Building Information Modeling

APPLICATIONS AND PRACTICES



EDITED BY
Raja R. A. Issa, Ph.D., J.D., P.E.
Svetlana Olbina, Ph.D.

ASCE

Building Information Modeling

Applications and Practices

Sponsored by
Technical Council on Computing and Information Technology
of the American Society of Civil Engineers

Edited by
Raja R. A. Issa, Ph.D., J.D., P.E.
Svetlana Olbina, Ph.D.



Published by the American Society of Civil Engineers

Library of Congress Cataloging-in-Publication Data
Building information modeling (American Society of Civil Engineers)
Building information modeling : applications and practices / sponsored by Technical Council on Computing and Information Technology of the American Society of Civil Engineers ; edited by Raja R.A. Issa, Ph.D., J.D., P.E., Svetlana Olbina, Ph.D.
pages cm
Includes bibliographical references and index.
ISBN 978-0-7844-1398-2 (print : alk. paper) — ISBN 978-0-7844-7913-1 (ebook)
1. Building information modeling. I. Issa, Raymond. II. Olbina, Svetlana. III. American Society of Civil Engineers. Technical Council on Computing and Information Technology. IV. Title.
TH438.13.B845 2015
720.285—dc23

2015009357

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia 20191-4382
www.asce.org/bookstore | ascelibrary.org

Any statements expressed in these materials are those of the individual authors and do not necessarily represent the views of ASCE, which takes no responsibility for any statement made herein. No reference made in this publication to any specific method, product, process, or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASCE. The materials are for general information only and do not represent a standard of ASCE, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document. ASCE makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefor. The information contained in these materials should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing such information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

ASCE and American Society of Civil Engineers—Registered in U.S. Patent and Trademark Office.

Photocopies and permissions. Permission to photocopy or reproduce material from ASCE publications can be requested by sending an e-mail to permissions@asce.org or by locating a title in ASCE's Civil Engineering Database (http://cedb.asce.org) or ASCE Library (http://ascelibrary.org) and using the "Permissions" link.

Errata: Errata, if any, can be found at http://dx.doi.org/10.1061/9780784413982.

Copyright © 2015 by the American Society of Civil Engineers.
All Rights Reserved.
ISBN 978-0-7844-1398-2 (print)
ISBN 978-0-7844-7913-1 (PDF)
Manufactured in the United States of America.

22 21 20 19 18 17 16 15 1 2 3 4 5

Back cover credit: Illustration by Raja R. A. Issa

Preface

Building Information Modeling (BIM) has become a significant area of endeavor in the architecture, engineering and construction (AEC) industry that has transcended all disciplines. The models generated from BIM are being used for analyses and design of buildings as well as infrastructure. The ability to integrate schedule and cost data with the analysis and design process in BIM has made it a very popular tool in the AEC industry. Harnessing the as of yet unrealized potential of the full lifecycle use of the model by integrating it with the facilities and asset management phases of buildings and infrastructure will eventually maximize the benefits of BIM to the AEC industry and owners.

This monograph aims to offer a comprehensive overview of the recent advances in the application of BIM across the AEC industry. The monograph can be a useful reference for architects, engineers, contractors, building owners, and facility managers, as well as for the students majoring in AEC disciplines. Towards this end, the included chapters focus on BIM as a unified information management tool; as a framework for structural design; in cost estimating; in an adaptive Cyber-Physical System; in construction progress monitoring and control; in project management; in green building project delivery; in owners' requirements; in commissioning and facilities management, integrated with Augmented Reality; in military construction; and in model checking.

Chapter 1 presents the development of a BIM framework that aims to enrich the design process by advancing the understanding of the relationship between architectural and structural design in education. This chapter can be useful reading for architecture and civil engineering students as well as for practitioners such as architects and structural engineers.

Chapter 2 explores the relationship between BIM and current contractual models. It identifies hindrances to BIM collaboration and presents a number of key supporting mechanisms that may better facilitate meaningful early BIM collaboration. Building owners, designers and contractors can benefit from reading this chapter.

Chapter 3 focuses on the use of BIM for cost estimating and proposes standards that define the information exchange needed between the design model and cost estimator. The chapter can be beneficial for architects and contractors.

Chapter 4 proposes an adaptive cyber-physical system (aCPS) for project monitoring and control. