1: Heat Island Effect- Non Roof, which requires 50% of the hardscape be: shaded by trees (within 5 years), architectural devices with an SRI of 29 or greater, or solar panels; be an open grid paving system, at least 50% pervious; or consist of materials with an SRI of 29 or greater. Following the ULDC's requirement for canopy cover should shade 20% of the entire site, assuming that canopy cover yields the same percentage of shade. Depending on the size of the site and building footprint, SSc7.1 can be met, since hardscape is only a percentage of the whole site

Table 1-2: Sustainable Sites Findings

Credit	Addressed by Code?	Code	Achievability Score
SSp1: Construction Activity Pollution Prevention	Yes	3307.1 FBC & 406.12 ULDC	4
SSc1: Site Selection	Yes	406.26, 406.43 & 406.57 ULDC	2
SSc2: Development Density and Community Connectivity	No	N/A	0
SSc3: Brownfield Redevelopment	No	N/A	0
SSc4.1: Alternative Transportation: Public Trans. Access	No	N/A	0
SSc4.2: Alternative Transportation: Bicycle Storage and Changing Rooms	Yes	407.15 ULDC	2
SSc4.3: Alternative Transportation: Low-Emitting & Fuel Efficient Vehicles	No	N/A	0
SSc4.4: Alt. Trans.- Parking Capacity	Yes	407.15 ULDC	4
SSc5.1: Site Development: Protect or Restore Habitat	No	N/A	0
SSc5.2: Site Development: Maximize Open Space	Yes	407.52 ULDC	2
SSc6.1: Stormwater Design: Quantity Control	No	N/A	0
SSc6.2: Stormwater Design: Quality Control	No	N/A	0
SSc7.1: Heat Island Effect- Non-roof	Yes	496.12 ULDC	2
SSc7.2: Heat Island Effect- Roof	No	N/A	0
SSc8: Light Pollution Reduction	No	N/A	0

WATER EFFICIENCY

The Water Efficiency (WE) Category of LEED-NC 2009 deals with water use reduction and wastewater reduction. The 2007 FBC does not address any of the requirements of the LEED-NC 2009 WE Category. Alternatively, the Alachua County ULDC, address strategies used to achieve WE Credit 1: Water Efficient Landscaping, see Table 1-3: Water Efficiency Findings. The ULDC suggests appropriate landscaping for the climate and even a species list of recommended vegetation. In section 407.43, the ULDC has basic xeriscaping requirements,

requiring: plants be grouped into high, moderate, and low water zones to reduce over-watering; planted areas have three inches of mulch; and turf grass only be planted in areas that have pedestrian traffic, recreation, or to be used for soil erosion control. These ULDC requirements all have implications for landscaping water use reduction. Water Efficiency Credit 1: Water Efficient Landscaping has two compliance paths; the first requires a 50% reduction from midsummer baseline calculation. Following the ULDC xeriscaping requirements will not fully comply with the WEc1 requirements. However, a reduction in water use for landscaping can be seen.

Table 1-3: Water Efficiency Findings

Credit	Addressed by Code?	Code	Achievability Score
WEp1: Water Use Reduction	Yes	N/A	0
WEc1: Water Efficient Landscaping	No	407.43 ULDC	1
WEc2: Innovative Wastewater Technologies	No	N/A	0
WEc3: Water Use Reduction	No	N/A	0

ENERGY AND ATMOSPHERE

The Energy and Atmosphere (EA) category of LEED-NC 2009 deals with the aspects of a projects energy and the refrigerants effects on the atmosphere. The 2007 FBC has many similarities with the LEED-NC 2009 Standards via primarily the Energy Code. No similarities were found between the Alachua County ULDC and the EA Category of LEED-NC 2009. See Table 1-4: Energy and Atmosphere Findings.

Analysis of 2007 FBC With Regard to LEED 2009 EA

Energy and Atmosphere Prerequisite 1: Fundamental Commissioning of the Building Energy Systems requires six prescriptive items be met. The six requirements are: develop owner's project requirements and basis of design; verify the installation and performance of the system to be commissioned; designate a commissioning authority to lead, review and oversee the commissioning process; incorporate commissioning requirements into the construction documents; implement a commissioning plan; and complete commissioning summary report. The systems LEED requires be commissioned are: lighting and day-lighting controls, domestic hot water systems, HVAC&R, and renewable energy systems. Support for Prerequisite 1 is seen in Section 13-407.ABC.2.6 of the 2007 FBC, stating "HVAC Control systems shall be tested to ensure control elements are calibrated, adjusted, and in proper working condition." This suggests some form of commissioning or testing and balancing needs to occur, but only requires HVAC control systems be tested. Therefore by following the 2007 FBC, EAp1 cannot be achieved.

Energy and Atmosphere Prerequisite 2: Minimum Energy Performance requires new buildings have a 10% improvement in baseline building performance above ASHRAE/IESNA Standard 90.1-2007. The 2007 FBC only meets the standards of ASHRAE/IESNA Standard 90.1-2004. The 2007 FBC does not meet the requirement of EAp2: Minimum Energy Performance, however, it is partially achieved. By

following the 2007 FBC an improvement above ASHRAE/IESNA Standard 90.1-2007 can be assumed, although it will not equal 10%. The same problem is seen with EA Credit 1: Optimize Energy Performance. By following the 2007 Florida Building Code a typical building is around 15% more efficient than a baseline building as defined by ASHRAE/IESNA Standard 90.1-2004. This does not carry over to being 15% more efficient than ASHRAE/IESNA Standard 90.1-2007. Therefore, by following the 2007 Florida Building Code no points will be awarded for EAc1: Optimize Energy Performance.

The FBC does not address refrigerants because they are addressed under the 1990 Clean Air Act Amendments to the Montreal Protocol. These Amendments require no new Chlorofluorocarbon (CFC) refrigerants be used beyond 1996. EA Prerequisite 3: Fundamental Refrigerant Management requires that zero CFC-based refrigerants be used in new buildings HVAC&R systems for compliance. By obeying the Clean Air Act Amendments, EAp3 is achieved.

One of the six requirements of LEED-NC 2009 EAc3: Enhanced Commissioning is met by following the 2007 FBC. It requires a systems manual be created for future operating staff, Section 13-102.1 states:

> An operating and maintenance manual shall be provided to the building owner for all commercial buildings. The manual shall include basic data relating to the design, operation and maintenance of HVAC systems and equipment.

Only one of the other five requirements for EAc3: is met by the 2007 FBC providing only minor support for credit achievement.

Table 1-4: Energy and Atmosphere Findings

Credit	Addressed by Code?	Code	Achievability Score
EAp1: Fundamental Commissioning of Building Energy Systems	Yes	13-407.ABC.2.6 FBC	1
EAp2: Minimum Energy Performance	Yes	Section 13 FBC	3
EAp3: Fundamental Refrigerant Management	Yes	1990 Clean Air Act	4
EAc1: Optimize Energy Performance	Yes	Section 13 FBC	3
EAc2: On-Site Renewable Energy	No	N/A	0
EAc3: Enhanced Commissioning	Yes	13-102.1 FBC	1
EAc4: Enhanced Refrigerant Management	No	N/A	0
EAc5: Measurement and Verification	No	N/A	0
EAc6: Green Power	No	N/A	0

MATERIALS AND RESOURCES

The Materials and Resources (MR) Category of LEED-NC 2009 addresses building reuse, recycling, waste diverting, and sustainable materials. These items are not directly related to the focus of the 2007 FBC or Alachua County ULDC. Thus, no MR Credits are obtained or partially obtained by following the 2007 FBC or the Alachua County ULDC.

INDOOR ENVIRONMENTAL QUALITY

The Indoor Environmental Quality (IEQ) Category of LEED-NC 2009 deals with indoor air quality, lighting, views and thermal comfort. There are no similarities between the IEQ Category of LEED 2009 and the Alachua County ULDC. However, there are similarities between the 2007 FBC and the IEQ Category of LEED-NC 2009, see Table 1-5: Indoor Environmental Quality Findings.

Analysis of 2007 FBC With Regard to LEED 2009 IEQ

The first IEQ prerequisite, Minimum Indoor Air Quality Performance, for mechanically ventilated spaces (only feasible option currently in Alachua County) requires indoor air meet the more stringent of sections 4 through 7 of ASHRAE 62.1-2007 or the local code. The 2007 FBC requires in section 13-409.ABC.1.1 that the ventilation system meet the minimum requirements of ASHRAE 62.1- 2004, section 6.1. The 2007 FBC uses a dated standard, thus no portion of IEQp1 is satisfied.

Prerequisite 2: Environmental Tobacco Smoke Control, Option 1, requires that smoking be prohibited in the building and outdoor smoking areas be located at least 25 feet from entries, air intakes and operable windows. This is not addressed by the FBC, but is addressed by the Florida Clean Indoor Air Act (s.386.204, F.S.), which prohibits individuals from smoking in an enclosed indoor workspace. Therefore this credit can be achieved by following Florida law.

Credit 2: Increase Ventilation for mechanically ventilated spaces requires that the quantity of outdoor air being brought into the building be 30% above the more stringent of ASHRAE 62.1-2007 or the local code. The 2007 Florida Mechanical Code is more stringent than ASHRAE 62.1-2007 and by more than 30%. Thus, it can be assumed IEQc2 is achievable by following the 2007 FBC.

LEED-NC 2009 IEQc6.1: Controllability of Systems: Lighting requires individual controls for at least 90% of occupants, with multiple occupant spaces having controls for their lighting needs. The 2007 FBC seems to be in line with IEQc6.1 requirements. Section 13-415.ABC.1.2 states:

> Each space enclosed by ceiling-height partitions shall have at least one control device to independently control the general lighting within the space. Each manual devices shall be readily accessible and located so the occupants can see the controlled lighting.

This suggests every area must have controllability of the lighting for that particular area. In addition, section 13-415.ABC.1.3 requires lighting controls for task lighting and supplemental task lighting for some workspaces. Complying with these two sections of the 2007 FBC provides minor support from achieving IEQc6.1.

Indoor Environmental Quality Credit 8.1: Daylight and Views: Daylight, Option 1 requires a simulation showing all regularly occupied areas receive 25 foot candles of light and a max of 500 foot candles on September 21 at 9:00 AM and 3:00 PM on a clear day. Section 1205.2 of the 2007 FBC requires a minimum net glazed area that is 8 percent or greater of the floor area being served, which would have satisfied the requirements of IEQc8.1 LEED 2.2. Assuming that the old LEED 2.2 compliance path of a 2 percent glazing factor meets the 25 foot candle minimum, the

FBC's 8 percent glazing factor should meet the requirement. Implying, that by following the 2007 FBC, IEQc8.1 can be achieved or is very close to being achieved.

Table 1-5. Indoor Environmental Quality Findings

Credit	Addressed by Code?	Code	Achievability Score
IEQp1: Minimum Indoor Air Quality Performance	Yes	13-409.ABC.1.1 FBC	3
IEQp2: Environmental Tobacco Smoke Control	Yes	The Florida Clean Indoor Air Act (s.386.204, F.S.)	4
IEQc1: Outdoor Air Delivery Monitoring	No	N/A	0
IEQc2: Increased Ventilation	Yes	403.2 FBC	4
IEQc3.1: Construction Indoor Air Quality Management Plan- During Construction	No	N/A	0
IEQc3.2: Construction Indoor Air Quality Management Plan- Before Occupancy	No	N/A	0
IEQc4.1: Low-Emitting Materials- Adhesives and Sealants	No	N/A	0
IEQc4.2: Low-Emitting Materials- Paints and Coatings	No	N/A	0
IEQc4.3: Low-Emitting Materials- Flooring Systems	No	N/A	0
IEQc4.4: Low-Emitting Materials- Composite Wood and Agrifiber Products	No	N/A	0
IEQc5: Indoor Chemical and Pollutant Source Control	No	N/A	0
IEQc6.1: Controllability of Systems- Lighting	Yes	13-415.ABC.1.2 and 1.3 FBC	2
IEQc6.2: Controllability of Systems- Thermal Comfort	No	N/A	0
IEQc7.1: Thermal Comfort- Design	No	N/A	0
IEQc7.2: Thermal Comfort- Verification	No	N/A	0
IEQc8.1: Daylight and Views- Daylight	Yes	1205.2 FBC	2
IEQc8.2: Daylight and Views- Views	No	N/A	0

INNOVATION IN DESIGN

The Innovation in Design Category of Leadership in Energy and Environmental Design –New Construction 2009 deals with innovation in design, exemplary performance, and LEED Accredited Professional involvement. Innovation in design and exemplary performance points are awarded for issues not covered by LEED and

for exceeding LEED standards. The 2007 FBC and the Alachua County ULDC have no similarities with the ID Category of LEED-NC 2009.

REGIONAL PRIORITY

The Regional Priority (RP) Category of LEED-NC 2009 awards additional points to credits viewed as important in different regions. The RP credits for Alachua County are EAc1.3, WEc1, WEc1.2, MRc2, MRc3.1, MRc5 Options 1&2, and IEQc8.1. None of these credits were achieved by following the Alachua County ULDC, as previously discussed. However, one credit IEQc8.1 was achieved or partially achieved by the 2007 FBC, as discussed in the IEQ analysis.

CONCLUSION

Alachua County Codes do not bring a project into compliance with LEED prerequisites and therefore LEED certification is not possible by just building to code. Very few credits and prerequisites are achieved through the 2007 FBC and the Alachua County ULDC. One category that requires a lot of attention is EA, due to dated standards many credits are not fully achieved. In addition, no credits or prerequisites are achieved in the WE or MR.

Six prerequisites are addressed by the Alachua County Codes. The achieved prerequisites are: SSp1, EAp3, and IEQp2. The partially achieved prerequisites are EAp1, EAp2, and IEQp1. The remaining two prerequisites, MRp1 and WEp1, however, are not addressed by code. Following Alachua County Codes also earn two credits. The credits achieved are SSc4.4 and IEQc2. Three points are achieved through following the Alachua County Codes and one additional point through standard building practice. In addition, nine credits were partially achieved through following the Alachua County Codes: SSc1, SSc4.2, SSc5.2, SSc7.1, WEc1, EAc1, EAc3, IEQc6.1, IEQc8.1, and RPc1. Equaling 13 to 15 points are partially earned through following Alachua County Codes.

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Life Cycle Assessment Modeling of Heavy Construction Activities

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Abstract

Cost and time are the traditional criteria for selecting heavy equipment for construction tasks. However, non-road diesel-powered construction equipment can have health and environmental effects. For example, particulate matter and nitrogen oxide emissions from diesel engines impact local air quality, carbon dioxide emissions lead to climate change, and diesel fuel consumption is a non-renewable resource. In addition, diverse materials are used for manufacturing heavy-duty construction equipment, which can also impact the environment. An environmental life cycle model of construction equipment including uncertainty was developed to select equipment combinations for tasks based on the environmental impact associated with the life cycle of the construction equipment in addition to time and cost. Selecting equipment for a task based on life cycle environmental impact is another criterion that may be relevant for construction companies seeking to reduce their environmental impact. Results of modeling alternative equipment combinations that can be used to accomplish an example construction activity are presented in terms of time, cost, and life cycle global warming potential.

Introduction

Heavy construction equipment is used in many stages of construction. Loaders, trucks, and graders are common types of heavy equipment on most construction sites. Heavy equipment is vital for earth moving activities such as initial site clearing and grading, excavation, and hauling, as well as hoisting, lifting, and carrying, such as for structural steel or precast concrete erection. In the last twenty years, the technology used in construction has advanced, and manufacturers have developed more efficient construction equipment.

Cost and time are the traditional criteria for selecting heavy equipment for construction tasks. However, non-road diesel-powered construction equipment can have health and environmental effects. For example, particulate matter and nitrogen oxide emissions

from diesel engines impact local air quality, carbon dioxide emissions lead to global warming, and diesel fuel consumption is a concern from a non-renewable resource perspective. In addition, diverse materials are used for manufacturing heavy-duty construction equipment, which can also impact the environment.

This paper presents a computer model that was developed to examine the life cycle environmental performance of construction equipment used for common construction activities. A goal of this approach is to analyze and select the most efficient and economic equipment combinations for construction tasks that include the environmental impact associated with the life cycle of the construction equipment. It can also be used to assess the importance of individual equipment types for environmental performance and determine improvements along the supply chain, i.e., at manufacturing, production, or end of life.

The model will allow for the selection of heavy construction equipment for a task based not only on cost and time, but also on environmental concerns. Selecting equipment for a task based on life cycle environmental impact is another criterion that may be relevant for construction companies seeking to reduce the environmental impact of their activities. This tool can also be used to compare alternative scenarios such as the combination of equipment types that can be used to complete one activity.

Background

Several computer tools and methods have been developed to assist with the selection of construction equipment. For example, Eldin and Mayfield (2005) developed a Microsoft *Excel* application that recommends the most economical scraper. The application considers the performance characteristics of the equipment and the site conditions in terms of road conditions and travel distance to calculate the number of scrapers required, the cost, and the time. The application considers that the activity may also require a pusher to assist the scraper, and considers the dependency between them. The broad environmental concerns of construction have also been examined. For example, Hendrickson and Horvath (2000) analyze the environmental implications of the construction sector in terms of resource use and pollutant emissions using EIO-LCA input-output environmental life cycle assessment software. Guggemos and Horvath (2003) developed a spreadsheet tool that used a life cycle assessment framework to analyze the general construction process of structural frames. Bilec et al. (2006) demonstrated a hybrid life cycle assessment of the construction of a precast concrete parking garage. Sharrard (2008) and Bilec (2009) examined hybrid life cycle assessment modeling in construction. None of these models, however, have focused on the selection of heavy equipment for on-site construction activities based on their life cycle environmental performance.

The model in this paper focuses on estimating the environmental aspects of the use of heavy construction equipment on site, and in addition also calculates the cost and duration of the task. The model uses conventional performance characteristics of equipment such as bucket volume and fill factor for loaders, and distance, speed, and spot time for trucks to calculate production. The user can enter particular site conditions for activities, such as excavation volume and bank density. The model is implemented in Analytica® (2009) and is stochastic - some variables, such as the bucket

fill factor for loaders, are described with a distribution. The results can be viewed for cost, activity time, and environmental aspects for the equipment combinations. Graphs of activity time and cost relative to environmental aspects can be generated. Cost, time, and environmental performance parameters can therefore be concurrently examined.

Model Structure

The model is a life cycle study or assessment as described by ISO (1998), i.e., a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an life cycle inventory of relevant material inputs and emission outputs of a product system, evaluating the potential environmental impacts associated with the inputs and outputs and interpreting the results of the subsequent analysis. A life cycle consists of generic stages such as material production, manufacturing, use and service, and end-of-life management. These four stages can be elaborated for the construction equipment life cycle into raw material extraction, i.e., concentration, separation and refining; chemical and metallurgical material processing, i.e., metal, plastic, composite, glass; vehicle parts manufacturing, i.e., mechanical systems and electric and electronic devices; equipment manufacturing, i.e., final assembly line; sales and maintenance; end of life vehicle recycling; processing of recycled materials; and final disposal of non-recycled materials.

The model structure is described in three sections: construction equipment manufacturing; diesel fuel extraction, refining, and combustion; and estimation of the equipment use, task duration and cost. The energy consumption and environmental impacts of these three sections are analyzed and calculated based on equipment specifications and the duration of use (see Figure 1).

Equipment use, task duration and cost

Heavy equipment manufacturers generally produce equipment in multiple sizes resulting in different levels of performance, such as bucket volume and speed.

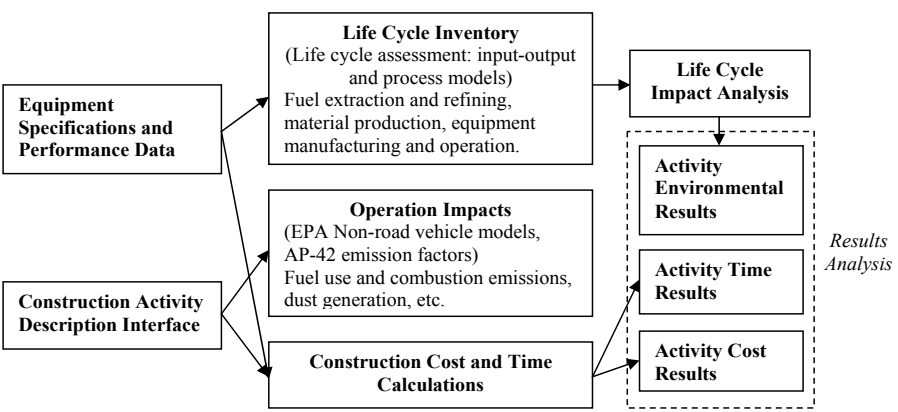


Figure 1: Structure of the life cycle assessment model of heavy construction activities

There are often dependencies between pieces of equipment required for a task that,

along with the characteristics of the task itself, influence the overall activity duration and cost. The equipment selected, therefore, impacts overall time and cost for a given task size, and it is important to match the capacity of the equipment with the task. Mathematical representations of equipment operations that calculate the estimated activity duration based on the task type, the task size, and the performance attributes of equipment have been developed for a number of common construction operations. These relationships are used in this model to calculate the task duration and cost. Although equipment capacity and productivity are typically used for selecting equipment based on budget and schedule constraints, the equipment type and the task duration is also required for calculating life cycle environmental impact.

The case study is a cut and fill task with four types of equipment, namely loaders, trucks, graders, and rollers. The following is a brief review of the basic steps used to determine the time required to complete the cut and fill operation. Loader production depends upon the loader bucket volume, the truck volume used to haul and loader load time, which includes loader cycle time, the number of cycles to load a truck and truck spot time. Truck production in cubic yards per hour is calculated from the truck volume and the truck cycle time. Grader and roller production is a function of grader speed, average width and thickness of each pass and the number of passes (Nunnally 2005). The roller load and shrinkage factors are used to convert compacted volume into loose volume.

The model assumes that the loaders are governing production. The total task cost calculation considers the task duration, the number of pieces of equipment and their fuel consumption per hour. The operator and rental costs are calculated and included in the total cost (see Table 1).

Construction equipment manufacturing

The life cycle effects of the construction activity, i.e., the upstream and downstream manufacturing of equipment, equipment maintenance; and operational impacts, i.e., fuel consumption, including the fuel cycle and fuel combustion emissions, were estimated with life cycle assessment. The life cycle inventory (LCI) was obtained by combining two approaches to calculating life cycle inventories, namely process modeling (ISO) and the economic input-output approach (Lave et al. 1995). The combination of input-output and process LCI utilized the strengths of each approach to develop the overall inventory.

The diesel fuel extraction and refining inventory was modeled using the process approach because specific, good quality data on this process is available. However, very little information was available on the manufacturing process for heavy equipment. Manufacturers would not provide the exact composition of the material and no information was available for the energy needed for its production or for the emissions released from its production. For the equipment manufacturing inventory, Economic Input Output-Life Cycle Assessment (EIO-LCA) software was used to determine which economic sectors provide inputs for the construction equipment manufacturing. The EIO-LCA model captures all the various manufacturing, transportation, mining and related activities used to produce a product or service.

Table 1: Sample equations used to calculate duration and cost in the model

Content		Calculation
Equipment production (cy/hr)	Truck	truck spot time + travel time + loader load time
	Grader	16.3 * speed * thickness per pass * average width * efficiency/ number of passes
	Roller	16.3 * speed * thickness per pass * average width * efficiency/ (number of passes * load factor * shrinkage factor)
Equipment quantity (pieces)	Truck	Round (truck cycle time/total loader load time)
	Roller	Round (truck production*number of trucks/roller production)
Duration of task (hr)		loose volume/loader production
Total task cost ($)		project duration*(total rental cost hr +fuel cost + total operator cost) + total cost of precast)
Operator cost ($/hr)		(1+number of graders + number of roller + number of trucks)*operator cost
Rental cost ($/hr)		total grader rental + total loaders rental + total roller rental + total truck rental

The data in EIO-LCA is developed from a variety of public datasets and assembled by commodity sectors. For the most part, the data is self-reported and is subjected to measurement error and reporting requirement gaps. Many countries produce input-output models of their economies, although very few are as large as the United States' approximately 500 sector model used in EIO-LCA. EIO-LCA provided the economic inputs from other sectors of the economy required to produce a given amount of heavy construction equipment. EIO-LCA is a linear model, i.e., a $200,000 demand on a sector has twice the economic inputs and environment-related inventory of a $100,000 demand. By analyzing the input sectors, an estimate of the materials and other inputs needed to manufacture the equipment was generated.

A process-based life cycle inventory model was developed based on the manufacturing material breakdown developed from EIO-LCA. Basic material process data for commonly used materials is available from existing LCA databases. For consistency, a set of process data from one source, ETH-ESU (Frischknecht and Jungbluth 2004), was selected for all the raw materials and diesel inventory. This process inventory data has more than 400 individual emission and resource types for each process. In all process descriptions, it is assumed that resource inputs and emission outputs are linearly related to process output.

Extraction, refining, and combustion of diesel fuel

The life cycle inventory data for diesel fuel extraction and refining was developed from ETH-ESU process data, in a similar manner to the equipment materials discussed above. Multiple inventories were used together to generate probability distributions for the inventory parameters. For diesel fuel combustion, emissions were modeled based on the Environmental Protection Agency's AP-42 emission factors for non-road

vehicles (USEPA 2003). AP-42 emission factors include PM10, i.e., particulate matter less than 10 microns, PM2.5, and NO_x. Since emissions may vary depending upon site conditions, they are defined with uniform distributions.

Combining the model components

The three components of the model are combined in the following way. The equipment use and task duration models are used to calculate the operating time and equipment types used, which, along with engine horsepower, translates into diesel fuel consumption. Total diesel consumption is used to generate the demand for diesel extraction and refining, and a life cycle inventory for the diesel fuel used in the activity is created. Task duration is also used together with equipment type to determine the upstream equipment manufacturing demand. Each activity represents a portion of the equipment's life, and that is used to allocate a portion of the manufacturing inventory to the task. The emission inventory for the combustion of diesel fuel for the activity is calculated from the AP-42 emission factors for each piece of construction equipment based on the equipment horsepower and the equipment operating time. The total combustion emission inventory is the sum of the individual equipment inventories in an activity. The inventory for the activity is obtained by summing diesel extraction and refining, fuel combustion, equipment manufacturing, and end of life inventories.

The next step in a life cycle assessment is a life cycle impact assessment (LCIA). A life cycle impact assessment generates an estimate of impact in categories using category indicators, e.g., global warming potential (GWP) to evaluate the impact of emissions of substances that cause global warming. Impacts of emissions in the categories are generally estimated relative to a reference substance through the use of equivalence factors and the mass of the emission in the inventory.

Example construction activity

The cut and fill activity involves loading trucks with earthen material from a stockpile area on the project site with loaders, hauling the material to the fill site on a haul road, spotting and dumping of the material, and returning to the stockpile empty. The material is then spread with graders, and compacted with roller compactors. The example cut and fill operation involves 100,000 cubic yards of earth, and the round trip transportation distance is 16 km (10 miles). Fifteen different loader, five different truck, five different grader, and five different roller compactor alternatives are included in the model. The main objective is to find the best combination of the equipment in terms of life cycle environmental impact. However, total project cost and project time are also calculated and the environmental impact results are presented relative to cost and time.

The equipment specifications included in the model vary, particularly in load capacities and task performance (Caterpillar 2008). For example, in terms of loaders, the Caterpillar 904B has the lowest bucket capacity and the 994F has the maximum bucket capacity; likewise, trucks have a range of capacity: the Caterpillar 725 has the lowest capacity of the trucks included and the Caterpillar 773E has the largest. Engine horsepower, which affects fuel consumption, varies across all machines from less than 100 hp to greater than 1500 hp.

The feasibility of loader and truck combinations are considered in that the height of loader must be higher than the truck, otherwise, loading is impossible. Thus, in the

results discussed below, not all 15 loaders are presented and not every loader is usable with all five truck types. The number of loaders is determined by the user. The loader-truck combination was found to be a driver for performance that clustered the results. Hence, the alternatives are presented with a loader-truck-combination orientation. That is to say, the number of graders and rollers are determined by the working capacity of loader and trucks. Although the model is stochastic, the results presented are the mean value of each loader-truck combination in terms of time, costs and GWP.

Results

In the relationship between time and GWP emissions, see Figure 2, a positive correlation can be seen between the loader-truck combinations. CAT 966G, CAT 980H and CAT 962G are the exceptions. For all combinations, mean time ranges from 110 hours to 355 hours, and the corresponding GWP is between 241,300 and 300,800 kg carbon dioxide equivalent (CO2e), yielding an average GWP emission intensity of 243 kg per hour. GWP ranges from 228,700 to 318,900 kg CO2e, and the corresponding range of task duration is 154 hours to 228 hours, yielding an average GWP intensity of 1,219 kg/hour.

The time, cost, and GWP performance of the CAT 994F, CAT 992G, and CAT 990W loaders with the truck type CAT 773E are superior to other alternatives. In terms of these three combinations only, the range of task duration is 44 hours, and the range of the CO2e emissions is 12,600 kg. In terms of time, the opportunity costs for reducing CO2e emissions in equipment selection among this group is 286 kg CO2e for every hour of task duration. The range of performance in terms of mean time of the best performing loader, the CAT 994F, is 110 to 228 hours with a corresponding range of 241,300 to 318,900 kg CO2e. The mean GWP emission rate for this loader's equipment combinations over this range are approximately 660 kg CO2e per hour.

Figure 3 shows the relationship between task cost and GWP. It can be seen that the loaders CAT 994F, CAT 992G, and CAT 990W cover a wide range of both cost and

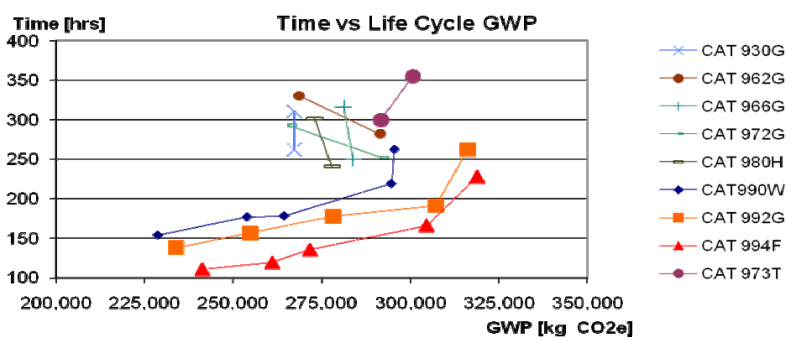


Figure 2: Relationship between total mean task time and global warming potential for the equipment combinations in the cut and fill operation

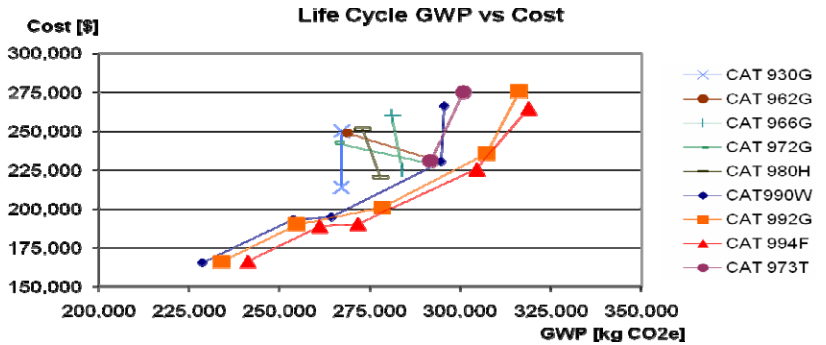


Figure 3: Relationship between total mean task cost and global warming potential for the equipment combinations in the cut and fill operation

GWP. Other loader combinations have costs and GWP that are greater and therefore are not the preferred alternatives. The best alternatives in terms of mean cost and GWP for each of these loaders (CAT 994F, CAT 992G, and CAT 990W) are within $900 (less than 1%) in terms of task cost: CAT 994F, $166,200; CAT 992G, $165,900; and CAT 990W, $165,300. The performance in terms of GWP vary by 6% (12,600 kg CO2e): CAT 994F, 241,300kg; CAT 992G, 233,900kg; and CAT 990W, 228,700kg. The cost for reducing CO2e emissions in equipment selection is 14 kg CO2e per dollar. On the other hand, it must be pointed out that for a given loader, the costs and GWP of the alternative combinations have a wide range. For example, the mean cost for the the best performing loader in terms of GWP, the CAT 990W, when combined with different types of trucks, roller compactors, and graders, can increase by 61%, and the mean GWP could increase by 29%.

Figure 4 presents the relationship between the total number of loaders, trucks, graders, and roller compactors and GWP emissions for the construction task. As can be seen in the figure, there is not a strong correlation between these two factors. Similar total equipment quantities yield a wide range GWP emissions. The CAT 962G loader has the combination with the least equipment (11 pieces). However, its GWP is among the highest. Combinations of the CAT 994F loader range from 16 to 18 pieces of equipment. Its mean GWP emissions range from nearly the lowest to the greatest, and its equipment quantity differs by one piece at these minimum and maximum points. The best combination in terms of both minimum GWP and equipment quantity is the CAT 990W with 12 pieces of equipment and a GWP of 228,700 kg CO2e.

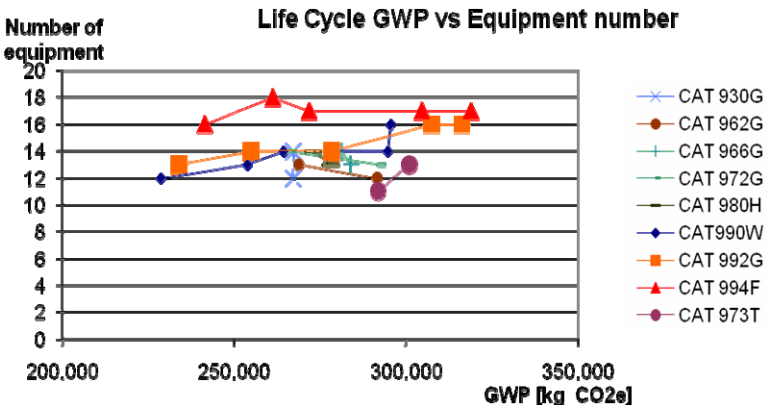


Figure 4: Relationship between total equipment quantities and global warming potential for the equipment combinations in the cut and fill operation

Conclusions

Construction equipment selection can have an impact on environmental performance as well as task time and cost. The model discussed here can be used to estimate and compare environmental performance, time and cost for some tasks using alternative combinations of heavy equipment. In many cases, the GWP emissions, cost, and time trends were aligned, meaning that optimizing cost and time would also minimize GWP emissions. The trend did not always hold true, however, and some combinations in the case study cut and fill operation, minimizing cost and time resulted in increasing GWP.

Empirical validation was not a part of the study. The models used, such as the equations for productivity and cost estimation, the life cycle inventory assessment models, and the EPA's AP-42 non-road vehicle emission models are widely used and recognized.

The model will continue to be tested, evaluated, and developed. For example, empirical validation for life cycle assessment studies deserves further work. Additional work is needed in uncertainty. Although only the mean values are presented here, the model is stochastic and uses distributions to represent many variables. Latin hypercube sampling is used to propagate variability and uncertainty. Also, the model contains a range of typical life cycle assessment environmental impact factors in addition to GWP and can be used to estimate these. The correlation among the aspects of environmental impact will be examined.

Overall environmental performance of construction can be improved through the careful selection of construction equipment that considers the dependencies among equipment combinations. The theoretical 10%-20% reduction in terms of GWP emissions by main-stream construction equipment is a significant reduction for site construction activities. Other strategies, such as switching to alternative fuels, or using

alternative construction equipment that may have better performance in fuel efficiency or pollutant emissions, were not investigated as a part of this research. These alternatives, however, are likely to be costly and in any case would also benefit from the trade-off analysis this model provides. Therefore, with a focus on the equipment in use today, this model can be used to estimate the environmental impact of construction equipment selection and planning decisions, which can have benefits for construction companies seeking to reduce the consequences of construction activities.

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LIFE CYCLE COST ANALYSIS AND REAL OPTION THEORY FOR IMPROVED SUSTAINABILITY IN EXISTING BUILDINGS

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ABSTRACT

This paper investigates a number of challenges related to making existing buildings more sustainable to meet the increased demand for green office, residential and retail space. Some of these challenges include integrating the owner and user requirements, determining and prioritizing the required modifications to reduce the gap between the existing conditions and the required green standard, and finally aligning the alternative options for sustainably retrofitting the building with the available capital and resources. In particular, this paper will investigate innovative approaches to studying alternative greening solutions for existing buildings by augmenting the traditional life cycle cost analysis method with principles from financial and real options. These techniques are investigated because they provide the owner with the flexibility to value different alternative solutions for their buildings under conditions of uncertainty especially those related to demand for green space, fluctuating cost of energy and the perceived savings in the building operation and maintenance costs after sustainably retrofitting the existing building.

INTRODUCTION

According to a study by the United Nations Environmental Program Sustainable

Construction and Building Initiative (UNEP-SBCI 2007), the building sector accounts for 30 to 40 percent of the global energy use. Among the key findings of this study is the fact that 80 percent of the energy consumed by a building during its life-cycle occurs when the building is in actual use. In the Unites States (US), several studies indicate that residential and non-residential buildings contribute up to 50 percent of the total carbon emissions (Yudelson 2010). In fact, activities in buildings consume up to 70 percent of electricity produced in the US, use 14 percent of non-industrial water, and generate 40 percent of the non-industrial waste (Hawthorne 2003). Therefore significant reduction in global warming can be achieved if methods to reduce energy consumption and improve energy efficiency of buildings are adopted during their operation and maintenance phase (UNEP-SBCI 2007). A study by the consulting firm Mckinsey indicates that the most cost effective approach to "transform to a low carbon world" is best done by investing in energy efficient buildings (Mckinsey 2008).

In an effort to reduce the significant effect of building on the environment the Energy Policy Act of 2005 requires all federal new buildings to be designed to achieve energy reductions that are at least 30 percent below the levels established by the ASHRAE Standard or the International Energy Conservation Code (EPA 2005). The EPAct however emphasizes that these reductions need to be achieved only if measures that are life-cycle cost effective are adopted. This act was followed by Executive Order 13426, signed by president George Bush in 2007, which required that 15 percent of all existing federal capital asset building inventory incorporate sustainable practices by the end of the fiscal year 2015 (GSA 2009). In doing this, major renovations to existing buildings need to achieve a reduction in energy consumption of more than 20 percent below the pre-renovation baseline. These renovations need to be life-cycle cost effective when compared to the baseline year of 2003.

A study conducted by Nelson (2008) concluded that the greatest opportunities for green building investment will be in the United States. This is mainly due to the large number of existing buildings ("existing stock"), sizeable growth in population, increased interest and adoption of green business practices, and rising government regulations. In addition, the UNEP-SBCI 2007 report emphasizes that in developed countries the main challenge is to achieve emission reduction among mostly existing buildings. Therefore, sustainably retrofitting existing buildings is particularly important if the market demand for green buildings continues to increase as projected. However, there are many challenges to greening existing buildings. These include demonstrating achievement of the necessary energy efficiency while respecting

allocated budgets and working with tenants/occupants to reduce their resistance to change (Yudelson 2010). A study by Turner Construction in 2008 of 750 corporate real estate executives cites the following as the main obstacles to green construction: high construction costs (61 percent), long pay back periods (57 percent), and difficulty in quantifying the benefits of green building (43 percent) (Turner Construction 2008).

This paper investigates a number of challenges related to making existing buildings more sustainable to meet the increased demand for green office, residential and retail space. One of these challenges is determining and prioritizing the required modifications to reduce the gap between the existing conditions and the required green standard, and finally aligning the alternative options for sustainably retrofitting the building with the available capital and resources. As required by the EPAact of 2005 and Executive Order 13423, the effectiveness of any retrofitting approach is measured by using life cycle cost analysis to measure the actual savings in energy use from the perceived retrofitting plan. However, the life-cycle cost analysis technique requires a lot a data and at times "educated guess work" related to the actual amount of energy consumed during the life of the facility (Dell'lsola and Kirk 2003). This paper will investigate innovative approaches to studying alternative greening solutions for existing buildings by augmenting the traditional life cycle cost analysis method with principles from financial and real options. These techniques are investigated because they provide the owner with the flexibility to value different alternative solutions for their buildings under conditions of uncertainty especially those related to demand for green space, fluctuating cost of energy and the perceived savings in the building operation and maintenance costs after sustainably retrofitting the existing building.

LIFE CYCLE COST ANALYSIS

Most existing building owners rank the concern about energy prices and volatility as one of the main drivers to sustainably retrofit their buildings because energy is the largest cost of building operations and the least controllable (Yudelson 2010). However, sustainably retrofitting existing building projects requires the expenditure of initial costs to achieve energy savings during the life the facility. These costs are in some cases perceived to outweigh the benefits and therefore are one of the main barriers facing sustainable retrofits of existing buildings (Yudelson 2010).

For existing buildings, there are a number of opportunities to improve the energy performance. Examples include improving the thermal performance of the building envelope to reduce heat loss in the winter and gain in the summer; updating the heating, ventilation and air conditioning systems (HVAC); adopting electricity efficient techniques; managing the generation and disposal of solid wastes; and reducing water use (Yedulson 2010; USGBC 2009; Fuller And Petersen 1995). Each of these opportunities can be achieved through several competing and mutually exclusive alternative options. These kinds of projects where alternative scenarios need to be considered within the limitations of a specified budget provide the best example for the application of the life-cycle cost analysis (LCCA) technique (Fuller and Petersen 1995).

Therefore, LCCA can help the decision maker to analyze these options based on initial costs, reduced energy costs and other cost implications over the project life-cycle, and determine whether or not these alternatives are economically justified from the owner's (or investor's) viewpoint (Dell'lsola and Kirk 2003; Fuller and Petersen 1995). In essence, both present and future costs should be taken into account and related to one another. These costs include initial and annual project costs.

Traditionally, two methods have been used to calculate the LCCA for each alternative as shown in Figure 1. Dell'lsola and Kirk (2003) and Fuller and Petersen (1995) provide a detailed discussion on the application of each of these two methods.

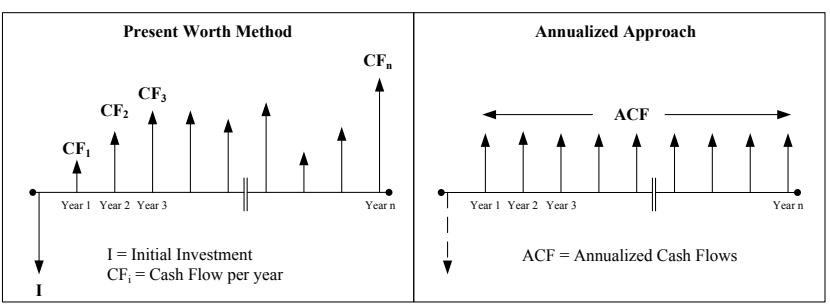


Figure 1: LCCA Analysis Methods

CHALLENGES IN PERFORMING LIFE CYCLE COST ANALYSIS FOR EXISTING BUILDINGS

Two main challenges in performing LCCA to sustainably retrofit existing buildings are:

1) Discount Rates: Discount rates for federal energy- and water related projects are published annually by the Department of Energy (DOE) in the Annual Supplement to Handbook 135, Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis (Rushing and Lippiatt 2009; Fuller and Petersen 1995). However, in other cases, it is the "prerogative of the owner" to select the discount rate to be used in the analysis (Dell'lsola and Kirk 2003). Some examples of discount rates used by owners and their limitations in the analysis are summarized in Table 1.

Table 1: Discount Rates for LCCA (Adapted from Dell'lsola and Kirk 2003)

Type	Limitations
Cost of Borrowing Money in the market place or the highest interest the organization expects to pay to borrow money needed for the project.	Does not take into account the risk of loss associated with the loan or the expected return from the investment itself.
Minimum Attractive Rate of Return which includes the cost of borrowing money plus an increment that reflects the associated risk	It is not easy to quantify the risk as a percentage increment to the cost of borrowing money.
Opportunity Rate of Return which is the rate that could be earned from some alternative forgone investment opportunity	Realistic discount rate selection criteria but hard to apply to projects for the public sector
After-Inflation Discount Rate which indicates that project's rate of return is over and above the general rate of inflation	All costs in the LCCA must be stated in terms of constant dollars relative to the base year which makes them artificial rather than real amounts

2) Estimating Energy Consumption, Maintenance and Operation Costs

The two traditional valuation tools (i.e., present worth and annualized costs) can be used to perform the LCCA only when explicit assumptions regarding the expected future cash flows for each alternative under consideration can be made with certainty (Fuller and Petersen 1995). For example, energy costs in existing buildings include heating, cooling, ventilation, lighting, domestic hot water, and other miscellaneous equipment loads (Dell'lsola and Kirk 2003; Fuller and Petersen 1995). However, it is always impossible to measure energy use accurately due to differences in occupancy, hours of building system operations, control-point settings, building and system maintenance conditions, and actual versus estimated weather conditions (Dell'lsola and Kirk 2003). Another significant cost item for existing buildings is the operation of maintenance costs.

Given the above identified two challenges to performing LCCA for sustainably retrofitting existing buildings, LCCA method needs to be augmented by other quantitative methods to provide the building owners with more accurate and useable information when making decisions about the best possible alternative retrofits to undertake and timing of these retrofits. In the subsequent section, real option approach is presented as one method that can be used in conjunction with LCCA to

overcome the uncertainty in the discount rate and cash flow estimates in the traditional LCCA method.

REAL OPTIONS

The application of option pricing theory in capital investment decisions comes in the form of Real Options, which exploits the fact that "investment flexibility" in real (that is, non-financial) projects, e.g. the ability to defer investment or expand, contract, or abandon a project, is analogous to financial options (Boute et al. 2004; Trigeorgis 1993). For example, investments made to acquire a real asset are analogous to Call Options while disposing of a real asset for a salvage value is similar to exercising a Put Option (Fichman and Tiwana 2005; Luehrman 1995). Real options are "active" management tools that provide the decision maker with the flexibility to change the course of an investment, as more information regarding the uncertain future cash flows becomes available (Trigeorgis 1993). Options to defer, expand, stage, or abandon the investment at any time in response to changes in the future circumstances of the project add more value to a project (Boute et al. 2004, Trigeorgis 1996). The market value of the real options depends on the value of the underlying asset (e.g., project cash flows), and how this value changes during the life of the project due to inherent uncertainties (Ng and Bjornsson 2004). Real options have been used as a financial valuation technique for different types of capital budgeting endeavors where flexibility and active decision making is essential for the success of the project under uncertainty. Table 2 below summarizes the most typically used real options and their possible application during the LCCA analysis to sustainably retrofit existing buildings.

FRAMEWORK TO ANALYZE LIFE CYCLE COSTS OF EXISTING BUILDINGS USING REAL OPTION APPROACH

A preliminary model of the integration between LCCA and real option to improve decision making for sustainably retrofitting existing buildings is described in this section. The premise for this model is the put option. An investor typically buys a put option to insure against the possible decrease in the price of a stock he/she already holds below a certain value referred to as the exercise or strike price after a certain period of time. If the stock price (S) is above the strike price (X), then the option will go un-exercised and the investor will only lose the premium he/she paid to acquire the option (OP). However, if the stock price falls below the strike price, then the investor will sell the stock for the strike price and make profit equal to the difference between

the strike price and the stock price (X-S) as shown in Figure 2 (McDonald 2003).

Table 2: Real Option Application to Sustainably Retrofit Existing Buildings

Real Option Category	Definitions (Adopted from Fichman et al. 2005)	Application to Investments in Sustainably Retrofitting Existing Buildings
Option to Stage	The project is divided into distinct stages. The costs/benefits of a completed stage are assessed to determine if subsequent stages can be pursued.	The retrofitting can be divided into stages depending on available budget. First stage might involve replacing light bulbs with more energy efficient ones, and use plug-load occupancy sensors to turn off lights when no one is using the space.
Option to Abandon	Terminate a project any time prior to completion and deploy resources to other projects.	An exhaustive feasibility study of the existing building condition might indicate that the associated incremental costs to make the building energy efficient are too high. In this case the owner might abandon the project.
Option to Defer	A decision on whether to invest in a project can be postponed without imperiling the potential benefits	A decision to sustainably retrofit an existing building can be deferred until debt financing becomes available at attractive rates to the owner, or until the tenants can arrange to lease alternative space for the duration of the retrofitting project.
Option to Grow	An initial baseline investment allows the project managers to pursue a variety of follow on opportunities.	The owner of several existing buildings nationwide can decide to retrofit one building as a pilot project, and decide to expand retrofit work to the remaining of his/her existing building stock once perceived benefits from retrofitting the pilot project outweigh the costs incurred.
Option to Reduce	Reduce current scale of the project and save costs.	Reduce the scope of the retrofitting endeavor when the costs of the retrofitting exceed the allocated budget. For example, replacing the existing HVAC system might exceed the allocated costs due to lack of information about the existing system and how it is distributed throughout the building. In this case, other scheduled energy efficient replacements or updates for the building will need to be postponed or forgone all together.
Option to Switch	An asset developed for one purpose can be switched or redeployed to serve another purpose	An existing office building owner might decide to switch the tenant occupancy of certain floors from three to four tenants per floor to only one tenant per floor.

For existing buildings, the actual costs of energy consumption, operation and maintenance prior to sustainable retrofit represent the baseline (X) or the amount the owner is paying to ensure that the building is functioning as expected by the tenants when they initially leased the building space. Therefore, the initial step in sustainably retrofitting the building would be to compare the baseline (X) to required sustainability standard (e.g LEED or ENERGY STAR). Once this value is determined it can be used to establish the expected cost saving in the project from implementing the retrofits. If the LCC of the proposed retrofits is below (X) (i.e., the baseline costs of the building when maintaining the status quo), then the savings for the sustainable

retrofit will be (LCC – X). This of course is achieved at an initial investment to obtain the sustainable retrofits equal to I.

Therefore and transforming this to real option terminology, the owner of an existing building is paying a premium I, which corresponds to the put option premium (OP), for the option to reduce the baseline value of the energy consumption, operation and maintenance costs (X) to LCCA, and achieve savings (i.e., profits) equal to (LCC-X). Thus, the owner is exercising the option to make profits by sustainably retrofitting the building the same way an investor exercises the option to make a profit when the stock price falls below the strike price (or the price at which the original stock was purchased). The owner of the existing building is protecting themselves against the high baseline costs (X) by investing to reduce those costs to LCC. Since the baseline cost (X) can vary depending on the building condition, the higher the baseline cost (X), the higher the required initial investment (I) will be because the perceived savings from implementing the retrofit project increases as shown in Figure 3. This Figure also indicates that sustainably retrofitting an existing building is more valuable when the baseline costs are higher (i.e., baseline costs equal to X_2 versus baseline costs equal to X_1). Ultimately, aligning with the methodology of a put option, as the price of energy continues to rise, so will the profits (i.e., saving) of the owner that paid a premium for the initial investment.

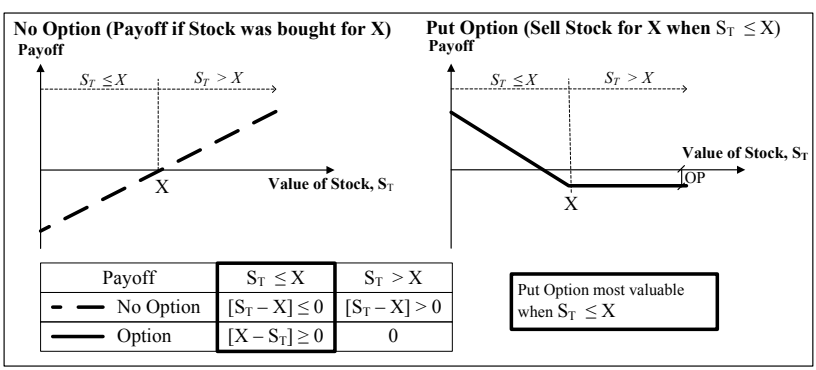


Figure 2: Payoffs from Buying a Put Option

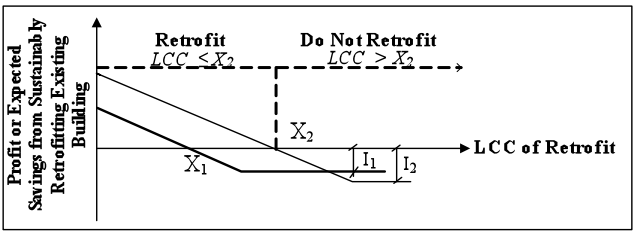


Figure 3: LCCA as a Put option

CONCLUSIONS

This paper discussed some of the challenges in sustainably retrofitting existing buildings, and the effect of these challenges on conducting the LCCA to compare alternative retrofitting schemes. In particular, this paper investigated innovative approaches to studying alternative greening solutions for existing buildings by augmenting the traditional life cycle cost analysis method with principles from financial and real options. These techniques are investigated because they provide the owner with the flexibility to value different alternative solutions for their buildings under conditions of uncertainty especially those related to fluctuating costs of energy and the perceived savings in the building operation and maintenance costs after sustainably retrofitting the existing building.

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Life Cycle Cost Analysis of Hybrid Chiller Plants under Dynamic Utility Prices

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Abstract

The problem with electric motor-driven HVAC systems is high electric demand charges during on-peak periods. Although the peak demand for electricity occurs for a limited time, electric demand charges can often account for approximately half of the total air-conditioning bill. Hybrid HVAC systems have been proposed as efficient solutions to offset these charges. The hybrid HVAC plant employs a chiller combination powered by electricity and natural gas. It can be programmed to select the most cost-effective energy source. An innovative approach to evaluate the economic performance of hybrid HVAC systems is presented. This model is based on the Life Cycle Cost Analysis Methodology. Our model considers dynamic changes in gas and electricity prices and compares the overall benefit of hybrid systems with traditional gas or electricity systems. For predicting the future electricity and natural gas prices, the discount factors adjusted for fuel price escalation, by end-use sector and fuel type should be provided. In the proposed method, an increasing factor is modeled by a binomial lattice. By conducting a Monte Carlo simulation based on the binomial lattice the factor range for each period is obtained. One of Georgia Institute of Technology's chiller plants is considered as a case study. Through conducting a case study on one of the Georgia Institute of Technology's chiller plants, it is shown that the overall cost-saving benefit of hybrid systems is sufficiently large to justify the additional expenses

1- Introduction

The energy cost is the major percentage of a central cooling plant's annual operation and maintenance cost. The chillers, condenser pumps, cooling towers and air handlers are the most energy consuming parts of heating, ventilating and air conditioning (HVAC) systems.

Most of water cooled chillers sold in United States were electric motor-driven units while others were gas chillers. The most important matter with electric motor driven chillers is the expensive electricity charge demand during on-peak periods. The electric demand charge can often account for approximately half of the entire air-conditioning bill even though the peak demand time for electricity is relatively short compared to the whole operation time of cooling systems in hot seasons. (Nowakowski 1995) The two basic types of gas chillers are absorption systems and gas engine chiller systems. In regions with high electric demand charges, using the gas chillers is attractive.

Hybrid chiller plants have been proposed as alternative systems to reduce Collin/Heating costs. A hybrid chiller plant employs a combination of chillers powered by both electricity and natural gas. It captures the best of both gas and electric usage. The energy use schedule is programmed in the microprocessor control units of hybrid HVAC systems. The system, then, switches between natural gas and electricity sources according to the planned schedule. In a typical hybrid system, the electricity-driven chiller takes advantage of the lowest time-of-use costs during off-peak hours. The absorption chiller is used as the primary source during the on-peak hours.

In addition, U.S government participation in Kyoto Accords and global climate change initiatives expands the federal government's focus on efficient energy use. Reducing carbon-dioxide emissions will require that end-use efficiency improve. 'Natural gas cooling systems have greater resource efficiency than similar electric systems. Approximately 65% - 75% loss in the initial energy resource of the fuel occurs in typical electricity generation and distribution. In contrast, only about 5% to 10% of the fuel resource is lost with a gas system'. (Southern California Gas Company 1998) Also, natural gas-powered air-conditioning equipment offers substantial advantages to the environment because CFCs and HCFCs are not used in the absorption cycle.

A Life Cycle Cost Analysis (LCCA) for hybrid systems can result in an attractive return on investment. First-cost, energy performance, and maintenance costs are the major components of life-cycle costing.

The major objective of this research is to develop an innovative approach to evaluate the economic performance of hybrid HVAC systems and compare it with conventional hybrid systems. To achieve this objective, the paper's structure is as follows. The research background, introduction to LCCA, different kinds of utility rate plans and hybrid chillers are summarized in section two. The model for conducting LCCA for electric, absorption and hybrid HVAC systems is coming in section three. In addition, the method of price forecasting and conducting LCCA are described. Then, one of the Georgia Institute of Technology chiller plants is considered as a case study. Finally, conclusions and suggestions for future work are given.

1. Research background

Several studies have been conducted to evaluate the financial performance of non-electric chillers. In a guideline for absorption chillers – developed by New Building Institute of Southern California Gas Company (1998) – it is shown that these chillers can provide relatively higher benefits to commercial office building owners than electric chillers. These buildings have different kinds of applications, like office building, school and hospital, and are located in different cities. (Southern California Gas Company 1998) In another study, Sohn and Alvarado (2002) did a research about using absorption chillers instead of electric one. It was reported that for the large capacity chillers (600 ton), the natural gas chiller is the best alternative. (Sohn 2002) Finally, in the research by Meckler (1999), different kinds of chillers like electric, absorption and hybrid were considered. It was shown that using hybrid systems could bring some benefits. (Meckler 1999)
In the mentioned researches, the future utility price is not considered or escalated by the constant rate. Also, in Milton Meckler's work the maintenance and replacement was not considered. In the current research the future utility prices are calculated in two ways.

2.1. Life Cycle Cost Analysis

One of the most important concerns of building owners is to investigate the cost of building operations over the life of a building. The National Institute of Standards and Technology (NIST) Handbook 135, 1995 edition, defines Life Cycle Cost (LCC) as "the total discounted dollar cost of owning, operating, maintaining, and disposing of a building or a building system" over a period of time. (Laboratory 1995) Life Cycle Cost Analysis (LCCA) is an economic approach to evaluate the total cost of owning and operating a facility over period of time. Also, LCCA was developed to calculate the Net Present Value (NPV) of mutually exclusive design alternatives for a given functional requirement on the basis of all costs and benefits arising from their implementation, consisting of both future and present costs/benefits.

There are two major cost categories in a LCCA, initial expenses and future expenses. Initial expenses are incurred prior to occupation of the facility, like initial investments and buying the equipments. In contrast, future expenses are incurred after occupation of the facility, like operation, maintenance and replacement costs. The future expenses should be discounted by the appropriate discount rate.
Once all costs have been calculated and discounted to their present value, the costs can be summed to generate the total life cycle cost of the project alternative. Then, the alternative with the lowest life cycle cost is selected.

2.2. Utility Rates

There are many different kinds of pricing plans exist in the United States. The pricing is typically determined by two main factors: the total energy consumption (in kilowatt hours), and the demand charge (in kilowatts). Most electric rate plans can be categorized as one of the following three types:

1- Energy plus Straight Demand: This rate plan consist of the energy charge based on the total kilowatt hours consumed, and the demand charge based on the billing demand in kilowatts during the billing period. A customer's demand is the highest one-half hour of energy use during a billing cycle.

2- Real Time Pricing (RTP): This rate plan is based on the market fluctuation. The proceeding time period (usually 24 hours) is notified in advance to the customer.

Gas has many of the same pricing parameters that characterize the electrical industry, like future option and constant rate.

2.3. Hybrid Chillers

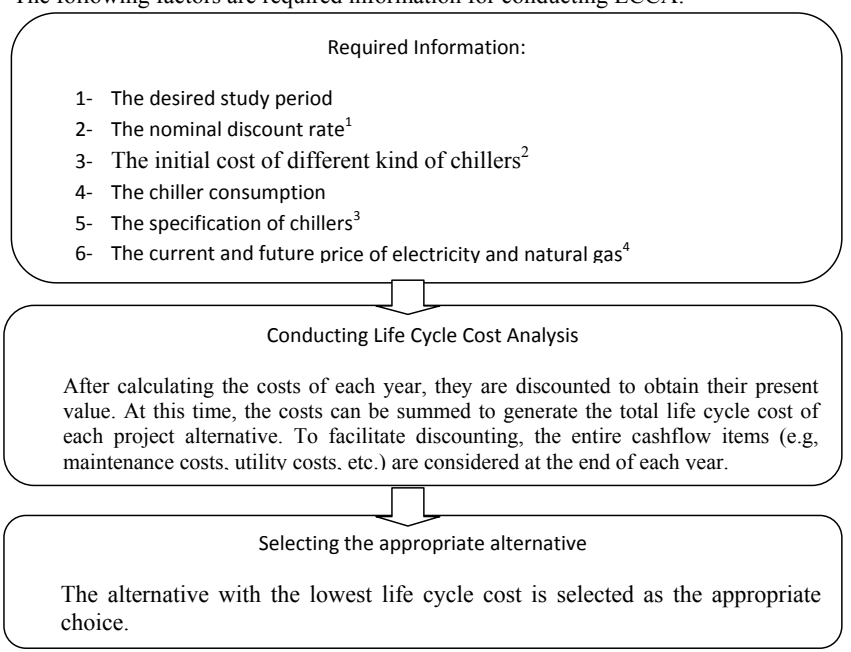
Dual-fuel systems are applicable in any market where the customer wants to have the flexibility to choose the cost and comfort options of gas versus electricity. Because of the uncertainty in utility prices, it would not be wise to install all-gas or all-electrical systems. So, the hybrid systems are proposed to assist owners in meeting their expected need for flexibility. Depending on the price of electricity and natural gas, either the electric motor or the gas-engine can be selected to drive the compressor. This flexibility allows the building owner to control operating costs.
The cost of installing hybrid systems is more expensive than electric chillers. So, the annual energy savings need to be large enough to overcome higher initial costs and potentially higher maintenance costs of hybrid chillers.

There are two different kinds of hybrid chiller plants, traditional and nontraditional. The typical operating strategy for traditional hybrid plants is avoiding peak electric charges by operating alternative-drive chillers. The operating plan for this kind of plant is using the alternative-drive chiller to be base-loaded and electric chiller handles the remaining load, during hours of high electric costs. On-peak periods are defined by the electric utility, and penalties such as demand charges applying during those times. Nontraditional hybrid is used as alternative-drive chillers to carry the entire load during the high-cost electric or natural gas hours. This completely eliminates the use of both chillers simultaneously.

3. Developing a Model.

3.1.The model flowchart:

The following factors are required information for conducting LCCA:



Where:
[1]The nominal discount rate: It is based on long-term Treasury bond rates averaged over the 12 months prior to the preparation of the case study. It could vary from 3% to 5% per annum compounded annually.
[2]It can be derived from RS MEANS Facilities Construction Cost Data or chiller dealers.
[3]The specification of chillers: The efficiency of electric chillers (kW/ton), Coefficient of Performance (COP) of absorption chillers, service life and maintenance cost of each system. These specifications are defined by the producers.
[4]The price of electricity and natural gas: Many factors like utility plan, state, city and provider affect the utility price. The average of utility prices for each state is available in the DOE website.

3.2.The price forecasting method

The used method for forecasting is as follows.
In this method, the discount factors adjusted for fuel price escalation, by end-use sector and fuel type are modeled as a binomial lattice. The first step is calculating the price volatility (σ). The risks, uncertainties and price fluctuations are reflected by the price volatility. It can be obtained from historic prices. Then, a binomial lattice for increasing factor is structured. The up and down factors are calculated by following equations:

$$U = e^{\sigma\sqrt{\Delta t}}$$
$$D = e^{-(\sigma\sqrt{\Delta t})} = 1/U$$

Then, the index for each node is equal to

$$I_n = I_{n-1} * U^{N_U} * D^{N_D}$$

where:

$$N_U = Number\ of\ up\ moving$$
$$N_D = Number\ of\ down\ moving$$

The number of up moving and down moving for each period is cumulatively considered.

The probabilities of up and down movements are p and 1-p, respectively.
Where:

$$P = \frac{1}{2}\left(1 + \frac{\vartheta}{\sigma}\sqrt{\Delta T}\right)$$
$$\vartheta = r - \frac{\sigma^2}{2}$$
$$r = The\ risk\ free\ rate\ of\ return$$

The Table. 1 shows the binomial lattice of electricity index.

0	1	2	3	4	5	6	7	8	9	10
										5.612962
									4.723598	
								3.975152		3.975152
							3.345295		3.345295	
						2.815239		2.815239		2.815239
					2.369169		2.369169		2.369169	
				1.993778		1.993778		1.993778		1.993778
			1.677867		1.677867		1.677867		1.677867	
		1.412012		1.412012		1.412012		1.412012		1.412012
	1.188281		1.188281		1.188281		1.188281		1.188281	
1		1		1		1		1		1
	0.841552		0.841552		0.841552		0.841552		0.841552	
		0.708209		0.708209		0.708209		0.708209		0.708209
			0.595995		0.595995		0.595995		0.595995	
				0.50156		0.50156		0.50156		0.50156
					0.422089		0.422089		0.422089	
						0.35521		0.35521		0.35521
							0.298927		0.298927	
								0.251563		0.251563
									0.211703	
										0.178159

Table 1. The index's binomial lattice

The Monte Carlo simulation is used to generate several paths for each period, based on the binomial lattice. As a result, the range of index for each year is obtained. Then, the mean of indices for each year can be considered as an appropriate increasing or decreasing index for calculating the future price. The future price is equal to the index times the current price.

3.3.Conducting LCCA

After determining the initial and future expenses as mentioned in required information chart, the LCCA should be conducted. By conducting LCCA, the present value (PV) of each expense is calculated. Then, the costs are summed to generate the total life cycle cost of each project alternative

For calculating the PV of expenses, the following formulas are used:

3.3.1. Replacement Cost:

$$PV = {}^{FV}/_{(1+r)^n}$$

where:

FV: the future value of chiller

n: the service life

r: the risk-free rate

3.3.2. Maintenance cost:

$$PV = \frac{A}{r-g}[1-({}^{1+g}/_{1+r})^n]$$

where:

A: the annual maintenance cost
r: the risk-free rate
g: the maintenance escalation rate
n: the study period

3.3.3. Utility cost:

After determining the annual utility cost, the PV is calculated by the following formula.

$$PV = {}^{FV}/_{(1+r)^n}$$

where:
FV: the future value of utility cost
n: the related year
r: the risk-free rate

4. A Case Study

One of the Georgia Tech's chiller plants, 10th St., is considered as a case study. It is consisted of six electric chillers. Four of them are Centrifugal and the others are Dual Centrifugal. The total capacity of the chiller plant is 12,250 tons.

Georgia Tech is using Real Time Pricing for buying electricity. The price of electricity is notified an hour in advance. If Georgia Tech used the hybrid system, it could give the opportunity to select the appropriate source for the next hour. The hourly price of electricity bought by Georgia Tech is available. The price of natural gas is assumed constant for each month. The price is extracted from the Energy Information Administration (EIA).

For evaluating hybrid systems, four different kinds of chiller combination are considered.

1. 12 units of centrifugal electric chiller. Each chiller capacity is 1000 ton.
2. 10 units of single-stage steam absorption chillers. Each chiller capacity is 1250 ton.
3. 6 units of electric chiller and 5 units of absorption one. In this case, the absorption chillers are used for as the primary source during on-peak hours.
4. 12 units of electric chiller and 10 units of absorption one.

The first and second combinations use the electricity and natural gas, respectively. For the third combination, the price of utility determines which kind of chiller works. It gives the owner the flexibility in selecting the appropriate source. If the price of electricity is higher, the absorption chillers handle the load up to 6000 ton. If the load is greater than 6000 ton, the remaining load is carried out by the electric chillers. It happens reversely, if the natural gas is more expensive than electricity. For the last combination, when the price of natural gas is lower than electricity price, the absorption chillers could handle the entire load. In the other hand, when the price of electricity is lower than natural gas, the entire load is handled by electrical one.

The following assumptions are made regarding the research:

Input information

1- The study period is 30 years
2- The 3% Department of Energy (DOE) nominal discount rate is considered for conducting the LCCA.(Commerce 2009)
3- The initial costs of different kinds of chillers are extracted from RS MEANS Facilities Construction Cost Data 2006.
4- The following specifications are considered for electric chiller:
    a. The efficiency is considered 0.68 (kW/ton) based on the ASHRAE Standard 90.1.
    b. The maintenance cost is considered 1% each year
    c. The service life of is 23 years.
5- The following specifications are considered for absorption chiller:
    a. The COP is considered 0.95
    b. The maintenance cost is 2% each year
    c. The service life is 15 years
6- The maintenance cost of chillers is increased due to getting aged. So, the assumption of 2% per year escalation rate is used for the maintenance escalation cost.
7- For forecasting the future price, the following assumptions are considered:
    a. The industrial prices, from January 1990 through December 2008, are used for calculating the price volatility.
    b. The 10,000 iterations are done for the Monte Carlo simulation to ensure all possible indices are generated.

Conducting Life Cycle Cost Analysis

Based on the mentioned assumptions, the LCCA is conducted. The results are shown in the Table 2.

Selecting the appropriate alternative

Based on the results shown in Table 2:

The combination of 6 units of electric chiller and 5 units of absorption is the appropriate choice.

The results of conducting LCCA are shown in Table 2:

	Initial Cost (per unit)	Total Initial Cost	Maintenance Cost (one year)	Total Maintenance Cost	Replacement	Utility Cost	Total Cost	Percentage of Savings
12*1000 ton Electric Chiller	374,000	4,488,000	44,880	1,138,799	2,274,033	49,939,589	57,840,420	100.0%
10*1250 ton Absorption Chiller	548,500	5,485,000	109,700	2,783,561	3,520,613	88,850,722	100,639,895	174.0%
6*1000 ton Electric Chiller & 5*1000 ton Absorption Chiller		4,986,500	88,260	2,239,536	2,897,323	44,593,383	54,716,741	94.6%
12*1000 ton Electric Chiller & 10*1000 ton Absorption Chiller		9,973,000	147,100	3,732,560	5,794,645	44,203,939	63,704,144	110.1%

Table 2. Results of using second method of forecasting

By using the combination of six electric and five absorption chillers, the owner can save 5.4% in costs.

5. Conclusions and Future Work

It is shown that the overall cost-saving benefit of hybrid systems is sufficiently large to justify the additional expenses.

Natural gas cooling systems have greater resource efficiency than similar electric systems. Approximately 65% - 75% loss in the initial energy resource of the fuel occurs in typical electricity generation and distribution. In contrast, only about 5% to 10% of the fuel resource is lost with a gas system'. Life Cycle Assessment in terms of Energy Consumption and Carbon Dioxide Emission Generation should be conducted on various chiller alternatives to determine the environmental impacts of these systems. Life Cycle Cost Analysis (LCCA) should also be performed considering the evolving uncertainty about gas and electricity prices. Modeling utilities uncertainty is required for this purpose.

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Modeling Construction Waste Generation towards Sustainability

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Abstract

On-site waste management is considered as an important part of the sustainable construction process in any construction project. In fact, almost all Leadership in Energy and Environmental Design (LEED) projects require considerable effort in waste management as part of the requirement to obtain the LEED credits and rating. However, sustainable waste management is achievable only if the process is cost effective in addition to the underlying societal and environmental benefits. Planning on-site waste management process is essential to achieve economic benefits. However proper planning and execution is not possible without prediction of construction waste quantities linked to the project execution plan. The paper presents a novel method of grouping factors, thus reducing the number of variables for statistical analysis which requires for establishing relationships between quantity of waste and many factors such as labour, material and environmental related factors. . The research outlined in the paper considers the principles of "Activity Based Waste Generation" which enables the prediction of total waste from a project (i.e. cumulative waste from each of the activities). The presented methodology is part of the research on "developing a planning tool for construction waste management" which involves site monitoring, and data collections from several building construction projects in Calgary, Alberta.

Introduction

Sustainable development practices, which ensure societal and environmental advancements in addition to economic benefits, are well recognized and enforced by almost all municipalities/ local governments in Canada if not across the globe. Construction waste management can be considered as one good example of the construction industry's sustainable practices. It's noteworthy that Leadership in Energy and Environmental Design (LEED), one of the mostly accepted and widely recognized sustainable building rating systems (Syal et al. 2007), gives an impeccable place to on-site construction waste management within the rating system. On-site construction waste management often focuses on reuse, recycle and proper disposal of waste materials at landfills. However, it has been observed by researchers that adopting recycle and reuse without proper planning generates the desired environmental and societal benefits but may not produce economic benefits (Wimalasena et al. 2009). Although the focus on reduction or minimization of waste has been negligible over the past years, employing waste reduction strategies may still be the best approach towards minimizing the intensity of the construction waste problem.

Because economic benefits are not usually revealed from waste reduction, reuse and recycling activities, contractors usually give little consideration on environment compared to meeting targets and schedules (Poon et al. 2001). However, managing building material waste can in fact lead to achieve higher construction productivity, save time and improve on-site safety (Gavilan and Bernold 1994; Poon et al. 2001). To achieve economic benefits while receiving environmental and societal benefits from on-site waste management program, it is necessary to proceed planning even before start of the program (Osmani et al. 2008a; Ruwanpura et al. 2003; Tam 2008; Urio and Brent 2006; Wimalasena et al. 2007). There are researches that focus on planning construction waste management, and decision support management tools (Tam 2008; Ruwanpura et al. 2003; Chandrakanthi et al. 2002). However, quantifying the waste materials from construction projects is yet to be achieved. Authors recognize that to facilitate front end planning of on-site waste management process, it is essential to predict the quantities of waste generation and its generation pattern over the project duration. Therefore the existence of the much wanted research on predicting the construction waste quantities proves authors work on the same area, valuable and this paper focuses on this area.

Background

Estimations of construction waste quantities were often based on per capita multipliers similar to the municipal solid waste estimates. Identifying the limitations of the per capita multipliers based estimates (Yost and Halstead 1996) developed a method based on the financial value per square footage of the building, and the empirically estimated waste quantity (by weight) per square footage of the building. The method establishes the relationship between the financial value of the building and the quantity of waste (weight) as follows:

$$\underset{(tonnes)}{Quantity\ of\ waste} = \frac{Financial\ value\ of\ construction\ (\$)}{Financial\ value\ per\ SF\ of\ structure\ (\$/sq.ft)} \times \underset{(tonnes/sq.ft)}{Waste\ generation\ rate}$$

A system analysis tool for construction and demolition waste management was then introduced in 2004 where the material quantities for each building category were determined as a function of the number of building permits issued, the average floor area of a building of the category in concern, and the weight of the materials contained in a unit area of a building of the category (Wang et al. 2004). The aforementioned method assumes 10% of the material quantity generated as above to be produced as debris for construction projects, while for demolition projects 100% of the material quantity physically present in a building was assumed to be produced as debris. Cochran et al. (2007) identified the quantities of C&D waste generated and its material composition in terms of quantities as information of immense use in developing "C&D debris management policies" for a given region. Therefore, Cochran et al. (2007) developed a methodology that predicts regional waste quantities and composition, from construction (both residential and non residential), renovation, and demolition projects. However, the quantities of waste generation are estimated as the product of the "activity level of construction, demolition, or renovation in a region" and "waste produced per activity". Therefore, considering on-site waste management this quantification has little applicability. However, Hao et al. (2008) adopted a different approach in the study of managing construction waste though system dynamics modelling where, construction waste quantity is estimated as a fixed percentage of the purchased material quantity.

The above studies identify the quantities of waste generation as related to the net worth of construction, demolition, or renovation, building category, size etc.; however, these studies avoids a comprehensive analysis into the sources and courses of construction waste generation. Moreover, these methods are incapable of predicting the time variable nature of waste generation. It is evident that handful amount of researches identify the origins and causes of waste generation which are the contributory factors of construction waste generation (Bossink and Brouwers 1996; Gavilan and Bernold 1994; Osmani et al. 2008b). The above researchers identified causes of construction waste generation throughout project life cycle. For instance, initiation stage, design stage, procurement stage, material storage and management, site operation and residual management stage. Causes identified were categorized under the respective stage of the project life cycle. Other factors such as weather, theft and vandalism were also among the causes identified. Osmani et al. (2008a) mainly focussed the study on reduction of waste during the design phase and the study considered factors contributing to waste generation in Architectural designs.

This paper focuses on prediction of construction waste using activity-based waste generation principle. The study explained in the paper incorporates the identified factors' contribution towards the quantity of waste generation.

Activity based Quantification of Construction Waste Generation

Construction waste management related research work carried out by Chandrakanthi et al. (2002), which produced a simulation model for assessing cost/benefits of reuse and recycle, successfully recognised the activity based nature of construction waste generation. Adapting the same principle, a methodology for prediction of construction waste quantities is presented in this paper which can also be incorporated in to a simulation model for on-site waste management planning purposes.

Principle of activity-based waste generation assumes that total quantity of construction waste generated at a particular time in a construction site is the accumulation of waste quantities from each construction activity that is being executed at that moment. Therefore, prediction of total quantity of construction waste is possible only if each and every activity's waste generation can be predicted. Because of the nature of building construction, the quantity of waste generation from an activity is highly dependent on many factors. The following are the factors that considered in the study:

- **Activity Specific factors** such as construction method, activity duration, budgeted work (e.g. square footage), number of change orders, and expected rework due to damages caused by other trades.
- **Labour and Equipment related factors** such as number of labours, labour skill level, supervisor/foremen skill level, number of events of equipment malfunctioning/errors, and number of accidents.
- **Material & Storage related factors** such as material quality, transportation wastage, distance to the store, ordering quantity/required quantity, and ordered size/required size.
- **Site condition and Weather related factors** such as working temperature, humidity, wind, precipitation, lighting conditions, and site congestion.
- **Company policies** such as worker safety policy, pay method, hours of operation, and instruction method.

However the extent of dependency can only be quantified with a detailed site investigation followed by a comprehensive data analysis. Some of the above factors can be measured directly through manual observations but some requires qualitative analysis to quantify the contribution. Therefore, the nature of the study requires both quantitative and qualitative data collection and analysis in order to account for the actual conditions at site.
This paper is based on the development of a common methodology for quantifying activity specific waste generation in a building construction project. Methodologies of assessing human factors and non-human factors are discussed later within this paper. Although the author's discussion limits to the development of methodology as it plays a significant role in the prediction process, statistical data analysis, which is not explained in detail, is essential to establish the correlations and will be carried out.

Methodology for assessing factors contributions towards waste generation

The study incorporates two types of data, qualitative and quantitative, merging of the two needs to be carried out. Two approaches are available for this purpose. Statistical approach which analyses the identified variables, through both quantitative and qualitative approaches, combines into an appropriate test of a model using different techniques. Some of the techniques available are multiple regression analysis, multiple analysis of variance (MANOVA), a linear structural relations approach (LESREL), etc (Mitchell 1986). If the variables are specifically defined, conceptually different from each other, and not highly inter-correlated, the above statistical analysis tools can be used to assess the relationships.

The factors considered in the study can be categorized in to two as Human Factors (HF), and Non-Human Factors (NHF). The data collected through questionnaire surveys and interviews that represent human perceptions, skills, attitudes, etc. are assessed separately through HF aggregation process. In order to assess contributions from each human factor (HF), the methodology developed a range of relevant evaluation criteria against which the work groups (crew) are tested. A similar approach adapted by Deere et al. (2009) in assessing the group performance in ship designing has proven success. Thorough this methodology several factors, both HFs and non-human factors (NHFs), can be aggregated which makes the process of complicated multivariate analysis more feasible on one hand. On the other hand, it creates a platform for data triangulation, using both qualitative and quantitative data. However, it should be noted that, some factors that prefers to be analysed separately need not be grouped.

Estimating Human Factor Aggregates (Variables, V_i)

The first step to determine the correlation between variables and Quantity of waste from activity A (Q_A), is the assessment of V_i using the human factor scores. Human factor (HF_1,HF_2,..,HF_n) scores have been obtained through a questionnaire survey that targeted each worker in the work group. Aggregated factor values, therefore represent the workgroup. However, the importance of each factor in the aggregated factor can be different to one another. Similarly the role each worker play within the workgroup can also be different to each other. Therefore, it is essential to consider that in the aggregation process through assigning different weights for each worker (wk_1,wk_2,….wk_m).Table 1 illustrates criteria for Human Factor aggregates (variables) considered in the study.

Table 1: Variable- Human Factor aggregation criteria

Variable (V_i)	**Factor aggregate criterion**	**Human Factors (HF_k)**
V_1	Competency	Worker skills
		Adaptability to the organization and work site
		Knowledge about on-site construction waste management
V_2	Work satisfaction	Satisfaction on working hours
		Satisfaction on Instruction method

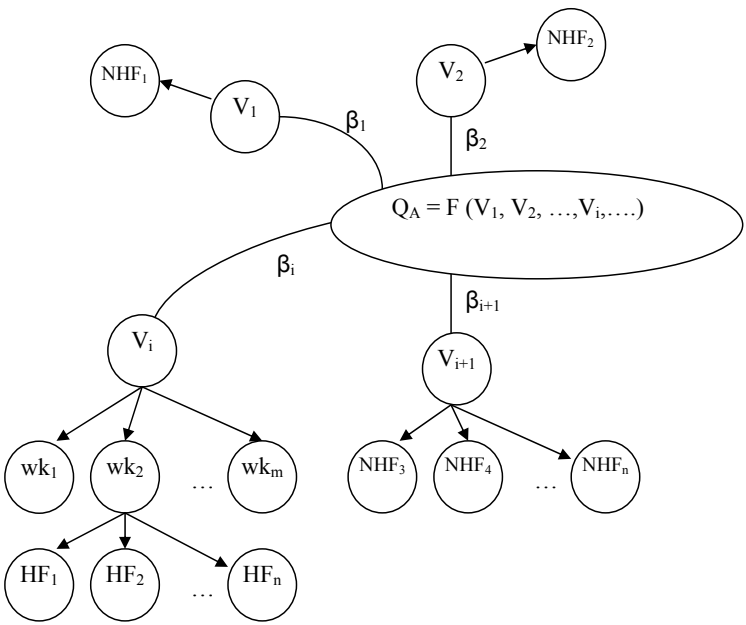
Estimating Non-Human Factor Aggregates (Variables, V_i)

Non-human factor (NHF) grouping helps aggregating factors under different assessment criteria which also minimizes the number of variables for statistical analysis. Table 2 shows the NHF aggregation criteria used for the study and the related NHF. NHF aggregation is a two-step process which includes determining the NHF score, and multiplying the score by respective importance factor (weight).

Table 2: Variable- Non-Human Factor aggregation criteria

Variable (V_i)	**Factor aggregate criterion**	**Non-Human Factors (NHF_k)**
V_{i+1}	Comfort level	Working Temperature
		Humidity of the working environment
		Light Level
		Precipitation (snow or rain)
V_{i+2}	Worker convenience	Distance to material storage area
		Available work space (congestion)
		Material (ordered size/required size)

The next step involves estimation of correlations between each variable and the quantity of waste generation. Figure 1 illustrates the overall process of construction waste generation prediction which involves both human factors and non-human factors.



Q_A = Quantity of waste from activity A, V = Variable factors affecting waste generation, β = Correlation coefficient, HF = Human factor, NHF = Non human factor, wk = Construction worker

Figure 1: Relationship tree-diagram of factors (HF and NHF), Variables (V) and Quantity of waste (Q_A)

The above research procedure enables the estimation of activity based waste quantities. As the name implies the amount of waste is determined in relation to the corresponding activity. The term "activity" refers to a single construction activity such as, "concreting level-1 columns". If the waste types generated as a result of execution of each activity are considered to be known before start of an activity, the quantity of each waste type can be calculated based on the above mentioned prediction technique. Figure 2 illustrates the importance of activity based waste quantification towards the planning on-site waste management program.

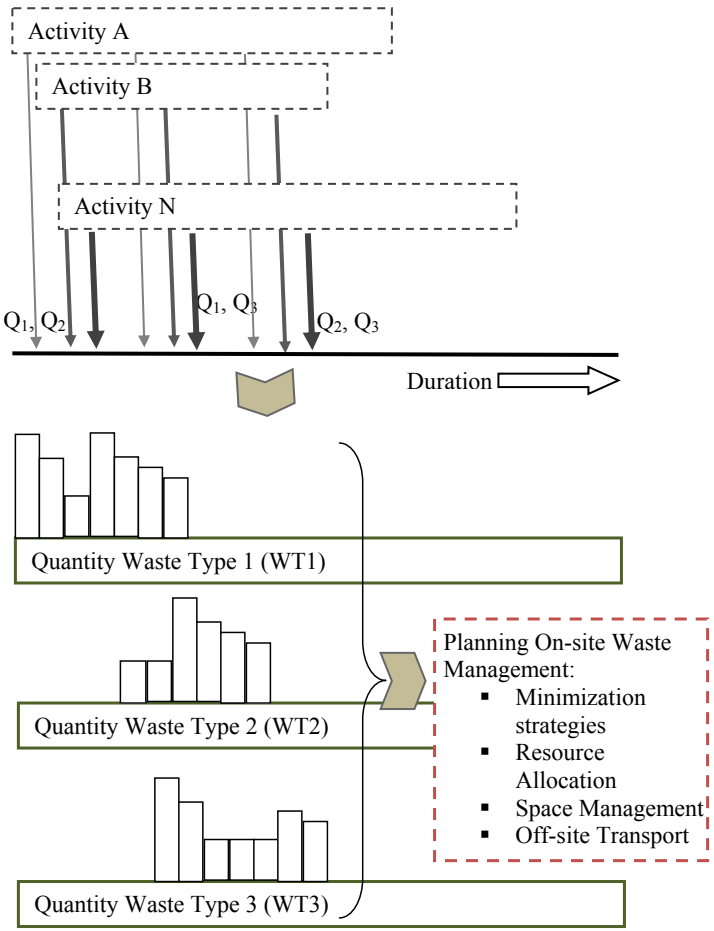


Figure 2: Planning Aspects of Construction Waste Prediction

With the use of generated results (quantities of waste generation from each type, WT1, WT2, etc.), it is possible to carryout planning and execution of the on-site waste management program effectively. In addition to scheduling the waste management activities, further analyses to determine effectiveness are also possible. For example, a analysis of the cost/benefits of landfill disposal, recycling, reusing, and combinations of aforementioned could be carried out to predict the best waste handling technique for the waste collected over a given time segment.

Conclusion

Prediction of construction waste quantities is of paramount importance for construction waste management planning. Prediction based on activity-based waste generation principle, a novel concept, can be considered more realistic than other methods available in literature. However taking causes of waste generation into consideration, better predictions could be achieved since it considers every possible cause throughout the project lifecycle. Since the study involves both qualitative and quantitative data collection, careful analysis is required to formulate better results. The study explained in the paper introduces a new method for merging both quantitative and qualitative data while reducing the number of variables for statistical analysis. The importance of prediction towards effective planning of the on-site waste management program is also highlighted in the paper.

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Current Status of C&D Waste Management and Green Building Standards in Canada

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Abstract

The research and literature reviews in the recent years clearly noted the immense economical, social, and environmental impacts created by the construction waste. Many developed countries have developed strategies and mechanisms to reduce the landfill deposits of construction and demolition (C&D) waste. Many European countries and Japan have been practicing C&D waste management for a much longer period and have effectively increased the percentage of recycled and/or re-used wastes in C&D. Landfilling construction waste materials has been recognized as a threat to the environment, especially due to its impact on groundwater quality. In addition, many previous researchers have clearly noted the immense economical, social, and environmental impact created by the construction waste. It was noted that the amount of recycled and/or reused waste use in the Canadian construction industry is much lesser than many other developed nations. Canada recycles and/or reuses only 22% of the solid waste while Denmark recycles and/or reuses 95% of the solid waste.

There are many green building rating systems and standards- such as LEED, BREEM, CASBEE, and GreenStar - in the world. The LEED standards are quite popular in Canada. Each rating system uses different methods and weights to analyze the sustainability in construction projects. Although many Canadian construction projects use the LEED 'ratings' to assess sustainability, it does not have a broad focus on C&D waste. The need for comprehensive and integrated waste management mechanisms, technologies, rating systems, and policies is widely visible in Canada comparing to some European countries.

Introduction

Buildings have a significant impact on the environment, consuming 32% of the world's resources, including 12% of its water and up to 40% of its energy. Buildings also produce 40% of waste deposits in landfills and 40% of air emissions (GBCA, 2009). According to Statistics Canada (2000), Construction and Demolition (C&D)

waste can be defined as waste material produced in the process of construction, renovation, or demolition of structures (including both residential and non-residential) as well as roads and bridges. The C&D waste generated by the Canadian construction industry accounts for 35% of total municipal solid waste generated in Canada (CCA, 2001). However, it is evident that much of what the construction industry generates as waste, has a residual value, and therefore; could be recycled and/or reused. For construction projects, 10% of the material quantity is considered as debris, while for demolition projects 100% of the material quantity is assumed to be debris (Wimalasena et al, 2008). The construction industry consumes enormous amounts of natural resources and at the same time produces vast quantities of C&D waste. Approximately 40% of all raw materials are extracted from the earth for construction purposes, with 25% of virgin wood use attributed to building construction (Bechtel, 1997).

Europe, Japan, and USA started recycling and/or reusing C&D wastes as soon as the end of World War II. These countries have introduced legislation and policy measurements to encourage the use of recycled material. These incentives often implemented in the form of higher land filling costs, taxes and imposing taxes on the use of virgin material; therefore, more incentives toward investments in C&D waste sorting and recycling facilities (Poon, 2007). Disposal of construction waste materials that could have been reused or recycled can be viewed as a resource under utilization. Although there is a scarcity of available land masses which could be utilized as landfills, landfill disposal rates have increased over the recent years and will continue to increase. Therefore, using landfills for construction waste is proven to be an economically impracticable (Poon, 2007). In addition to the shortage of land and the increasing prices of landfills and dumpsites, the driving force behind waste management in the C&D sector is environmental protection and conservation of natural resources. According to the European Union guidelines in wastes, the reduction of the present levels of waste generation and the increase in energy and materials recovery, represent two of the most important future requirements for environmentally sound waste management practices (Marchettini et al, 2007).

This paper aims to point out what Denmark, Finland, Netherlands, United Kingdom, Japan, and U.S.A have achieved in C&D waste management. It creates a practical pathway for the C&D waste management in Canada to review and make necessary changes to the current system.

Recycling, Reusing, Incinerating and Land filling

Denmark, Finland, Netherlands, United Kingdom, Japan, Canada, and U.S.A have introduced the Green Building tools to minimize the amount of waste generation in the project construction and maintenance phases. Respectively, these countries have introduced practices to minimize the amount of waste dumped in landfills by minimizing waste generation. Using different approaches Denmark and Finland have been able to recycle and/or reuse C&D waste up to 90% as shown in table 2 and 3. Table 1 shows how the C&D waste is sorted into 10 categories and what percentage has been recycled and/or reused in Netherlands. Netherlands has recycled and/or reused 76% of total C&D waste. They also recycled 90% of Core C&D waste and 3% of the major construction waste.

Table 1: Netherlands C&D waste recycling (Annex, 1999)

Netherland Waste	Arising (m tones)	Reused (%)	Recycled (%)	Incinerated (%)	Land filled (%)
Concrete, Brick, Tiles, etc	10.48	0	93	1	6
Wood	0.26	0	50	10	40
Glass					
Plastic	0.21	0	5	12	83
Metals	0.18	0	100	0	0
Insulation					
Mixed & other C&D	0.04	0	0	0	100
Core' C&D	11.17	0	90	1	9
Soil, Stones, etc.	6.2	0	40	0	60
Road planings (mainly asphalt)	2.72	72	28	0	0
Total	20.09	10	66	1	23

As indicated in table 2 Denmark has recycled and/or reused 90% of total C&D waste generated. Denmark recycled 81% of core C&D waste. Table 3 shows that Finland has recycled and/or reused 88% of total C&D waste generated. They recycled and/or reused 45% of core C&D waste and 80% of concrete, brick, tiles, etc.

Table 2: Denmark C&D waste recycling (Annex, 1999)

Denmark Waste	Arising (m tones)	Reused (%)	Recycled (%)	Incinerated (%)	Land filled (%)
Concrete, Brick, Tiles, etc.	1.8	1	97	0	2
Wood	0.2	30	30	15	25
Glass	0.05	15	40	0	45
Plastic	0.01	0	20	30	50
Metals	0.16	38	60	0	2
Insulation	0.05	40	30	0	30
Mixed & other C&D	0.37	0	0	10	90
Core' C&D	2.64	6	75	3	16
Soil, Stones, etc.	7.7	16	6	0	0
Road planings (mainly asphalt)	0.37	74	26	0	0
Total	10.71	36	54	1	9

Table 3: Finland C&D waste recycling (Annex, 1999)

Finland Waste	Arising (m tones)	Reused (%)	Recycled (%)	Incinerated (%)	Land filled (%)
Concrete, Brick, Tiles, etc.	0.52	4	76	0	20
Wood	0.44	2	7	69	22
Glass	0	1	29	0	70
Plastic	0	5	5	0	90
Metals	0.17	6	75	0	19
Insulation	0.02	10	45	0	45
Mixed & other C&D	0.2	0	0	8	92
Core' C&D	1.35	3	42	24	31
Soil, Stones, etc	8	40	55	0	5
Road planings (mainly asphalt)	0.1	95	5	0	0
Total	9.45	35	53	3	9

As shown in table 4, United Kingdom has recycled and/or reused 47% of total C&D waste generated.

Table 4: United Kingdom C&D waste recycling (Annex, 1999)

United Kingdom Waste	Arising (m tones)	Reused (%)	Recycled (%)	Incinerated (%)	Land filled (%)
Concrete, Brick, Tiles, etc.					
Wood					
Glass					
Plastic					
Metals					
Insulation					
Mixed & other C&D					
Core' C&D	30		45		55
Soil, Stones, etc	29.5	41			59
Road planings (mainly asphalt)	7.5		80		20
Total	67	18	29		53

As discussed above some European countries have high standards in recycling and/or reusing C&D waste, and have minimized the amount that needs to be dumped in landfills which causes major environmental issues. Recycling and/or reusing decrease the amount of use of virgin raw material which is economically and environmentally beneficial.

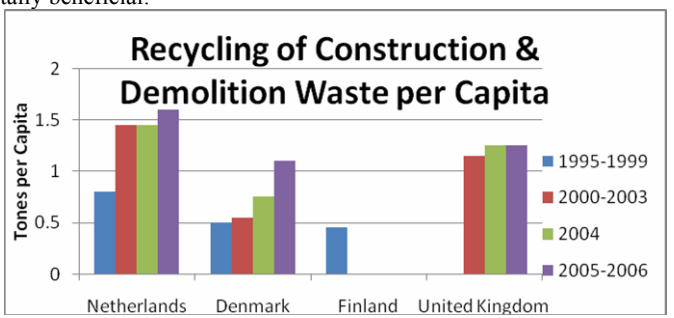


Figure 1: Recycling of C&D waste per capita (Fischer, 2009)

Figure 1, clearly shows that these European countries have progressively increased the amount of recycling in the C&D sector in the past decade. Canada on the other hand has not yet introduced significant incentives that can effectively motivate the construction industry in recycling and reusing the C&D waste. As mentioned, the amount of waste generated through the construction portion (10%) is not as significant as it is in the demolition phase. Therefore the C&D waste that is being dumped in landfills in Canada is mainly from the demolition phase (Wimalasena et al, 2008). As shown in table 5, Canada is dumping almost eight times the amount of waste (as a percentage) in landfills compared to Denmark. It is evident that 74% of Canada's solid waste is dumped into landfills, a quantity that can be recycled and/or reused up to 95% (Sawel *et* al, 1996). As indicated in table 5, only 22% of the total solid waste generated in Canada is recycled and/or reused. Canada is lagging far behind to the other developed nations in its practices and policies in waste management. Unfortunately very little or no statistics are available on the amount of recycled C&D waste in Canada, and limited research has been conducted on this manner. However, as shown in figure 1, some European countries have been practicing recycling seriously and are maximizing their efforts on reducing the amount of waste being dumped in landfills.

Table 5: Canada Solid waste recycling (Statistics Canada, 2006)

Canada waste	Arising (m tones)	Recycled/Reused (m tones)	Incinerated (m tones)	Land filled (m tones)
Solid waste	12.5	22	4	74

Comparison of Green Building Standards

Construction consumes and discards resources and energy in enormous quantities, and it is necessary to act urgently to develop and promote techniques and policies which assist the drive towards sustainability. There has been a growing movement towards sustainable construction since the second half of the 1980s, leading to the development of various methods for evaluating the environmental performance of buildings. Methods developed overseas include BREEAM (Building Research

Establishment Environmental Assessment Method) in UK, LEED (Leadership in Energy and Environment Design) in USA, CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) in Japan, Green Star in Australia, and GB Tool (Green Building Tool) as an international project. Canada developed LEED Canada (Leadership in Energy and Environmental Design) by performing minor changes to the LEED USA. Green building assessments, with the publication of the results, is one of the best methods now available to provide an incentive for clients, owners, designers and users to develop and promote highly sustainable construction practices. These green building practices effectively help in sustaining construction waste and reduce the amount of waste generated. These practices are now playing a large role in waste management for the construction industry and have attracted interest around the world.

i. LEED USA

LEED is internationally recognized for its green building certification system, providing and verifying that a building or a community was designed and constructed using strategies to improve its performances in what matters most, energy savings, water efficiency, CO2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts (USGBC, 2009). Developed by the U.S. Green Building Council (USGBC) between the years 1994-1998, LEED provides building owners and operators a concise framework for identifying and implementing practical and measurable green building design, construction, operations and maintenance solutions. LEED is now the most widely used rating system in the US, and has made a major impact in the design and construction of buildings in US for the last decade (USGBC, 2009).

LEED schemes: 1) New Construction 2) Existing Building: Operation & Maintenance 3) Commercial Interiors 4) Core & Shell 5) Schools 6) Retail 7) Healthcare 8) Homes 9) Neighborhood Development

LEED Ratings: 1) Sustainable sites (SS) 2) Water Efficiency (WE) 3) Energy & Atmosphere (EA) 4) Material & Resources (MR) 5) Innovation in Design (ID)

There is a 100 base point:

Leed USA Rating	Certified	Silver	Gold	Platinum
Points	40-49	50-59	60-79	80-100

Waste reduction rating for Commercial Interior: 1- Storage and collection of recyclables (1 point) 2-Tenant space-Long term commitment (1 point) 3-Building reuse- maintain interior nonstructural components (40% 1 point, 60% 2 point) 4-Construction waste management (50% 1 point, 75% 2 point) 5- Materials reuse (5% 1point, 10% 2 point) 6- Materials reuse-Furniture and furnishings (1 point) 7-Recycled content (10% 1point, 20% 2 point) 8- Regional material (1 or 2 points) 9-Rapidly renewable material (1 point) 10- Certified wood (1 point).

ii. LEED Canada

LEED was adopted by the Canadian Green Building Council (CaGBC) with minor variations in 2004, and the outcome was LEED Canada-NC Version 1.0, which was followed by LEED-Canada CI in 2005. LEED Construction rating system is specifically applicable to new designs and major renovations on new commercial

buildings, institutional buildings, and high rise residential buildings. Being a voluntary and consensus- based method system which can be used as a design guideline; LEED Canada aims to improve occupant well-being, environmental performance and economic returns of buildings using established and innovative practices, standards and technologies (CaGBC, 2004).

LEED Canada schemes: 1) New Construction 2) Commercial Interiors 3) Core & Shell 4) Existing Building 5) Homes 6) Neighborhood Developments

LEED Canada Rating: 1) Sustainable Sites (SS) 2) Water Efficiency (WE) 3) Energy & Atmosphere (EA) 4) Materials & Resources (MR) 5) Indoor Environmental Quality (IE) 6) Innovation and Design Process (ID)

There is a 70 base point, which certifies the building in the following certifications:

Leed Canada Rating	Certified	Silver	Gold	Platinum
Points	26-32	33-38	39-51	52-70

Waste reduction rating for Commercial Interior: 1- Construction waste management (50% 1 point, 75% 2 point) 2- Resource reuse (5% 1 point, 10% 2 point, 30% 3 point) 3- Recycled Content (10% 1point) 4- Potential technologies and Strategies (1 point)

iii. BREEAM

BREEAM is the world's longest established and most widely used environmental assessment method for buildings. It sets the standards for best practice in sustainable development and demonstrates a level of achievement. It has become the de facto measure of a building's environmental performance (BRE, 2008). The BREEAM assessment process was created in 1990 with the first two versions covered offices and homes. All versions are updated regularly in line with UK Building Regulations. Different building versions have been created since its launch to assess various building types (BRE, 2007). BREEAM addresses wide-ranging environmental and sustainability issues and enables developers and designers to prove the environmental credentials of their buildings to planners and clients.

BREEAM schemes: 1) Other Buildings 2) Courts 3) Sustainable Homes 4) Ecohomes 5) EcohomesXB 6) Healthcare 7) Industrial 8) International 9) Multi-residential 10) Prisons 11) Offices 12) Retail 13) Education 14) Communities

BREEAM Rating: All these versions essentially look at the same broad range of environmental impacts, which are, Management, Health and Wellbeing, Energy, Transport, Water, Material and Waste, Land use and Ecology, and Pollution. Credits are awarded in each of these categories according to performance. A set of environmental weightings then enables the credits to be added together to produce a single overall score (BRE, 2007).

BREEAM Rating	Pass	Good	Very Good	Excellent

Waste reduction rating for Offices: BREEAM has allocated 9.97 points for the materials used in the design stage assessment and 9.99 points for management and operation assessment for office constructions.

iv. CASBEE

Development of CASBEE started from perception that the current Green building practices are not including all possible measures for a sustainable construction.

CASBEE took in hand the reconstruction of the current environmental performance assessment framework into a new system clearly based on the perspective of sustainability. Environmental assessment began when it was recognized that the capacities of local environments, and the world as a whole, were reaching a limit. As a result, the concept of closed ecosystems became essential for determining environmental capacities when conducting environmental assessments (JSBC, 2006). Therefore a hypothetical enclosed space bounded by the borders of the building site is proposed here in making environmental assessments of buildings. The environmental loadings can thus be defined as "the negative environmental impact that extends outside to the public environment beyond the hypothetical enclosed space." The improvement of environmental performance within the hypothetical enclosed space is defined as "the improvement in living amenities for building users. Hence CASBEE claims that this method encloses more detail in sustainable construction (JSBC, 2006).

CASBEE was developed according to the following policies:

1) The system should be structured to award high assessments to superior buildings, thereby enhancing incentives to designers and others.
2) The assessment system should be as simple as possible.
3) The system should be applicable to buildings in a wide range of applications.
4) The system should take into consideration issues and problems peculiar to Japan and Asia.

CASBEE schemes: CASBEE has two main categories:

1) Q (Quality): Building Environmental Quality & Performance: Evaluates "improvement in living amenity for the building users, within the hypothetical enclosed space (the private property)" (JSBC, 2006).
2) L (Loadings): Building Environmental Loadings: Evaluates "negative aspects of environmental impact which go beyond the hypothetical enclosed space to the outside (the public property)" (JSBC, 2006).

CASBEE covers the following four assessment fields: (1) Energy efficiency (2) Resource efficiency (3) Local environment (4) Indoor environment

Assessment Categories: 1) Q (Building Environment Quality & Performance) is broken into three categories: 1.1) Q-1 Indoor Environment 1.2) Q-2 Quality of Service 1.3) Q-3 Outdoor Environment on site (JSBC, 2006). 2) LR (Reduction of Building Environmental Loadings) is also sub graded into three categories: 2.1) LR-1 Energy 2.2) LR-2 Resources & Materials 2.3) LR-3 Off-site Environment (JSBC, 2006).

CASBEE Rating: A five-level scoring system is used, and a score of 3 indicates as "average".

Weighting: Each assessment item, such as Q-1, Q-2, Q-3, is weighted so that all the weighting coefficients within the assessment category Q sum up to 1.0. The scores for each assessment item are multiplied by the weighting coefficient, and aggregated into SQ; total scores for Q or LR; total scores for LR respectively (JSBC, 2006).

CASBEE Rating	Poor	Average	Good	Very Good	Excellent
Points	C	B-	B+	A	S

Waste reduction rating: CASBEE has allocated 3 points before multiplying the coefficients in for Materials of low environmental load

v. Green Star

The Green Building Council of Australia's (GBCA) objective is to promote sustainable development and the transition of the property industry by promoting green building programs, technologies, design practices and operations (GBCA, 2009). After an industry survey conducted by the GBCA, Green Star was developed to be a comprehensive, national, voluntary environmental rating scheme that evaluates the environmental design and achievements of buildings (GBCA, 2009). Green Star has built on existing systems and tools in overseas markets including the British BREEAM and the North American LEED system. In addition, VicUrban, in its work with the Melbourne Docklands' ESD Guide, provided the intellectual property to assist in the development of a local system. Green Star has established individual environmental measurement criteria with particular relevance to the Australian marketplace and environmental context (GBCA, 2009).

Green Star schemes: 1)Multi Unit Residential 2)Health Care 3)Retail Centre 4) Education 5) Office 6) Industrial

Green Star Rating:

Green Star Rating	One Star	Two Star	Three Star	Four Star	Five Star	Six Star
Points	10-19	20-29	30-44	45-59	60-74	75-100

Green Star rating tools award points for achievement of specific credits in each rating category, as defined in the applicable Green Star Technical Manual.

Waste reduction rating: Green star has allocated 2 points for waste management in their rating criteria.

In table 6, the schemes of LEED, LEED CANADA, BREEAM, and Green Star are compared. It can be concluded the BREEAM green building method has a larger range of categories and analyzing each category more precisely.

Table 6: Green Building summary

	LEED USA	LEED CANADA	BREEAM	Green Star
Other Buildings			✔	
Courts			✔	
Sustainable Homes		✔	✔	
Ecohomes			✔	
EcohomesXB			✔	
Healthcare	✔		✔	✔
Industrial			✔	✔
International			✔	
Multi-residential			✔	✔
Prisons			✔	
Offices/Commercial Interiors	✔	✔	✔	✔
Retail	✔		✔	✔
Schools/Education	✔		✔	✔
Communities/Neighborhood	✔	✔	✔	
New Construction	✔	✔		
Existing Buildings	✔	✔		
Operation & Maintenance	✔			
Core & Shell	✔	✔		
Rating System	100 point scale	70 point scale	Letter Scale	100 point scale
Estableshment	1993	2003	1990	2003

Current Research

The literature reviews and field observation conducted in the past clearly noted the immense socio-economic and environmental impacts created by the construction waste. The construction waste management research program at the University of

British Columbia, Okanagan actively involved in developing the technologies, policies, rating systems, and management solutions for construction and demolition waste in construction projects. Figure 2 is an integrated map of current focus areas of waste management in the CWM research program.

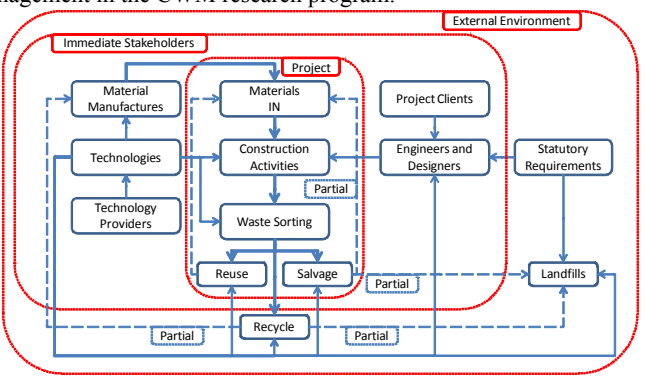


Figure 2: Integrated Network for Research in Construction Waste Management

Following are the key current research projects in the research program.

i. Identify the sources, activities, and quantities of construction waste (CW) in the project lifecycle, and propose relevant design focuses and best management practices for waste minimization.
ii. Investigate the potentials for re-using, salvaging, and recycling the hazardous CW by considering the cost/benefits to the project stakeholders and the environment as a whole.
iii. Develop practical and efficient sorting mechanisms for CW, by integrating the project planning, designing, and construction phases.

Conclusion

In conclusion, it is noted that the construction Industry has a great impact on the environment, and governments have taken steps to prevent and minimize the amount of waste generated in the construction industry. LEED-USA, LEED-Canada, CASBEE, GreenStar, and BREEM are the leaders in construction 'Green Building' ratings. CASBEE and Green Star analyze the projects individually and have a greater span of categories. Canada is lagging far behind to some of the other developed nations such as Denmark, Finland, and United Kingdom in terms of the recycling and reusing the construction waste. For example, Denmark is recycling and /or reuse over 90% of the solid waste, where Canada recycles/ and or reuse only 22% of the solid waste material. Green Building practices has made a landmark in promoting the possibilities of reducing and minimizing waste generation in the construction industry. However, the need for a more focused green building practices and policies for construction waste in needed to minimize the landfill deposits of C&D waste. Canada should focus on achieving a practical target of recycling or reusing 90% of the C&D wastes as similar to Denmark and Finland. To achieve such a target, the

government may implement the necessary regulations and incentives to encourage the construction industry to move towards recycle and/or reuse C&D waste.

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Process-Based Approach in Sustainable Impact Analysis of Rebar Supply System

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Subject Area: Sustainable Construction, Lean Construction

Abstract:
Although attempts to assess sustainable impacts have been made for specific building components in construction domain, the study of material supply systems has been neglected due to the difficulty of analysis. The research intends to apply a process-based approach in which the analysis is based on processes instead of resources to investigate sustainable assessment of material supply systems in the construction domain. As part of the pilot study, the researchers did a case study where a process-based approach is applied to investigate financial and environmental impacts of rebar supply systems in building construction. The main purpose of this paper is to demonstrate how a process-based approach can be applied and address the difference of process design of alternative supply systems while traditional product-based approach does not.

1. Introduction

Attempts to assess sustainable impacts have already been made to evaluate the life-cycle effects of commercial buildings, but most studies thus far have focused on specific building materials. In many studies, the impacts of the construction material supply system are ignored or simply approximated because the analysis of supply systems is complicated or the methodologies of analysis are limited. While most relevant research regarding supply systems have focused on how lead time can be reduced using either process improvements or external integration with suppliers, few research studies have investigated the financial and environmental impacts of a new material supply system even though it is critical in terms of sustainability.

As to financial impacts, previous research has been done on investigating their impact on direct costs such as material costs. However, a comprehensive approach, which investigates not only the impacts of direct costs but also overhead costs, is

required because such changes in a material supply system greatly influence the way administrative work, such as the procurement process, is done.

As to environmental impacts, recent descriptive research into environmental impacts has investigated a variety of factors. However, these studies lack consideration of environmental impact throughout the building life cycle (from materials and energy acquisition through building construction, use/maintenance, and demolition/materials recovery), as is captured using Life Cycle Assessment (LCA).

The research intends to use and validate a process-based approach in which the analysis is based on processes instead of resources to investigate sustainable assessment of material supply systems in the construction domain. As part of this pilot study, the researchers did a case study where a process-based approach is applied to investigate financial and environmental impacts of lean rebar supply systems in building construction. Lean rebar supply system in this paper refers to rebar supply system in which prefabricated rebar is delivered to the sites based on just-in-time delivery. The main purpose of this paper is to demonstrate how a process-based approach can be applied and address the process design of lean supply systems.

2. Alternative Rebar Supply System and Scope of the Paper

The supply system of reinforced steel bar to construction is considered one of the critical factors in meeting the budget and schedule goals of a construction project (Polat et al., 2003). The tradition of the construction industry has long been to fabricate (i.e., cut and bend) rebar on-site and rebar is delivered to the site in large batches. The traditional rebar supply system requires large on-site yard and holding costs. Since people have recognized that holding costs include yard space requirements, a new method has gained industry attention especially in construction projects in metropolitan areas. A new rebar supply system, called lean supply system, uses off-site cut & bent (i.e., prefabrication) with a frequent delivery of small batches. Even though this new system requires more frequent deliveries, it removes yard space requirements and deliveries within the sites (i.e, on-site yard to building). Arbulu and Ballard (2005) showed that a lean rebar supply system reduces the need for inventory space on sites and improves productivity due to prefabrication. The scope of this paper in the case study is on applying process-based sustainable impact analysis to lean rebar supply system.

3. Methodology: Process-Based Sustainable Impact Analysis

Once a product design is fixed, a process manager such as a contractor or installer needs to derive the process design such as best configuration of resources. The process-based sustainable impact analysis can address the difference of process design (e.g., how the materials are delivered and installed) while the current product-based analysis cannot. The process-based sustainable impact analysis consists of three parts: process mapping, process-based costing, and process-based life cycle analysis (LCA).

Process Mapping

The purpose of mapping a process is to make explicit which steps or activities make up the process, how these relate to one another in terms of sequencing and handoffs, and who is responsible for managing and executing them. A subsequent step is modeling, that is, to refine the process and collect and add all necessary detail. The process maps serve a ground work for the process-based costing and process-based LCA. The researchers collected information to develop process maps through interviews and observation. The researchers had interviews with key personnel including material procurement managers and site engineers as well as site visits.

Process-based costing (activity-based costing)

Process-based costing (or Activity-Based Costing) is a method of assigning the organization's resource costs through activities to the products and services (Cokins 1996). This research used the time-based ABC to trace related overhead costs as well as direct labor costs. Overhead costs include procurement costs, transportation costs, rent for assembly yards, and other miscellaneous costs. In implementing the time-based ABC (Kaplan and Anderson 2004), process mapping derives defining activities. In the time-based ABC model, overhead expense categories such as salaries of key personnel, energy consumptions of main equipment in a project sites, the rents for assembly yards, and transportation methods and distance were identified. This cost data could be obtained from interview, observation, and documentation.

The time-based ABC system for this project was developed using a three-step process: 1) estimating the cost per time unit for each resource, 2) estimating durations and resource consumption (i.e., cost equation) of activities, and 3) deriving activity costs.

Process-based LCA

LCA is a model-based approach for assessing where, and in what form, energy and materials are used (and wasted) throughout a life cycle (Cooper 2003; Cooper and Godwin, 2008). The life cycle of a building spans the acquisition and processing of building materials and fuels, building construction, building operation and maintenance, and demolition and materials recovery activities.

The core LCA model on which this analysis is based is as outlined in Heijungs and Suh (2002). The process mapping will outline what the system boundaries are and what functional units will be used for comparative analysis. The inventory analysis arranges the collected data into matrices that can then be solved to give the emissions and energy results for each scenario. The technology matrix, which is denoted A, consists of the economic flows for each of the processes. The intervention matrix, B, consists of the environmental flows for each of the processes. The demand vector, f, contains the quantities for each economic flow that are required to fulfill the desired scope. Once all of these inputs are acquired the scaling vector, s, can be derived by multiplying the inverse of A by the demand vector:

$$s = A_{-1} f \qquad \text{Equation (1)}$$

From s the final inventory vector, g, can be acquired by multiplying the inventory matrix by the scaling vector:

$g = Bs$ Equation (2)

The inventory vector is the final output of the system for the functional unit. The inventory results are then manipulated to give the total environmental impacts of each system in the impact assessment section.

Energy consumptions and air emissions, and material loss rates of the two delivery systems during the fabrication, transportation, and installation of rebar were measured. The energy types in this project include electricity, diesel, and propane. Air emissions include CO, NOx, Sox, VOCs, PM10, and greenhouse gases, such as CO2, CH4, and N2O. For this research, a two-step process LCA was developed: 1) inventory analysis based on sub-processes resulting from process mapping, and 2) impact analysis and interpretation.

Implementation Procedure of Process-Based Sustainable Impact Analysis

The process-based sustainable impact analysis consists of two phases as shown in Figure 1. The first phase, system boundary and defining processes, provides framework for cost analysis as well as environmental analysis. Process mapping based on interviews with key employees of different stakeholders and observation is used in the first phase. The second phase consists of two paralleled analyses: 1) process-based cost analysis and 2) process-based life cycle analysis.

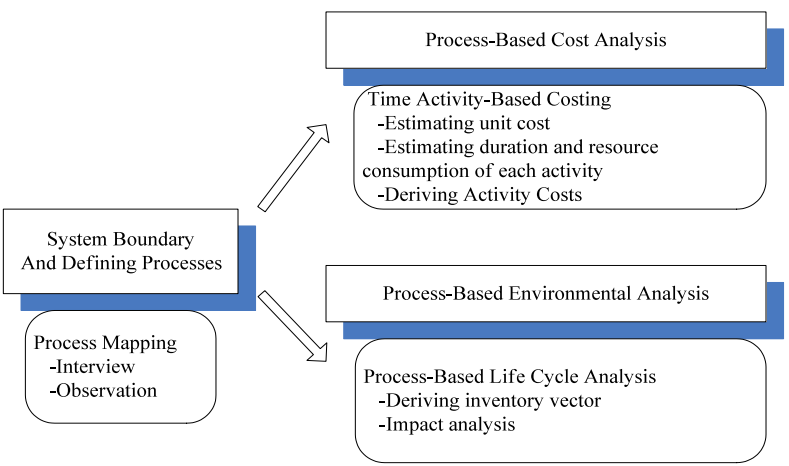


Figure 1. Procedure of Process-Based Sustainable Impact Analysis

4. Case: A High-rise Condominium Building Construction in Seattle, WA

Background

A high-rise condominium construction project in downtown Seattle is investigated for this research. The residential tower will be 19-stories tall with 135 one- and two-bedroom and sky townhomes units on floors 5 thru 19. All structural rebars were delivered using prefabrication and JIT on the project.

Process Mapping

The process map for the lean rebar delivery system has been developed for ABC and LCA. The researchers interviewed with key employees to identify their major activities and resource consumed for each activity. Interviewees included 1) material procurement managers and project engineers of general contractor and specialty contractor (assembler) and 2) engineering and manufacturing staff of fabricator. The system boundaries of the rebar delivery systems include the supply chains from the extraction of natural resources, raw materials and energy production, raw rebar manufacturing in a mill plant, fabrication and assembly of the rebar, installation of the assembled rebar, and transportation between each activities. The backhauls with material scrap were also considered in both systems. The supply chains after installation of the rebar products are not included in this study. Figure2 shows the process map at the aggregate level system which also shows system boundaries of the delivery systems.

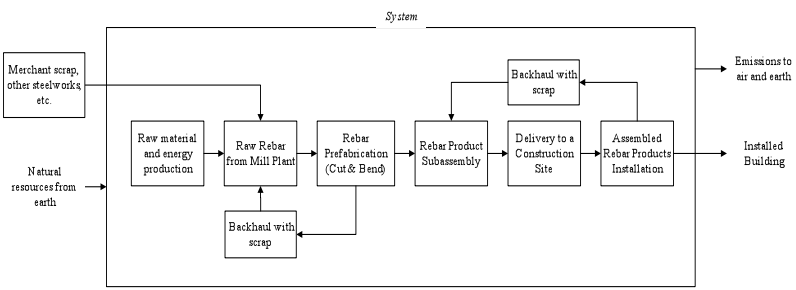


Figure 2. Rebar Delivery System Overview

Process-Based Approach in Analyzing Costs

Activity Definition and Cost Drivers

Process map provides framework for process-based cost analysis. Once activities are identified in the process map, sub-processes (activities) with their time consumed and cost drivers for each activity are investigated. An activity cost driver can be defined as any factor that causes a change in the consumption of an activity by other products, suppliers, or customers (Cokins, 1996; Cooper 1990). Examples of activities with their cost drivers are presented in Table 1. Information on time consumption for each activity is used in developing cost equations for each activity.

Table 1. Example of Sub Activity and Cost Driver

Act. Number	Activity	Cost Driver
5	Review the shop drawings	# of shop drawings
6	Approve the shop drawings	# of shop drawings
17	Subassemble the Fabricated Rebar	# of assembly
18	Deliver the assembled rebar to construction site	# of assembly
19	Inspect the delivered rebar assembly	# of inspection

Estimating the cost per time unit

The research team estimated the cost per time unit of each resource by dividing the operating time and total cost of each capacity by the total working hours per week. For instance, if an employee is available to work 40 hours per week, the salary of the employee is multiplied by the operating time, and then divided by 40 hours. The salaries per time unit for the stakeholders are shown Table 2.

Table 2. Example of Hourly Wage for human resources

Stakeholder	Position	Wage per Hour
General	Proj. Mgr.	$63
Contractor	Engineer	$40
	Labor	$40
	Rebar Keeper	$12

Moreover, the research team searched web sites to get raw rebar prices, rebar scrap prices, and energy prices, such as electricity price, diesel price, and propane price in Seattle and Tacoma.

Deriving time-based cost equation of activity

The research developed time-based cost equations based on the thorough analysis of the activities within the scope of the research. The results were summed to calculate the total time for the activities. Examples of time equations are shown in Table 3.

Table 3. Example of Time-based Cost Equations

	Activities	Activity cost per a cost driver
5	Review shop dwg	1.5 (GC E) + if shop gwgs revised[2(GC E)]
6	Shop dwg approval	2(A/E) + if shop dwg rejected [3(A/E)]
17	Assemble prefab. Rebar	40(SC Labor) + if assembly rejected[40(Plant Labor)]
18	Deliver assembled rebar to site	1.7(Plant Labor) + if assembly rejected[1.7(Plant Labor]
21	Install Rebar	4(GC E)+4(SC E)+20(SC Labor)

Note: Each variable indicates hourly wage for each staff. GC = General contractor, A/E= architect & engineer, SC=subcontractor, E = engineer, PM=project manager, SD=drafter

Process-Based Environmental Impact Analysis

Data Collection and Sources

The data for this LCA research came from several sources. The rebar prefabrication, assembly, and installation data were directly obtained at a rebar prefabrication plant and a general contractor. General production data came from GREET. Data sources for major processes are shown below in Table 4.

Table4. Data Sources for Processes

Process Category	Processes	Data Sources
Rebar Production	Raw rebar production	GREET
	Prefabrication (cutting & bending) of the raw rebar	Rebar production plant
	Subassembly of the fabricatedrebar in an assembly yard	Rebar prefabrication plant
Energy Production	Electricity production	GREET
	Diesel production	
	Propane production	
Transport	Delivery of the raw rebar to the prefabrication plant	GREET
	Backhaul with scrap	USEPA's NONROAD model
	Moving fabricated rebar to an assembly yard	Rebar production plant
	Delivery of the assembled rebar to a construction site	Rebar prefabricationplant
Installation	Unloading and inspecting the delivered rebar assembly	GREET
	Installation of the rebar assembly	USEPA's NONROAD model
		General Contractor

Analysis procedures

The model is developed using the methodology in The Computational Structure of Life Cycle Assessment (Heijungs and Suh 2002). Microsoft Excel 2007 was used for the model. The inventory data was separated into a technology matrix and an intervention matrix. The technology matrix consists of economic flows 17 unit processes based on the system boundary. The research followed the calculation based on equations (1) and (2). The intervention matrix consists of the 8 major gases: carbon dioxide, carbon monoxide, methane, nitrogen oxides, nitrous oxide, non-methane volatile organic compounds, particulates, and sulfur oxides.

Inventory Results

The inventory result from the one kg of rebar generation to the installation of the rebar is shown in Table 5.

Table 5. Inventory Results

Emissions	Rebar Supply
Carbon dioxide	5.50E+06
Carbon monoxide	2.11E+04
Methane	2.50E+03
Nitrogen oxides	4.83E+04
Nitrous oxide	1.58E+01
NMVOC	3.04E+03
PM10	3.35E+03
Sulfur oxides	7.68E+03

Impact Assessment

The classification in this study is mainly focused on air emissions causing acidification, eutrophication, global warming, and smog. The equivalency factors for these pollutions are acquired from EPA's TRACI. The contribution analysis was performed for each rebar delivery method by multiplying the equivalency factors calculated from the TRACI and the scaling vectors. Table 6 shows the contribution of the rebar supply to the categorized pollutions.

Table 6. Contribution Analysis using TRACI

Release Name	Global Warming Air (CO2-e / kg)	Acidification Air (H+ moles-e / kg)	Eutrophication Air (N-e / kg)	Smog Air (g NOx / m / kg)	Smog Air (g NOx-e)
Carbon Dioxide	5.50E+06	0	0	0	0
Carbon Monoxide	0	0	0	3.51E+02	2.83E+02
Methane	5.25E+04	0	0	9.20E+00	7.42E+00
Nitrogen Oxides	0	1.93E+06	2.14E+03	5.99E+04	4.83E+04
Nitrous Oxide	4.89E+03	0	0	0	0
VOCs	0	0	0	2.94E+03	2.37E+03
PM10	0	0	0	0	0
Sulfur Oxides	0	3.90E+05	0	0	0
Contribution Total	5.56E+06	2.32E+06	2.14E+03	6.32E+04	5.09E+04

5. Discussion and Conclusions

The paper showed the procedures and examples of a process-based sustainable impact analysis. One of lessons learned on the course of the case study is that the system boundary should be set up earlier so that data could be accessed. Because most products or processes in a supply chain have complicate networks, this method generally sets up the boundary within which analysis is made. Some processes in a supply chain are usually excluded. Unlike traditional methods, however, a process based approach can address the process design of the supply system. It is noted that the paper did not address detailed procedure of the process-based impact analysis.

The paper contributes to the body of knowledge in the area of sustainable construction by presenting a process of integrated model of process-based cost and environmental analysis based on process mapping.

6. Acknowledgements

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Shale Oil - An Opportunity to Revive the Construction Industry and Economy while Increasing Energy and Construction Job Security

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Abstract
The Strategic Petroleum Reserve (SPR) represents an investment in energy that no longer serves its original purpose. Created by the United States as a response to energy insecurity and instability, the original goal for this reserve was the creation of a one billion barrel reserve to offset supply insecurity. This original goal has slowly changed downward to the point where today the reserve could be depleted within a year in a national security event. This paper proposes a change in this policy with a significant investment in the energy sector to develop the domestic shale oil fields. Concurrently, the paper emphasizes how the energy sector has long represented a significant opportunity for the construction industry workforce. From oil fields to conventional power plants and nuclear energy generation, the construction industry has benefitted from the energy sector. Today, the opportunity exists to continue this tradition and provide the construction industry with the next generation of energy sector workforce.

Introduction

Up until 1947 the United States was an exporter of petroleum. However, following WWII, the US was in a major economic expansion and began importing oil in 1947/48 (History 2009). Imports would increase significantly until the rapid price increases in the 1970s, named OPEC I and OPEC II, where prices quadrupled and then tripled. This 12x increase in price would force industry to switch from oil to natural gas and coal, resulting in a significant decline in oil consumption in the US. This period also showed the US how vulnerable it had become to oil imports and due to the rivalry with the Soviet Union at the time, the US began studying the development of a Strategic Petroleum Reserve.

The Strategic Petroleum Reserve (SPR) was created following the 1973 energy crisis. The conditions and development of the SPR was written into the 1975 Energy Policy and Conservation Act (EPCA). The concept being to protect US national and economic security by developing a strategic petroleum reserve to replace imports which fail to arrive at American shores due to war, an embargo or other causes. The original plan was for the SPR to contain 1 billion barrels. However, future administrations reduced this goal to the low 700 million barrel range. Current capacity of the reserves are 727 million barrels and they are expected to remain usable until 2025. Construction of the sites began in July 1977 (IEA 2009).

From 1977 until 2000 the US would never achieve the goal of filling the reserve. During this period reserves would peak in 1994 at 592 million barrels. President George W Bush announced in 2001 that the SPR was an important element to the US National Security and ordered that the reserves be filled to capacity, which at that point in time was 700 million barrels. The Energy Policy Act of 2005 since directed the Secretary of Energy to fill the SPR to its original 1 billion barrel authorized capacity. This will however require a physical expansion of the reserve. By August 2005 the reserve had been filled with 700 million barrels (96% of capacity) of crude oil. Since then reserves have in essence reached the capacity of 727 million barrels. With the price of oil at $147/barrel in 2008, the value of the reserves at peak were worth $106.9 billion. Today at a price of approximately $70 to $80/barrel the reserves are worth between $50.9 and $58.1 billion.

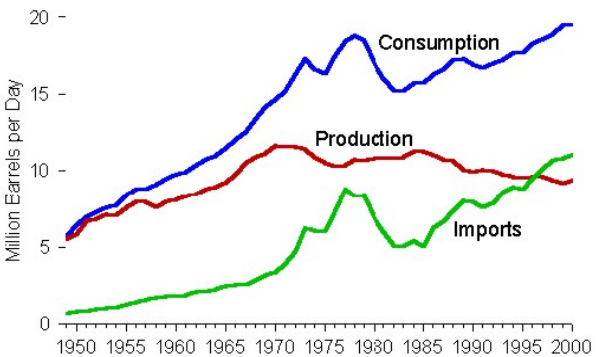


Figure 1: Consumption, Production and Imports of Petroleum (USA)
Source: http://www.eia.doe.gov/emeu/aer/eh/frame.html

The paper addresses the need to 1) increase the reserves in the SPR significantly to increase national and economic security, 2) have leverage to moderate global petroleum prices and 3) increase petroleum production capacity. The paper will address these issues in the context of creating a program to develop our shale oil resources. As illustrated, this increase in production can be accomplished.

Background

The US is not the only country to possess strategic petroleum reserves, other countries following the oil crises in the 1970s also established SPR equivalents. These include Japan (estimated reserves of 320 million barrels), Korea (76 million barrels), Germany (approximately 90 days of imports) as well as France and Italy (all 3 pool reserves), and newcomers India (started a small reserve in 2004 with an eventual goal of 45 days imports by 2016) and China (estimated reserves to be at 272 million by 2010) (IEA 2009).

These reserves are above and beyond the reserves held by oil companies, as oil companies hold reserves to manage their distribution and production systems, not for emergencies. These reserves are primarily held for emergencies, but as noted

above, require significant capital and perhaps more importantly are significantly limited in terms of production and duration.

While the US SPR may contain 727 million barrels and in the future could contain from 1 to 1.5 billion barrels, it is necessary to examine how many days of imports this would cover should all imports be temporarily stopped for any reason. This number peaked in 1985 at 115 days and has declined steadily since. With imports of over 13 million barrels per day in 2007/2008 the reserve would barely cover 50-55 days of imports. However, the situation is not so rosy, because the SPR has a physical production limitation of 4.4 million barrels per day. This would mean that only 4.4 million barrels of imports could be replaced by the SPR or approximately 34% of imports for a longer period of approximately 165 days. This means that in the event of a protracted global event which significantly reduced oil production in some region of the world, the SPR would be a blip in solving the problem. While its initial capacity is significant at 4.4 million barrels (larger than most countries production except for Saudi Arabia, Russia, US and possibly Iran), it is only sustainable for a period of 4-6 months when 1) production starts to decline due to reduced SPR reserves and 2) once the SPR runs out. And even if the reserve were doubled or tripled, in fact no matter how large it is increased, the US always remains vulnerable to stoppages as the SPR will always contain a limited amount of resources relative to the potential shortfall (Slack 2009).

Why is this and why have the number of days of imports covered by the SPR declined even though the SPR has increased? There is a simple explanation for this, it has occurred for two reasons: 1) US domestic oil production has declined leading to significant increases in imports and 2) US domestic consumption increased significantly especially in the transport sector, where alternatives to oil are almost non-existent (Figures 1 and 2).

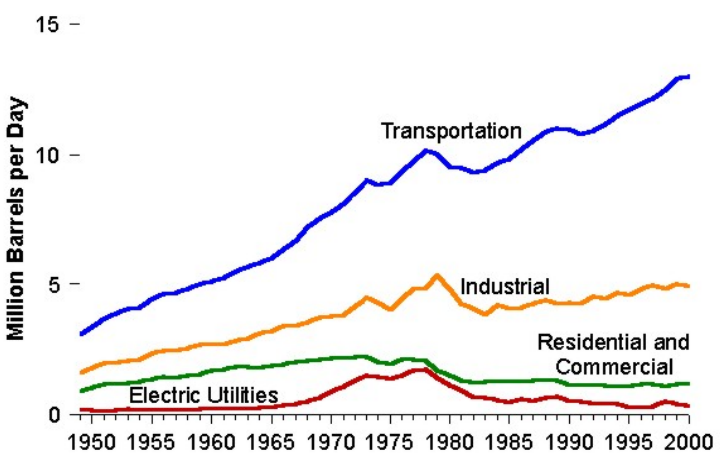


Figure 1: Consumption, Production and Imports of Petroleum (USA)
Source: http://www.eia.doe.gov/emeu/aer/eh/frame.html

Furthermore, even though the SPR has been in existence for almost 30 years, it has only been used on two occasions with minor draw downs. The first time was during the first Iraq Gulf War where the US and its allied used significant airpower and the threat of almost 500,000 troops to remove Iraq from Kuwait. In this case 30 million barrels were released from the reserve. And in the second case reserves were released because of the damage done to New Orleans and the Gulf in the wake of Hurricane Katrina, where approximately 22 million barrels were released. However, when oil prices reached $100, $120 and almost $150 the US and other countries were put in the hopeless position of not wanting to use their reserves to moderate prices because of the fear that in so doing they would increase their own vulnerability and therefore prices could skyrocket even higher.

This paper introduces a proposed solution to creating a Strategic Petroleum Reserve which can be relied on, thereby removing or reducing the dependence on imported oil, volatility in oil prices which are economically damaging and therefore eliminating the threat of a shortage or embargo. By analyzing the impact of peak oil combined with the politics of climate change and the reaction from oil exporting nations this paper introduces a strategy for an alternative energy source specifically by developing shale oil. The opportunity exists to not only develop this resource but to do so with a strategy which will provide funding for the development of shale oil as the new strategic petroleum reserve. The sections that follow lay out this strategy, concluding with a proposal that will produce sufficient revenues to fully fund the development of this emergency energy resource.

Peak Oil

Peak oil is the concept that global oil production will peak at some point in time in the relatively near future (Peak Oil 2009).

The concern about peak oil is elevated because of significant uncertainty with relationship to posted reserves of some countries, especially among OPEC, that their stated reserves are either potential reserves or significantly inflated and do not accurately reflect reserves that could actually be produced. However, there is another factor to consider with peak oil and that is one created by the limitation of resources to produce and explore for oil due to 1) other resource limitations (steel, drilling mud, personnel, concrete, etc) and 2) political limitations on exploration and production.

The estimates for this date range from today to sometime in the next 10-20 years, this includes the EIA, DOE, IEA, and CERA among others based on geological estimates of when one-half of oil resources will have been produced (Figure 3) (Chronicle 2009).

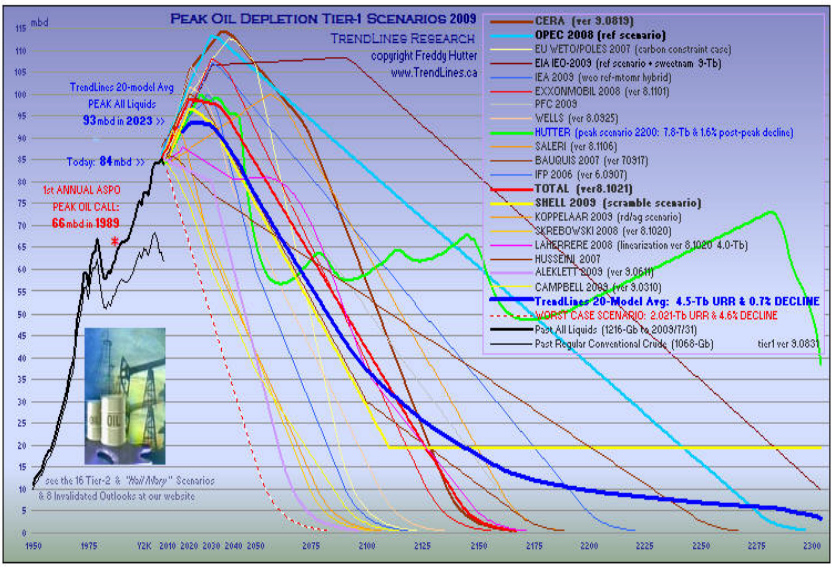


Figure 3: Peak Oil Predictions

Source: http://www.trendlines.ca/energy.htm

Peak oil is a concern for several reasons (Guardian 2009), but primarily because 1) it could cause significant price spikes which could severely weaken the global economy and 2) it could cause a rush for resources resulting in situations which could lead to war. Typically when oil fields peak, production proceeds to decline fairly rapidly, with decline rates of 3-10% per year being typical. Countries who have experienced peak have seen production declines of 1-4% per year due to their diversity of reserves. As can be seen in the graph below, oil (as well as other natural resources) tends to be demand inelastic. This means that price spikes can and do significantly differ from changes in demand and supply. A shortfall of 1-2% of global production can and has lead to increases of 30-300% in the price of oil. Should the world experience a peak in global oil production without planning for a transition phase with strategic petroleum reserves, it would be possible that we could see multi-year spikes in price that leads to a severe global recession if not a major depression.

A properly developed strategic petroleum reserve would allow for surge capacity for a sustained time period to ensure either that infrastructure could be built, to support national policy or to ensure that a transition to a new source of energy has time to occur.

Politics, Climate Change and OPEC

Ensuring energy resources are available and freely traded is also important to national and economic security. A number of countries (EU, US, Japan and Australia/NZ) have proposed reducing emissions of GHG's. If legislation is implemented as currently proposed it would be reasonable to conclude that it would include taxes and/or fees on energy imports and more significantly policy that could 1) potentially shift the major oil consuming countries to non-oil sources and 2) potentially result in taxes that a global body would levy on oil producing countries for their contributions to global emissions (Folmer 2009). It would be very reasonable for oil producing countries to want to oppose this legislation and in so doing it would be reasonable for these countries to potentially attempt to control the outcome of legislation by imposing production limits and / or curtailing production. Using oil as a political tool to extract favorable decisions has been done previously, 1) by the US against Japan and Germany in WWII and 2) by OPEC against the US.

The ability to control the oil spigot and in this case legislation or national interests be it in emissions policies or in other policy proposals is an issue of significant concern. For the agencies that foresee peak oil production also clearly show that OPEC's share of oil production and share of oil available to be traded increase significantly in the years ahead. From today's share of around 25-30% to over 50% in the next 10 or so years and therefore a significant increase in the ability to potentially impact future policy. This could lead some oil exporting nations to decide to curtail production to significantly increase the price of oil, thereby banking the profits and in essence demand that the countries imposing carbon limits drop them as they could significantly limit oil exporting countries future growth rates.

Finally, regional conflicts could result, whereby an SPR would need to provide immediate and sustained production, not only for 4-6 months, but potentially for several years. Should a conflict in the Middle East destroy one or two large terminals, it could take a few years before exports resume. In the meantime without a viable reserve in place, oil prices could again triple or quadruple, just like they did during the 1979 Iran Revolution. This would lead to significant economic disruptions and severe recessions, similar to what we are experiencing today.

Shale Oil

While shale oil is present in many countries, the largest deposits accounting for over 96% of total resources are based in the US, Russia and Brazil (Chakrabarty 2009). The US alone accounts for over 70% of the total resource base. However, even though other countries have a much smaller resource base, the reserves are still fairly sizeable, which is why shale oil is actually produced and used in Estonia, Russia, Scotland, Brazil, China, Australia and Germany. With mined shale, the Estonian experience suggests that once an investment is made and production begins shale oil used in power generation is competitive with coal import prices above $40/ton and with natural gas import prices of $3.50/MMBTU. Shale oil is also competitive with crude oil above $25/bbl and with heavy oil imports at $95/ton. However, the problem with mining is that significant tailings are produced and mining in general is not environmentally friendly as it brings to the surface all of the

by-products that in general we would prefer would be contained underground. In fact bringing the shale oil to the surface through mining results in a process which produces significantly more GHG emissions that the production of crude oil.

As mentioned above the US sits on massive shale oil reserves, with reserve estimates of approximately 800 billion barrels according to RAND and others, including Shell, that are economically recoverable using the latest in-situ technologies (Petherick 2009). This is approximately 3x the size of Saudi Arabia's reserves and enough oil to meet any emergency as well as current demand for transport until America has an opportunity to convert its transport industry into non-carbon energy.

But why would we want to develop these resources as a government project? There are several reasons, as explained above, the primary ones are: 1) If we developed our shale oil resources we could use them as a new strategic petroleum reserve if they are developed specifically for this purpose, the resource base is sufficient enough to provide sustained high-capacity production in times of need, 2) shale oil produced in-situ results in a very light hydrocarbon, akin to diesel or gasoline without the processing emissions, especially if low-emission power is used to heat the underground area, 3) this would allow us to expand the technology knowhow for both shale oil production as well as alternative energy resources and 4) it would provide excellent stimulus for the economy and for the construction industry in terms of jobs and projects while enhancing national and economic security. It would be possible with shale oil to achieve a significant new industry, many new jobs, a strategic petroleum reserve with real surge capacity, and a fuel with relatively low emissions, while ensuring that we can transition to the new energy future of low carbon energy.

Strategy and Policy

How would this strategy be paid for and in fact what is the strategy? We propose that this be a Federal Government supported and sponsored project, just like the current DOE Strategic Petroleum Reserve. In fact we would propose that the DOE manage the reserve while using firms such as Shell, Exxon and Chevron among others to produce the resources. The SPR exists to safeguard the nation against supply disruption, however, because of its current limited capacity it is not possible to use it as a policy tool. It has only been used twice, once during a war and the other time during a natural catastrophe. In both cases only about 5% of the reserves were released. And once released they are gone and need to be replenished. Should a significant event arise the current SPR would only provide limited relief for a limited time period.

The project as specified by the oil companies requires significant electrical power to be injected underground to form an ice wall to prevent the fuel from migrating and a significant number of heating rods drilled into the center to heat over a period of several years the shale so that it flows like oil/gasoline. This process takes approximately 3 years from beginning to end for the heating process. However, building a large scale facility, one that can produce 2-4-8 million barrels per day takes a significant amount of investment and risk. This level of investment and risk would strain even the largest oil companies in the world, especially the risk of volatile energy prices combined with the price of power to generate the oil in-situ. Yet the

US Government sits on 750 million barrels of oil in the current SPR which is worth between $50 to $100 billion depending on oil prices ($70 to $147 per barrel).

Preliminary estimates put costs at $70-120 billion to build all of the infrastructure needed for production capacity of 2-4 million barrels. This would be ramped up over a period of 3-6 years in an accelerated mode, which would be good for the economy and while there is significant slack in the economy this would also help to minimize costs. Over time, between years 6-15 this could be expanded up to a capacity of 8-10 million barrels per day capacity. At 8 million barrels per day 2/3 of imports could be covered for an indefinite period, which would add significant credibility to the concept of a strategic petroleum reserve. Furthermore, if a pro-active carbon policy is enacted with a CAFÉ standard for transportation that leads to a reduction in demand for petroleum and petroleum byproducts this could result in transport demand declining by as much as 15-30% over the next 15 years, making the resulting capacity of the new SPR at 8 million barrel per day at that much more valuable

A reasonable estimate for the development of the 4 million barrel per day capacity (including all power plants, pipelines, facilities as well as infrastructure for the cities that would need to be developed) is approximately $120 billion or $30,000 per barrel using the Shell method. First, according to RAND, this could potentially result in 300,000 to 400,000 direct and indirect jobs, which would significantly help the current unemployment of approximately 10% (Bartis 2009). Second, an investment of $120 billion would result in a significant amount of new power plants being built: wind, solar, geothermal and nuclear. These would provide significant power to the operation but as the operation does not need this power 24/7 it would mean that the power could be sold to the grid, using grid interconnections which could be built as part of the project. This would be low-carbon energy that would help to reduce total US emissions. This would also significantly advance the technology of these sources thereby reducing the cost of these new plants due to order size.

So how does the investment of $120 billion play out? Is this an entirely new investment or can most of it be covered with the existing SPR reserve? By committing to developing this resource the US would have in place a true long-time surge capacity which could be brought online at any time. It would also have developed the industrial capacity to build solar, wind, geothermal and nuclear power plants at significantly lower cost and on an accelerated time table allowing for a one-time approval based on pre-approved designs.

But more importantly the US government will have gained the opportunity to manage the price of oil in a more effective manner. And in so doing could set policy as to when the current SPR is released into the market place. For example, US policy could decide that a price up to $100 / barrel is acceptable, but beyond this the US government will pump oil into the market. Policy guidelines could be along the following lines:

Oil Price/Barrel	Release Strategy
Under $50	purchase oil for the SPR
$50-$100	no purchases or sales
$100	sell 100,000 barrels/day
$125	sell 250,000 barrels/day
$150	sell 500,000 barrels/day
$175	sell 1,000,000 barrels/day
$200	sell 2,000,000 barrels/day
$225	sell 4,000,000 barrels/day

Using this strategy the US government would recoup a minimum of $75 billion (towards the $120 billion investment) and more likely a total of about $100-$150 billion. Plus as capacity comes online through the development of the shale oil resources this means that with the current SPR surge capacity of 4.4 million barrels combined with a surge capacity of 4 million barrels in the new SPR, the total surge capacity within the time frame of development could actually reach 8.4 million barrels for a period of 50 days and 4 million barrels indefinitely.

With the shale resources online, the US government could also pursue a policy of allowing up to 25% of the shale oil capacity to be sold into the marketplace. According to RAND, production of 3 to 5 million barrels per day could result in savings of $15 to $20 billion per year for the American consumer. Yet, last year when prices reached almost $150 per barrel, it seemed that even much less production could have significantly reduced prices and saved consumers significant money.

The 25% sales would more than recoup operating costs and in fact would generate a royalty to the US government which could also be used to repay the investment cost of setting up the infrastructure and facilities. As previously mentioned this would be a boon to the construction, energy and infrastructure industries in the US. All of the industries have lost significant numbers of jobs and these would help power a US recovery though this investment in national and economic security. As geothermal, solar, wind, and nuclear power plants are built, as well as roads, schools and homes, and the infrastructure for the facilities as well as the pipelines.

Conclusion

In summary, the United States requires an alternative to its current dependence on foreign oil. The Strategic Petroleum Reserve was an attempt to provide this hedge, but has since been found to not meet its intended goal. Developing alternative energy sources is a requirement to reduce the traditional independence on foreign petroleum. However, traditional domestic sources cannot provide the amount of petroleum required. In contrast, the opportunity exists to develop the vast shale oil reserves that exist within the United States. Using the combination of the petroleum available from this resource together with the income from selling off the SPR, the United States will have the resources required to invest in additional alternative energy sources.

As an additional benefit, this development will lead to an extensive expansion of the engineering and construction jobs available in the construction industry. In a time where concerns are continuing over future employment potential and economic trends, this expansion will be a benefit not only for the individual construction sector, but to the economy as a whole.

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Carbon footprints analysis for Tunnel Construction Processes in the Preplanning Phase using Collaborative Simulation

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ABSTRACT

Under the fast-developing carbon trading market, the construction industry needs to mitigate carbon emissions from construction processes. Among various construction processes, tunnel construction produces a significant amount of carbon emissions, since it utilizes various types of high energy-consuming equipment. In order to identify and mitigate such carbon emissions of a tunneling project, it is required to reliably estimate carbon footprints of a tunneling project in the pre-planning phase. This paper presents the methodology for estimating the carbon footprints generated during tunnel construction processes using the collaborative tunneling simulation. A case study using this methodology shows that carbon footprints from a utility tunnel construction are significant compared with those from a building construction. In addition, the assessment of carbon footprints of the case study identifies the opportunities to mitigate such impact by supporting decision-making on equipment and operation plans in the planning phase and providing a control target level of carbon footprints in the execution phase.

INTRODUCTION

With growing concerns on global warming, a fast-developing market in greenhouse gas emission allowances raises an urgent need to quantify and reduce the carbon footprints of companies. Canada has already initiated the development of a carbon trading market where any project will be eligible for carbon credits (Environment Canada 2009). Even in the United States, the discussion on carbon regulation is rapidly moving to when and how such policy will be implemented. The construction sector is also facing this pressure, since the construction processes generate the third highest greenhouse gas (GHG) emissions among U.S. industrial sectors (EPA 2009). Hence, construction organizations need to manage and mitigate their carbon-related risks in the carbon-constrained future. In order to identify and mitigate such risks, it is critical to reliably estimate carbon footprints from a construction project in the pre-planning stage.

There exist several efforts to assess air emissions, including carbon emissions, from construction processes in the pre-planning phase. Guggemos and Horvarth (2006) developed a model to estimate the environmental impact of construction processes for a structural frame of buildings based on a life-cycle assessment (LCA) approach, a framework that holistically evaluates the environmental impacts of a product or process by analyzing the whole life cycle of the given product or process. The road construction emission model (SMAQMD 2009) provides the estimate of emissions per day of each air pollutants for four phases of road construction based on off-road engine emission inventory model. Similarly, the URBEMIS (Rimpo and Associates Inc. 2009) emission model, developed to comply with the California Environmental Quality Act, estimates air pollution emissions from land development projects such as building construction. Ariaratnam and Suhabuddin (2009) quantified construction emissions from two construction methods for installing a wastewater line, based on the equipment and activity data collected from actual construction operations. However, the quantification of carbon footprints from a tunnel construction project has not been attempted, even though various pieces of equipment employed in tunnel construction processes, such as tunnel boring machine (TBM), consume significant amount of energy. The carbon footprints from a tunnel construction project must be known in the preplanning phase, in order to enable builders and designers to minimize such impact of carbon emissions. Therefore, this paper presents the methodology for reliably estimating the energy consumption and carbon footprints of tunnel construction based on a collaborative tunneling simulation system. In addition, this methodology is demonstrated through a case study of *North Edmonton Sanitary Trunk tunnel* project which is being executed in Edmonton, Alberta, Canada.

This research is relevant to various stakeholders in the construction industry. Contractors and owners of a tunnel project can use the presented methodology to evaluate the carbon footprints of various means and methods for tunnel construction and to optimize them for environmental performance. Researchers can use the presented methodology to identify carbon footprints of infrastructure construction in an overall life-cycle assessment of infrastructure. Also, they can compare the environmental performance of infrastructure construction with that of building construction, which most of previous efforts on this issue has centered.

METHODS

There are many protocols to help organizations analyze their carbon footprints (CCAR 2007; WBCSD/WRI 2007). These protocols vary in details of their scope, but generally define carbon footprint inventories with several "tiers" (Matthews et al. 2008). The "tier 1" consists of the direct emissions from the organization, and "tier 2" includes the carbon emissions from purchased energy by the organization. An optional final tier expands the boundary to include other effects which can be generated along the entire supply chain of the organization.

The scope of carbon footprint analysis in this paper is bounded by "Tier 1" and "Tier 2" sources in the construction activities of a tunnel project. It does not include the effects from manufacturing materials, use and maintenance of completed infrastructure. Under a given scope of the analysis, the major sources of carbon footprints from tunnel construction activities are on-site operation of construction equipment, transportation for excessive soil and materials, and on-site electricity usage for site office trailers and underground lightings. This analysis focuses on construction equipment operation and transportation, since The estimation of on-site electricity usage for site office trailers and underground lightings is difficult due to lack of available data in this stage of the research, and it generally accounts a small portion of total energy consumption of construction projects (Guggemos and Horvath 2006; Bilec et al. 2006). With carbon emissions, this analysis also includes NO_x, SO_x, CO and particular matter (PM) emissions, which diesel exhaust emissions from construction equipment mainly contribute to.

Construction Equipment Use

Carbon emissions and other air emissions from the use of equipment are determined by a product of emission rate and predicted operation time of each piece of equipment. The emission rate of diesel equipment can be derived from Environmental Protection Agency's *NONROAD* model (EPA 2004), which provides off-road engine emission inventory. The emission rate of electricity equipment is a function of energy consumption rate of equipment and emission factors of the local plant which provides electricity to the project. Currently, most of equipment for underground work is using electricity instead of fuel due to air quality issues of underground job site.

The operation time of each piece of equipment is critical data in this analysis. The reliable prediction of equipment operation, however, is not an easy task in the preplanning phase. Previous efforts on construction emission estimation in the pre-planning phase determined the operation time of equipment based on a heuristic algorithm developed from historical project data and the average production rate of various types of equipment (SMAQMD 2009; Rimpo and Associates Inc. 2009) or did not determine those in the presented model (Guggemos and Horvath 2006). In these models, it is hardly possible to evaluate carbon footprints of various alternatives on construction means and methods, since the input variables of these models are limited to several basic project characteristics, such as project area and project duration.

Authors of this paper attempted to utilize discrete-event simulation (DES) that could incorporate various characteristics of construction operation plans for predicting operation time of equipment in construction emission estimates (Ahn et al.

2009). The application of DES for estimating emissions can enhance the reliability of these estimates by providing statistically reliable estimates on operating hours and the utilization rate of each equipment, which can vary by how the operation will be executed under given characteristics of project and construction equipment fleet. This analysis also utilizes DES to predict the operating time and utilization rate of equipment in tunnel construction processes.

Transportation

Transportation processes in a tunneling project includes the delivery of concrete liners and excavated soils to and from the site. Since current DES models for tunneling construction do not cover transportation processes, carbon emissions and other air emissions from transportation are determined by total combined ton-kilometers for transportation and average emission factors of trucks. The critical information for this analysis includes the distance from dumped area/fabrication shop to the site, and the total weight of excavated soil and concrete liners.

CASE STUDY

The North Edmonton Sanitary Trunk project located in Edmonton, AB, Canada is analyzed as a case study representing a typical utility tunneling process using TBM. The tunnel length of the case project is 3,707m, and its storage capacity is around 15,600 m^3. The construction started in Dec 2006, and it is expected to be completed by Dec 2010. The case study does not include the installation processes of vertical shafts and use of small hand tools.

Construction Equipment Use

DES is utilized to predict equipment use and its carbon/other emissions in tunneling construction processes. The simulation for tunnel projects has been attempted by many researchers (Ruwanpura et al. 2001; AbouRizk et al.1997; Touran and Asai 1987), since the tunneling processes are repetitive so that they are suitable for simulation. For this case study, a simulation model is developed to capture the operations of the case project under Construction Synthetic Environment (COSYE), a .NET implementation of the High Level Architecture (HLA) standard (AbouRizk 2006). The dependency of activities and equipment involved in a given operation is presented in Figure 1. Different individual simulation components, referred as *federates* under the HLA standard, are developed to capture each individual activity.

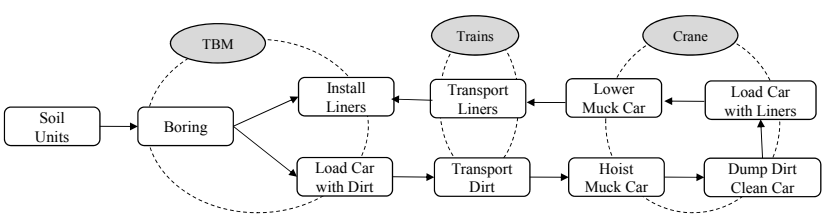


Figure 1. Dependency of activities and equipment involved in a tunneling operation

The details of equipment used in the case project are shown in Table 1. The energy consumption rate of the Tunnel Boring Machine (TBM) is not well-defined by the manufacturer. For the energy consumption rate of the TBM, we used measurements from the same TBM model at a different project with similar soil conditions. The energy consumption of the TBM was recorded by attaching a power meter to its 13,800 volt power cable and the rate was characterized depending on the penetration rate per hour of the TBM from the regression analysis of the power reading data (Kostelyk 2008). Within the tunnel simulation model, the penetrate rate of the TBM is determined by the distribution of historical data gathered from other projects where the same TBM was used. The energy consumption rate of the trains is defined by the manufacturer. It is a function of the distance and grade of the haul way, and the weight of load, and those factors are determined by a queue scheduling model in the tunnel simulation. The crane uses Caterpillar c6.6 diesel engine which is designed to meet *Tier 3* standards of EPA (EPA 2004). The operation time and utilization rate of the trains and crane is determined by the amount of soil excavated by TBM and hauled by trains in the simulation model.

Table 1. Equipment used for the NEST tunnel construction

Equipment	Specification	Fuel Type	Max Power (HP)	Number
TBM	Lovat M100	Elec.	449	1
Train & Muck Cars	Balco Inc, Model 601 6 Ton	Elec.	27	2
Crane	75 Ton Linkbelt 8075 RTC	Diesel	235	1

The energy consumption rate and emission rate of equipment are incorporated in the simulation model as an individual *federate*, which can capture the operation of equipment in other *federates*. The HLA provides the reusability and interoperability of this *federate*; the developed *federate* can be incorporated into other tunnel simulation model and analyze carbon footprints of other tunnel simulation model with changing input parameters of equipment specification.

Transportation

The total ton-kilometers for transportation were summarized in Table 2. Each segment (1 meter of length) of a tunnel consists of four concrete liners, and the total weight of concrete liners was determined by the total quantity of liners, the volume of each liner, and the density of precast concrete. The total weight of excavated soil was determined by the storage capacity of tunnel and the average density of soil. The distance from dumped area/fabrication shop to the site was obtained from the estimates of the contractor. The emission factors of truck transportation are derived from Facanha and Horvath (2007).

Table 2. Transportation

Transportation	Combined weight (t)	Distance (km)
Concrete liners	17,810	31
Excavated soil	39,620	7

Result

The carbon footprint estimates of a case study was obtained from a single run of the developed simulation model, which incorporates the tunnel operation processes and the energy consumption rate and carbon intensity data on equipment. Table 2 summarizes the result of a case study. The carbon footprints from the case project are estimated to be 475 Mg of CO_2 emissions; one day operation of the case study with 4.5 meter of average penetration rate generates around 580 kg of CO_2 emissions. The TBM accounts for at least 35% of total carbon footprints generated from equipment operation and transportation, while the transportation of concrete liners is the second contributor to carbon footprints. The major contributions to NO_x and PM emissions are diesel equipment including the crane and transportation. The direct carbon emissions from operations, referred as "tier 1" carbon footprints, account for around 56% of total carbon footprints of the case study, and the rest of carbon footprints are caused by the purchase of electricity.

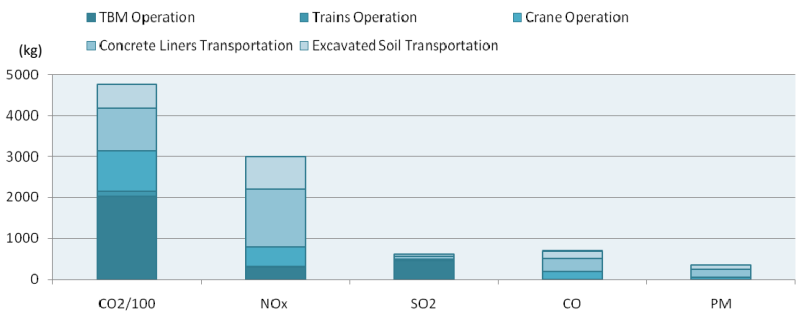


Figure 2. Carbon emissions and other air pollutant emissions caused by the NEST tunnel construction

DISCUSSION

The result of the case study shows the significance of carbon emissions from tunnel construction compared to that of building construction. The carbon footprints from a tunnel construction are roughly two times bigger than those from construction of structural frame of a 8,760 m^2 office building (Guggemos and Horvarth 2006) and four times bigger than those from construction of a typical residential single house (Sharrard et al. 2008); even these previous investigations include all the effects along the supply chains, such as manufacturing of temporary materials and other impacts. Also, the estimation of carbon footprints in the pre-planning phase identifies the opportunity to mitigate those. For example, The crane has much more significant contributions to carbon footprints compared to trains, even though the operation hours and operating cost of trains are higher than the crane; this identifies the priority of equipment to be replaced to more energy-efficient one when the stakeholders attempts to reduce the carbon footprints through the replacement of equipment.

The case study in this paper illustrates another benefit from utilizing a DES model for estimating carbon footprints, in addition to two benefits identified in the previous study (Ahn et al. 2009); (1) statistical results on estimating operating hours

of equipment and (2) comparison of emissions between various operation scenarios. The use of a DES model provides time-dependent patterns of energy consumption and emissions for each piece of equipment, as shown in Figure 2. For example, the pattern of energy consumption of the trains shows concave up increasing with time while that of the TBM shows linear increase. This identification on energy consumption patterns of equipment can help operation planners to take into consideration the carbon-related effects of their decision on the number and location of vertical shafts. Also, the estimation of carbon footprints at each milestone of the project will allow construction managers to set the control targets.

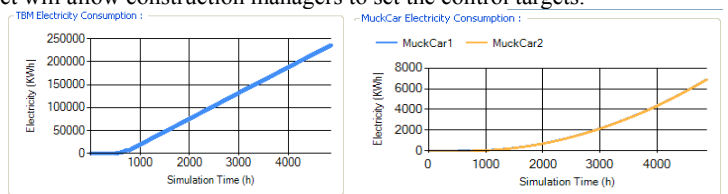


Figure 3. Time-dependent patterns of energy consumption of TBM and trains

CONCLUSION

This paper presented the methodology to quantify carbon footprints and other air emissions from tunneling processes based on discrete-event simulation. Using the presented methodology, the carbon footprints from equipment operation of the NEST tunnel project were identified with the time-dependent patterns of energy consumption and emissions of each piece of equipment, and its implications in terms of managing and mitigating carbon-related risks were discussed. In the preplanning phase, this methodology provides an opportunity to analyze carbon footprints of various construction means and methods which can be employed in a project and to minimize carbon footprints by comparisons between alternatives.

This research is still in the preliminary stage and has many remaining issues that will be addressed in further research. The presented case study needs to be more elaborated to include the small energy usage such as the liner erecting operation of TBM, extending the rail of trains, which was not taken into consideration in the presented result. The transportation processes could be analyzed more accurately if the simulation model incorporates those. It is also important to validate the methodology of the research by comparing the actual data on energy consumption and emissions with the presented estimation.

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Canadian Industry Practitioners Perception on LEED Credits

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Abstract: While the need for sustainable practices in building projects is globally recognized, some construction stakeholders still demonstrate resistance in adopting sustainable practices. The general perception is that attempting to achieve sustainability will increase the capital cost of construction and can delay the schedule. In recent years, societal pressure and government incentives as well as practitioners knowledge and acknowledgement, have led many construction projects to pursue sustainability credits. In 2002, Canada Green Building Council (CaGBC) adopted the Leadership in Energy and Environmental Design (LEED) standard as a tool to evaluate the sustainability of construction projects. The main objective of this research is to generate a better understanding of LEED professionals' perception of the impact of achieving LEED credits on projects parameters such as cost, schedule and future value. A survey was conducted to clarify their position towards the impact of each of the 69 points in the early version of LEED-New Construction on project factors. The survey targets factors in its three phases – prior to construction, during construction and post construction. The results can assist in improving the evaluating systems and developing sustainability design tools in the future.

1. INTRODUCTION

The construction industry is considered one of the contributors in polluting the environment. The residential and commercial construction sectors alone consume around 38% of the total Canadian secondary energy use, generate 30% of the total Canadian greenhouse gas emissions, and are responsible for 40% (equivalent to three billion tons annually) of raw material use globally (Schedler and Udall, 2005). These statistics indicate the necessity for sustainable designs and construction methods (Green Development, 2006). To encourage and accelerate the adoption of sustainable practices in building and construction, several guidelines and rating systems have been developed in recent years. The goal of these systems is to create universally understood and accepted performance criteria to evaluate sustainability of building projects.

Leadership in Energy and Environmental Design (LEED) is one of the most widely-adopted sustainability rating systems in the North American construction industry [Gonchar, 2005]. The LEED rating system was first introduced by the U.S.

Green Building Council's (USGBC) in 2000 and adopted by the Canadian Green Building Council (CaGBC) for Canadian climates, practices and regulations in 2002. Variations of LEED credit system has been developed for different types of construction projects including new construction, commercial interiors, core and shell, existing buildings, homes, and neighborhood developments. The LEED rating system for new construction (LEED-NC) is the most commonly used LEED certification. LEED-NC v2.2 considered 69 possible points for sustainability by evaluating performance in five (5) key areas of human and environmental health: 1. sustainable site development (14 Possible Points); 2. water efficiency (5 Possible Points); 3. energy efficiency (17 Possible Points), 4. materials selection (13 Possible Points); and 5. indoor environmental quality (15 Possible Points). An additional category, Innovation & Design Process (5 Possible Points), allocates points for using sustainable building expertise as well as design measures not covered under the aforementioned five categories (LEED-NC 2004). The certification review process is initiated by submitting the required documentation to the relevant regional Green Building Council. After reviewing the submission, the council will select 6 to 8 credits for audit, and requests submission of a report with specific details on the selected credits. The council will then make the final decision in awarding the level of LEED certification. Depending on the number of points achieved, four rating levels of LEED certification can be awarded to a project: certified (26-32 points), silver (33-38 points), gold (39-51 points) and platinum (52-69 points).

LEED is rapidly gaining acceptance in the Canadian construction industry over the last few years. In 2004, only five (5) projects were registered for LEED, and one (1) project received certification. This number rose to 466 registrations in 2007 where 31 projects received certification (CaGBC 2008). While these statistics indicate the growth in LEED acceptance by the industry, they also demonstrate low rate of success in achieving LEED certifications. Success in achieving sustainability depends on efficient team work among stakeholders performing integrated efforts in all phases of a project, from initiation and design all the way to the inception and construction. The attitude of the stakeholders towards the value of such efforts plays a major role in the success of sustainable construction. Myer (2005) reports a general concern that sustainable construction imposes extra costs and schedule delays on the construction project, and hence is not embraced by the owners, designers or contractors. It is also believed that sustainable construction requires higher management as it tends to be more complex than typical construction (Kibert, 2005). While the attitude of practitioners in complex projects such as sustainable building design and construction has a direct impact on the success of that project, there is no formal study to collect statistical data on such perceptions. This paper, conducts a study on the industry practitioners' perception on LEED credit system as one of the widely accepted sustainability measures in the building industry in the North America. The main objective of this paper is to generate a better understanding of professionals' perception on the impact of the sustainable design on a construction project. A detailed survey is conducted of LEED accredited professionals to determine their perceptions on the impact of each of LEED credits on various project factors in three distinct phases of pre-construction, construction and post construction. This study will identify the areas of concern for the industry

professionals. The identified areas can be of interest in future development of sustainability design tools and rating systems.

2. LITERATURE REVIEW

Despite its wide acceptance in North America, LEED certification process is receiving criticism on imposing significant challenges and setbacks on construction projects. Some research has questioned its actual environmental validity and impact and suggested that it lacks scientific rigor (Gonchar, 2005). LEED has also been criticized for over-simplifying the process evaluating sustainability (Schaffner, 2003). A large percentage of the credits that are earned by projects are those on which the professionals have experience in easily attaining, resulting in a building that only meets the minimum requirements to attain certification (Proctor, 2007). Studies have suggested on 80 to 99 percent of LEED accredited projects, there are approximately ten points that are commonly earned: LEED AP, site selection, bicycle storage/changing rooms, water efficient landscaping, recycled content and low-emitting materials (Miranda, 2005).

Another criticism on LEED credit system is that it is mainly prescriptive based rather than performance based (Proctor 2007, Post 2007). As a result, the points do not have a middle ground or a scale of achievement; they are either earned or not earned. The evaluations for the most part is based on hour system, and not based on a method of quantifiable measurement (Proctor, 2007). Any deviation from the standards that are set out by the credit requires that a consultant obtain an interpretation ruling from the Canadian Green Building Council (Gonchar, 2005). It is suggested that a more integrated metric could be formulated for initial construction and maintenance and operations (Post, 2007).

Schedler and Udall (2005) have identified the five (5) common problems that are associated with the process of LEED certification as: high costs; focus on receiving LEED credits without regard to the actual impact on environment; complexity of energy modelling; time consuming process of documentation; misleading and overblown claims of benefits of green buildings The same study indicated that the costs associated with achieving LEED can become as high as 17% to receive platinum certification for a small building. For a 10,000 square-foot building, the added cost reaches around $50,000 for LEED certification (Schedler and Udall, 2005). Kats (2003) discussed that the cost premiums for LEED certified buildings cost approximately 2% more, ranging from an average of less than 1% for a certified building to 7% for a LEED platinum rating. In another study, a cost comparison of six buildings in Los Altos, California, the LEED buildings had increased costs of approximately 1%, 13%, 15% and 21% for the certified, silver, gold and platinum buildings, respectively (Packard Foundation, 2002). Other studies suggest that any extra costs incurred by LEED certification pay for themselves as any other green building (Cost of Green 2007). The latter study also maintains that many projects in the construction industry are achieving LEED certification within their defined budgets and are within the same cost range as non-LEED projects. In other words, there are green building projects with low costs and high costs; and, there are non-green building projects with low costs and high costs.

While the cost has been the focus of attention for many studies, information on the impact of sustainable design on the schedule of projects is not documented in the

literature. Team challenge is another force that impacts the development of a typical construction project. Within the sustainable sector, team challenges tend to have higher impact on the delivering process of a building compared to non-sustainable projects (Foran et al. 2005). Implementation of an integrated design approach that applies to the sustainable sector for team cooperation and communication is needed (Prichard and Twinn 2001). Integrated design is a process that focuses on consultant coordination and resources allocation to facilitate an easier delivery of complicated projects with high-performance targets (Rogers and Ryan, 2001). LEED also utilizes the triple bottom line components: environmental, social, and economic, as a set of targets. As a result, LEED projects are considered complex systems that require higher planning and monitoring. While the research results can be contradicting, a clear understanding of the industry practitioners' perception of the impact of LEED rating system on a project can be beneficial to identify the areas that need to be addressed in future development of LEED and other evaluating systems.

3. THE SURVEY

In order to derive an understanding of the perceptions of Canadian construction industry professionals of the LEED-NC credit system, a detailed survey was created and sent to architects, construction project managements and consultants who have obtained LEED-AP accreditation in Ontario and British Columbia. The survey recipients were asked to rate each credit based on different aspects. Different aspects that can impact a building project within three phases of pre-construction, construction, and post-construction were investigated. These aspects were selected based on extensive preliminary interviews with professionals. Figure 1 depicts the structure of the survey question areas.

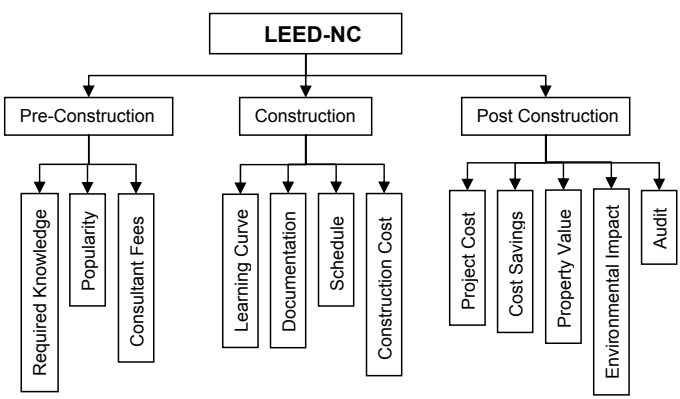


Figure 1. Survey Structure: Factors impacted by LEED in three phases

3.1 Factors in the Pre-Construction Phase

This section of the survey examines activities that occur prior to construction, such as planning, schematic design, design development and work drawing to determine the factors of the project that could be impacted in the process of achieving a LEED certification. The factors that were surveyed for this phase were the required knowledge, popularity and consultants fees.

Required Knowledge This factor describes how much specific knowledge on LEED is required to achieve a particular credit, and it was selected for its significance in early planning and design stages. The survey asked what level of prior knowledge is needed from the practitioner when working on each specific credit. The rating options available for this factor included:

0. No knowledge of credit
1. Worked on and did not achieved credit
2. Accomplished credit once
3. Accomplished credit twice
4. Accomplished credit more than two times
5. Specialist

Popularity This factor indicates the frequency of selection of this credit by the participant towards achieving LEED certification. The survey questioned how many times the practitioners had selected each specific credit in their past projects. The rating options available for this factor included:

0. Not selected previously
1. Selected credit once
2. Selected credit twice
3. Selected credit three times
4. Selected credit five times
5. Selected credit more than five times

Consultants Fees indicates the design and professional fees in the stages prior to construction. Perception of increased costs due to LEED certification is a concern for many projects, it is important to determine industry professionals' perceptions of consultant's fees in the early stages of a project. The survey asked how much the fees for each specific point would increase when aiming for LEED certification. The rating options available for this factor included:

0. No increase in fees
1. Fees increase less than 1%
2. Fee increase of 1% to 2.5%
3. Fee increase of 2.5% to 5%
4. Fee increase of 5% to 10%
5. Fee increase of more than 10%

3.2 Factors in the Construction Phase

This phase includes all activities that involve the actual construction of a building. Based on extensive preliminary interviews with professionals, the construction phase factors that could be impacted in the process of receiving LEED certification are: learning curve, documentation, schedules and construction costs.

Learning curve can be defined as the time required to learn how to accomplish a credit. The practitioners were asked what type of learning curve they experienced when working on each credit. The rating options available for this factor included:

0. No learning curve
1. Minimal learning curve
2. Moderate learning curve
3. Average learning curve
4. Excessive learning curve
5. Highest learning curve

Documentation refers to the required documentation and provision of proof of the work done to accomplish credit. Documentation was selected due to its significant role in registering and achieving LEED certification. Failure to properly document certain criteria and requirements for a credit could result in inability to receive the points associated with these credits. For each of the credits, the practitioners were asked based on their past experience what level of documentation was required to achieve the points allocated to that credit. The rating options available for this factor included:

0. Declaration form only
1. Declaration & explanation
2. Declaration, explanation & drawings
3. Declaration, explanation, drawings & specification
4. Declaration, explanation, drawings, specification & report
5. Declaration, explanation, drawings, specification, report & photographs

Schedule refers to the impact of the credit on the construction schedule. There is an assumption that attempts to achieve some credits may affect the project duration, leading to schedule delays. For each credit point, the LEED practitioners were asked what delay in the construction schedule they expect as a result of working on that credit. The rating options available for this factor included:

0. Minor expedition on the schedule
1. Neutral
2. Delay of up to 1 day
3. Delay of up to 1 week
4. Delay of up to 1 month
5. Delay of more than a month

Construction cost indicates the impact of cost of each credit as a percentage on the construction and capital costs of the project. As the assumption of the increase in costs due to LEED certification is a concern for many projects, it is important to determine industry professionals' perception on the cost impacts in the construction phases of a project. The rating options available for this factor included:

0. No increase in construction and capital costs
1. Increase of less than 1%
2. Increase of 1% to 2.5%
3. Increase of 2.5% to 5%
4. Increase of 5% to 10%
5. Increase of more than 10%

3.3 Factors in the Post-Construction Phase

This phase includes the activities that follow the construction phase of a project. Based on the interviews with industry practitioners, cost savings, property value, environmental impact, and audits are significant factors that are assumed a LEED certification process can have an impact on.

Cost savings refer to cost savings that can occur during the life-cycle of the buildings (e.g. maintenance, repair, operation, etc.) due to the selection of achieving a specific credit for a project. For each of the credits the practitioners were asked what cost savings can occur as a result of achieving that credit. The rating options available for this factor included:

0. No savings
1. Savings of less than 1%
2. Savings of 1% to 2.5%
3. Savings of 2.5% to 5%
4. Savings of 5% to 10%
5. Savings of more than 10%

Property value refers to the effect of achieving each credit on the overall value of the property. The survey asked what impact the achievement of each credit will have on the value of the building. The rating options available for this factor included:

0. No impact on property value
1. Property value increase of 0% to 1%
2. Property value increase of 1% to 2.5%
3. Property value increase of 2.5% to 5%
4. Property value increase of 5% to 10%
5. Property value increase of 10% and more

Environmental impact questions what the professionals perceive as the actual effect of each credit on the environment. Given that the main objective of obtaining a LEED rating is to reduce negative impacts on the environment, the survey strive to ascertain practitioners' perception on how each credit reduces the negative effect of the construction project. The rating options available for this factor included:

0. No impact on the environment
1. Minimal positive impact
2. Moderate positive impact
3. Average positive impact
4. Excessive positive impact
5. Highest positive impact

Audits refers to the frequency of the selection of certain credit by the CaGBC for further examination. When a project is submitted for LEED certification, some of the submitted credits will be selected by the CaGBC for further exploration. This process identifies whether the consultants' group has fulfilled all the requirements of the rating guidelines. This question aims to determine if the practitioner believe that

some credits are more frequently selected for audit by the CaGBC. The rating options available for this factor included:

0. Never selected for audit
1. Selected once
2. Selected twice
3. Selected three times
4. Selected four times
5. Selected five times or more

4. SURVEY RESULTS

The survey was sent out by email to 866 LEED accredited professionals (LEED AP) in Ontario and British Columbia. 59 responses were received, 47 of which were complaint. Table 1 shows the distribution of the responses based on the area of the LEED AP's specialization.

Table 1. Survey Response Distribution

Area of Practice	Total Survey Responses	Compliant Surveys
Architects	41	34
Project Managers	13	9
Other Consultants	5	4
Total	59	47

Table 2 shows a sectional view of the responses (from 9 respondents) questioning the impact of achieving credits under "Sustainable Sites" criteria on project schedule.

Table 2. Data Sample: Impact of Sustainable Site credits on Project Schedule

		Respondents								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SUSTAINABLE SITES	**Erosion & Sedimentation Control**	2	0	1	1	0	1	2	0	1
	Site Selection	1	0	1	1	0	1	1	0	1
	Development Density	1	0	1	1	0	1	1	0	0
	Redevelopment of Contaminated site	5	0	5	3	0	5	0	0	4
	Alternative Transportation									
	Public Transportation Access	1	0	1	1	0	1	1	0	0
	Bicycle Storage & Changing Rooms	1	0	1	1	0	2	5	0	1
	Alternative Fuel Vehicles	1	0	1	1	0	2	1	0	1
	Parking Capacity	1	0	1	1	0	1	1	0	1
	Reduced Site Disturbance	5	0	1	3	0	2	2	0	1
	Storm Water Management	1	0	1	3	0	2	3	0	1
	Heat Island Effect	1	0	1	1	0	1	1	0	1
	Light Pollution Reduction	1	0	1	1	0	1	3	0	1

The survey questioned the impact of 45 credit area on the 12 indentified factors in three main phases of a building project, resulting in 540 survey entries. The mean, mode and median for all the entries were calculated and tabulated in tables. While due to space constraints it would not be possible to discuss the results of all 540 entries in this paper, it is interesting to note some of the response trends.

- The respondents believed that achieving Construction Waste Management credit needed minimal prior knowledge (1.48), while the Innovation in Design and Durable Buildings required the prior knowledge of someone who has achieved the credit twice (3.91).
- The average of popularity score for selection of a specific credit in the past was between 2.00 ("selected credit once") for Green Power, and 4.86 ("selected credit 3 to 5 times") for Light Pollution Reduction and LEED AP credits.
- The respondents believed that none of the credits increase the cost of consultants by more than 1%. The highest impact on consultant fees was associated to Minimum Energy Performance (1.57) indicating an increase of less than 1%.
- Overall, the respondents did not see a high learning curve for any of the credits, with scores ranging from 0.36 to 3.09 for Minimum Energy Performance.
- In documentation the areas with the lowest requirements were identified as LEED AP (1.14), Bicycle Storage (1.18), and Site Selection (1.27). The areas that required the highest level of documentation were Construction Waist Management (4.77) and Low Emitting Materials (4.73).
- The respondents considered the impact of all credits on delaying the schedule negligible. The only exception was Redevelopment of Contaminated Sites with an average score of 2.90.
- The survey results showed that the APs believed conforming to LEED requirements will not increase the cost of project more than 2% (range of 0.04 to 1.87). The only exception to this was Renewable Energy that was deemed to increase the cost by 2.5% to 5% (score of 2.69).
- In the post construction phase, the survey showed that the impact of all the credits on the overall cost of the project was considered to be less than 1%. (0.05 to 1.59).
- The LEED AP associated the lowest cost savings to the Site Selection credit (0.14) and the highest to Fundamental Building System Commissioning (3.59) and Minimum Energy Performance (3.68) –i.e. 2.5% to 5% of cost savings.
- The practitioners believed that the impact of some of the credits on the future value of the property is negligible (e.g. LEED AP credit: 0.05), while Controllability of Systems (4.14), Thermal Comfort (4.23) and Daylight and Views (4.45) were believed to increase the value of the property by 5% to 10%.
- Under the environmental impact, all the credits received a score between 4 and 5, which shows the professionals believed all LEED credits have and *average* to *excessive* positive environmental impact. It is noteworthy that the mode and median for this factor were uniformly 5 across all credits.
- Based on APs' past experience, almost all credits were uniformly selected once or twice for audit (scores: 1.00 to 1.76). The only exception to this was Construction Waist Management (3.62) that was on average selected two to three times.

5. SUMMARY AND CONCLUSIONS

This paper presented a survey on industry practitioners' perception on the impact of a LEED certification process on the construction project. The impact of achieving every LEED credit was questioned on 12 factors that are deemed important in three phases of pre-construction, construction, and post construction. These factors were selected based on interviews with industry practitioners. This survey verifies which

areas are of concerns to construction industry practitioners when approaching a LEED certification project. The results of this survey are of interest to the future of sustainable developments for two main reasons: 1) the perception of the practitioners of the value and impact of each point will directly effect the success of achieving the set goals; and 2) a clear understanding of industry practitioners perception will assist developers of design tools and evaluation systems to identify the areas that need to be addressed, either by improvement, or by clarifications and trainings the practitioners. This survey only demonstrates the perception of the practitioners, which does not necessarily reflect the actual impact of the process. Future research includes the study of the actual impact of every point on the 12 identified credits and comparing it with the perception of the practitioners presented in this paper.

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A GIS Framework for Reducing GHG Emissions in Concrete Transportation

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Abstract:
Transportation is the largest Greenhouse Gas (GHG) emitting industry sector in North America. Between 1990 and 2005, emissions in Canada's freight transportation caused by Heavy Duty Diesel Vehicles (HDDV) increased by 18 mega tons of CO_2 (Carbon Dioxide) or 84% equivalent. Although many factors contribute and while different options such as increasing fuel economy and substituting alternative fuel for reducing GHG emissions from transportation exist, little attention is given to reduce these emissions via behavioral changes. This research investigates lowering emissions in the construction industry through intelligent and optimized route planning. The task of concrete delivery from batch plants to construction sites was identified to estimate GHG emissions. An emission map in ArcGIS environment using the road network of the Greater Toronto Area (GTA) was developed and later implemented in a decision support tool that enables construction industry practitioners to estimate GHG emissions from concrete transportation before ordering concrete from batch plants. Since material cost, delivery time, concrete quality, and availability often are the main criteria for practitioners to select concrete batch plants, the developed work offers practitioners with a choice for the lowest possible GHG emissions during concrete transportation. Although a more sustainable concrete delivery becomes feasible using the developed approach, results demonstrate that ordering concrete from batch plant varies depending on the search criteria selected.

Keywords: Concrete procurement, vehicle fleet, emissions, GIS, route planning, sustainability.

1. Introduction

According to several research studies, combustion of fossil fuels for transportation and industrial processes significantly contributes to global climate change. From 1948 to 2005, North America's surface temperature has increased by 1.2° C (2.2° F) (Climate Change, 2007). Excessive burning of fossil fuels and deforestation that has

started since the beginning of the industrial revolution has increased the atmospheric Greenhouse Gases (GHG) concentration. GHG are certain atmospheric gasses that capture reflected infrared radiation from the earth's surface, therefore creating a balanced greenhouse effect. Naturally occurring, the greenhouse effect increases the surface temperature to a suitable range which is essential for living beings. However, intensified concentration of these gases may represent an intolerable risk to the vitality of the earth. The amount of GHG emissions are commonly expressed in kilogram of CO_2-equivalent of six major gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs), using the 100-year Global Warming Potential (GWP) (EPA 2005).

Since the 19th century, more than 2.3 trillion tons of CO_2 have been released globally into the earth's atmosphere as a byproduct of industrialization. Recent scenarios developed by the IPCC and the Energy Information Administration (EIA) of the U.S. Department of Energy, believe that the GHG emissions of developed countries, including the United States and Canada, are expected to rise 35% by 2025 (IPCC 2008, Climate Change 2007). Both countries are among the top 10 emitting countries of GHG in the world. In Ontario, for example, these emissions were reported to be 183 megatons of CO_2 equivalent in 1990 and are forecasted to reach 240 megatons of CO_2 equivalent by 2020 (National Inventory Report, 2007).

The transportation sector is one of the largest contributors to global GHG emissions, where approximately 73% of these emissions are generated by road transportation (NIR 2007). As seen in Figure 1a, freight related traffic due to construction ranks at the top among truck miles generated by professional businesses in the United States (USCB 2004). Similarly, the majority of Canada's growth in transportation emissions came from an increase in total vehicle fleet, particularly light trucks and heavy duty vehicles, such as Heavy Duty Diesel Vehicles (HDDV) (Steenhof et al. 2006).

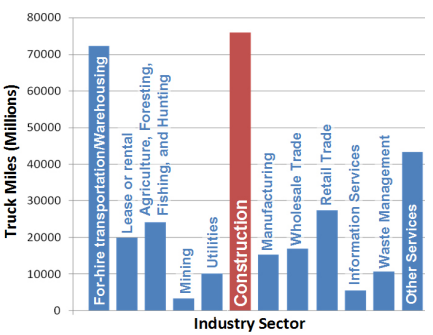


Figure 1: Freight truck mileage by industry sector (USCB 2004)

The construction industry has not paid adequate attention to GHG emissions pertaining to construction material transportation. This paper presents a GIS-based model that can assist the construction industry in reducing the GHG associated with

concrete transportation, by locating concrete batch plants with minimum transportation GHG emissions to construction sites. This paper first reviews the factors that cause transportation GHG emissions; it then introduces the developed methodology to calculate GHG emission; and finally demonstrates a decision support tool that utilizes Geographic Information System (GIS) to locate concrete suppliers that offer the lowest GHG emissions during transportation to a given construction site. Textual and graphical content is provided to enable construction professionals for better decision making. This research focuses on emissions related to concrete related to batch plants in the Greater Toronto Area (GTA), but the algorithm and logic is applicable to other construction material and geographic areas.

2. Background Review

The commonly known environmental loads include emissions to air, effluents to water and generation of solid wastes. Emissions to the air are categorized into two groups: GHG and Criteria Air Contaminants (CAC). The scope of this research focuses on GHG emissions to air caused by ready mix concrete transportation using diesel powered trucks, which emit carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

While various ways for reduction of GHG emissions from transportation exist, Green et al. (2003) identified four practical options: increasing vehicle fuel efficiency; substituting with alternative fuels; increasing system efficiency; and reducing transportation activity. Steenhof et al. (2006) demonstrated that there is a strong relation between transportation GHG emissions to change in freight activity. Other studies on fuel economy recommended behavioral or organizational changes, such as taking fewer left turns or reducing just-in-time delivery – which can consume up to twice the amount of fuel than standard delivery (TCSTC 2001).

Government policies play an important role in reducing transportation GHG emissions. Currently, fuel economy standards, education programs, low sulfur content for diesel vehicles exist. However, future standards are needed to address the air quality problem in large cities (TCEPA 1999) and the increased demand for freight transportation created through the Free Trade Agreement (FTA) (Steenhof et al. 2006).

3. GIS Framework for Concrete Transportation GHG

To assist in reducing GHG emissions generated by material transportation, a decision support framework was developed that guides practitioners in making a sustainable choice when selecting a concrete batch plant. This section presents an overview and the data that supports the developed framework. A mathematical model used to calculate GHG emissions is presented.

This research was conducted in three steps: (1) Collect data to the factors affecting transportation GHG emissions, (2) Generate a mathematical algorithm to calculate GHG emissions, and (3) Create a practical decision support tool for the selection of the batch plant with the least environmental impact using the existing GIS. The framework of the research is illustrated in Figure 2.

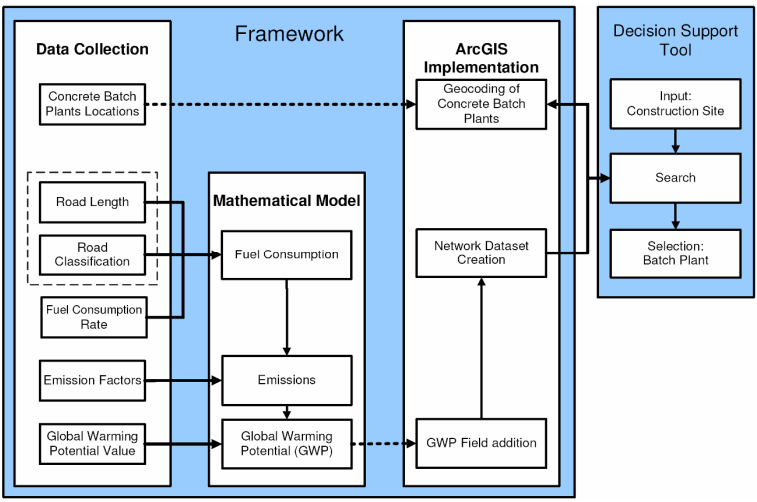


Figure 2: Research Framework

3.1 Data Collection

A report by Sparks (2007) contributed to a better understanding of the status of GHG emission measurement in the transportation sector. There are two potential approaches for estimating GHG emissions in concrete material transportation: tailpipe emission measurements of the HDDV and estimation based on fuel consumption and emission factors. The first approach could produce realistic values as it is based on direct measurement, but requires the installation of emissions sensors on each vehicle. Installation of emission sensors, however, was outside of the scope of this research. Further, GHG emission data for HDDV is not well documented.

In this research, the latter approach is utilized to calculate the GHG emission, which is also verified and utilized by Transport Canada (TC 2008) in developing the Urban Transportation Emission Calculator (UTEC). The National Inventory Report which follows the Intergovernmental Panel on Climate Change guidelines also uses this approach to calculate mobile source emissions (NIR 2007, IPPC 2008). UTEC estimates annual GHG and CAC emissions from transportation by different transportation modes using Vehicle Kilometers Traveled (VKT) as the main input. The framework developed in this research locates batch plants using a GIS database to calculate the exact travel distance to a construction site.

Additional required information was identified as: road information, fuel consumption rate, emission factors, and GWP values. Road information and fuel consumption rate are required to calculate the fuel consumption per road segment.

- ***Batch Plant Locations:***

Concrete suppliers in the Greater Toronto Area (GTA) were identified by consulting the Ready Mix Concrete Association of Ontario (RMCAO). Through reviewing the membership directory, the three main suppliers of ready mix concrete were identified

as Canada Building Material (CBM), Dufferin Concrete, and Innocon. The names and locations of all of their 24 batch plants in the GTA were obtained from each company's directory and geo-coded into the GIS database. Other and potentially much smaller suppliers may exist which are not currently listed in the association membership directory.

- ***Road Information:***

Road information is required to calculate the fuel consumption per road segment. The road properties needed for this calculation include road length and road classification. The latter is used to predict speed limit and the possibility of stops at intersections and the end of each road segment. To model the road information, the most recent GIS based road information from CanMap RouteLogistics Version 2007.3 for GTA and geospatial data was used. The road information modeled into the network included street name (STREET), unique identification number of street segment (UNIQUEID), Cartographic Road Classification (CARTO), adjusted road length in meters, calculated using actual distance (RDLEN_M_E), estimated travel time in minutes, based on speed limit and actual road length (TRVLTIM_E), and probability in percent to stop within road segment (P(S)). An example of a street instance with properties in the aforementioned order is: WEBB ST., 7084229, 5, 191.228, 0.143, 1.00.

- ***Fuel Consumption Rate (FCR):***

Fuel consumption rate is dependant on different factors. Vehicle load is one of the main factors effecting fuel consumption rate. Based on their Gross Vehicle Weight (GVW) of empty vehicle plus payload- vehicles are grouped into 8 classes. Concrete mixers belong to class 8 - with a GVW greater than 15 metric tons, the heaviest weight class for on road transportation vehicles- and are categorized as HDDV. While an empty mixer weights approximately 15 metric tons, when fully loaded its weight can reach up to approximately 37.1 metric tons. The developed framework assumes that on their return trip trucks typically generate lower emissions.

Fuel consumption and emissions are closely related to the power demand of HDDV as they change significantly when variations happen in speed, acceleration, and deceleration. Based on the information provided by fleet managers of concrete batch plants in GTA, loaded mixers on average consume 58-67 liter per 100 kilometers. The fuel consumption rate (L/100 km) of trucks at various speeds varies based on vehicle weight. The fuel consumption rate is typically relatively constant and optimized for vehicle speeds ranging from 50 to 80 kilometers per hour. While theoretically the lowest fuel consumption rate for a vehicle trip is achieved when vehicles make no stops, in real word conditions trucks are constantly in stop-and-go situations.

Delivery time has a direct impact on truck speed and its acceleration/deceleration. Since concrete without additives hardens more quickly, ready mix concrete should be delivered within an hour of mixing. Therefore, concrete suppliers often avoid delivery during rush hours. Under this assumption, the effect of traffic congestion was neglected in this research. As well, the developed model does not address the slope changes of roads.

- ***Greenhouse Gas (GHG) Emission Factors:***

Environment Canada (EC) and the Environmental Protection Agency (EPA) in the United States were used as main sources for information on GHG emission factors related to transportation. The major GHG emissions from HDDV are grouped as CO_2 and Non-CO_2 (CH_4 and N_2O). CO_2 emission of HDDV varies depending on the amount of fuel consumed, carbon content of fuel, and fraction of fuel oxidized. Non-CO_2 emissions vary with the combustion technology and fuel type. Based on information received from the fleet managers of the concrete batch plant operations, the average age of a concrete mix truck in the GTA was calculated to be 6.5 years.
This study used the emission factors provided for advanced control technology and the corresponding CO_2 (NIR 2007, EPA 2005, Jacques 1992, McCann 2000) and Non- CO_2 (NIR 2007, EPA 2005, Lipman and Delucchi 2002, SGA Energy Ltd. 2000, and ICF Consulting 2004) values in the literature. These emission factors are in accordance with the EPA420 (2005) fact sheet. It is important to notice that depending on the combustion technology used in HDDV, different emission factors were used based on the level of control technology.

- ***Global Warming Potential (GWP) Values:***

The notion of GWP was created to compare the radioactive efficiency and decay rate of each gas relative to that of CO_2. GWP is reported in kg of CO_2 equivalent using a 100 or 500 year GWP time horizon. Annual GHG (NIH 2007) is submitted to the UNFCC by different countries including Canada. This report is prepared based on the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Second Assessment Report (SAR). Under the Kyoto protocol, all parties are required to use GWP values calculated for the IPCC SAR in order to create a basis for comparison of results from previous years. This research applied the latest GWP values from the IPCC Assessment Report Four (2007) using the 100-year GWP time horizon in which CO_2 equivalent values are as following: Carbon Dioxide (CO_2) = 1 CO_2eq; Methane (CH_4) = 25 CO_2eq; and Nitrous Oxide (N_2O) = 298 CO_2eq.

3.2 Mathematical Model to Calculate GHG Emissions

Based on collected information, a mathematical model was developed to measure the GWP for the GHG emitted by a truck in each road segment of the developed network for the GTA. The mathematical model first estimates the fuel consumption per road segment, then calculates the GHG emissions using emission factors, and finally generates the total GWP per road segment using GWP values explained in the pervious section. The average fuel consumption per road segment is estimated using the maximum and minimum fuel consumption based on the classification of road segments. Minimum fuel consumption occurs when the vehicle speed limit per road segment without any stops and a constant speed. Maximum fuel consumption which accounts for stop-and-go at the end and beginning of each road segment also included acceleration, cruise, and deceleration stages of the vehicle. Since accurate location data of traffic signals is often not available, a variable probability factor based on road classification is used to estimate the actual fuel consumption. More detailed explanations to the model follow.

- ***GHG emission calculation:***

For estimating GHG emission of surface transportation, this research uses a methodology recommended by the revised IPCC guidelines from 1996 (IPPC 2008).

- ***GWP calculation:***

Using the IPCC 1990 guidelines (IPCC 2008), the GWP of transportation for each road segment can be determined as the cumulative value of the amount of each GHG emission generated by transportation.

3.3 Implementation of a GIS Based Tool

The developed model was implemented as a GIS based tool to support decision making of construction industry professionals. The main modeling platform used in the implementation of the model was ArcGIS 9. Geo-reference information of road segments, construction sites, batch plants and their attributes were stored in ArcMap 9.2 database. The GWP for each road segment was calculated and added to the existing road attribute table using the Unique ID field. Individual road segments were merged into a network using ArcCatalong. Creation of a network was necessary in order to find the routes of the concrete mixer trucks. Finally, a closest facility algorithm was applied. This algorithm is commonly known to locate and find routes to the closest services. It first identifies the shortest route to all candidate facilities using Dijkstra's algorithm and selects the service with the minimum cumulative cost impedance.

- ***Geo-Coding of Concrete Batch Plant Information:***

The locations of concrete batch plants were geo-coded using their address and/or postal code. CanMap Enhanced Canadian Postal Geography 2007.3 was used as an address locator in order to geo-code each batch plant by postal code. Geo-coded batch plants also stored *street name and number*, *city name*, *postal code*, *company name*, *phone number, contact information* and *website*. A multi-layer colorized map was generated that allows users to easily search for concrete batch plant of different suppliers. All attributes of the batch plants, such as contact information, are available to the user and later may be used to convey information, such as concrete availability and delivery times.

- ***GWP Data Implementation:***

The mathematical expression for GWP (defined earlier) was used to calculate the GWP values. The GWP values for each road segment were then associated with the corresponding road segment in the GIS database.

- ***Network Dataset Creation:***

This research used ArcCatalog 9.2 to create a network dataset based on GWP data. The "Network Analyst" feature of ArcGIS provided models to the existing roads in the GTA. Endpoint connectivity was modified with elevation field, and Global Turns was used to model turns in the network. The GWP attribute for each road segments was then added as a cost impedance to control navigation. Summary of driving directions were then reviewed and the settings were established for this network. A

new shape file based network dataset was created and the network was built. The shape file base network and system junctions were then added to ArcCatalog.

- ***Network Analyst "Closest Facility" Application:***

The "closest facility" algorithm, commonly used to locate and navigate services, was employed to identify the shortest route from the available concrete batch plants to the construction site. As a result, the developed model can 1) Rank concrete batch plants based on the GWP lowest cumulative cost impedance. and 2) Generate the lowest emission intensive route from any plant to a given construction site. An interface in ArcMap allows for modifications such as adding or removing concrete batch plants, or changing any of the features in the mathematical model. The optimal or selected route can be displayed in a road network map, along with other supporting information such as concrete batch plant contact information or directions for truck drivers.

4. Case Study

The model was used to identify the best batch plant to order concrete for a construction site near 600 Taunton Road, Ajax, Ontario, Canada. The model returned the closest batch plant and the travel distance and time it would take a concrete truck from the batch plants to arrive on the construction site. In addition, the model provided the Global warming Potential (GWP) values for each of the trips. The developed model was then used to determine the best route based on transportation GHG emission (blue) and the best route based on travel time and distance (purple). Both routes are illustrated in Figure 3a. The trip length of the sustainable route was measured at 13,405 meters. It takes a concrete mix truck 13.65 minutes from concrete batch plant to a construction sites. The Global Warming Potential (GWP) for this example was finally calculated and was 33.2 kg of CO_2 equivalent.

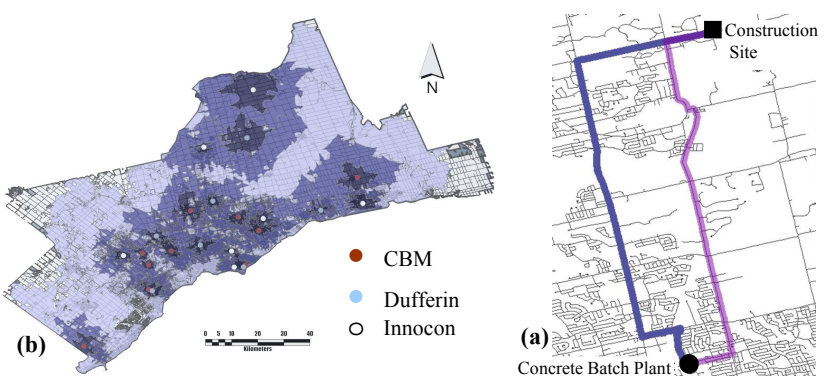


Figure 3 (a) sustainable (blue) and conventional (purple) routes from concrete batch plant to construction site (b) GHG Emission Map for Concrete Delivery in the GTA

Using this model, construction managers can choose the batch plant that has the most sustainable route to the construction site. As well, they can require concrete providers to use the more environmentally-sound route when transporting concrete from batch plant to the construction site. It is expected that concrete providers find such requirements attractive since it is directly connected to less fuel consumption, and thus reducing transportation expenses.

To give better oversight to construction decision makers, the Greenhouse Gas (GHG) emission map for concrete delivery based on the available geo-referenced information of the concrete batch plants in the Greater Toronto Area (GTA) was developed (Figure 3b). Three areas of GHG emission is highlighted in the map: 15 (dark blue), 30 (medium blue), and 60 kg (light blue) of CO_2 equivalent. Of particular note is the irregular shape that these areas. This is mainly due to the road network in a particular area of the map. Many areas do not have any concrete batch plants close by, which for some construction projects can become a critical factor or cost drive.

5. Summary and Concluding Remarks

A GIS based decision support tool was presented that takes into account the main factors contributing to emissions of Heavy Duty Diesel Vehicles (HDDV) in concrete transportation. A mathematical model was developed based on fuel consumption per road segment. It calculates emission values that HDDV generate while on route from concrete batch plants to construction sites. The first step included extensive data collection of concrete batch plants located in the Greater Toronto Area (GTA), including a GIS road network, traffic emission models, fuel consumption rates for various concrete truck types (HDDV vehicles), and their CO_2 (carbon-dioxide) and Non-CO_2 emission factors. Global Warming Potential (GWP) values were used to calculate the GWP per road segment for the GTA. A decision support tool was developed to identify the concrete batch plant with the lowest possible emission for concrete transportation. For the identified batch plant, the model further detects the route that generates the least GHG emission between the batch plant and construction site. This model will assist various decision makers from both construction procurement and concrete providers to make more environmentally sound decisions. With the current awareness on the impact of GHG emission on global warming, the importance of such models is becoming more apparent. Although the model is currently developed to calculate the GHG emission for concrete transportation, the logic and algorithms can be expanded to cover transportation of other construction material, which will be explored in future research work.

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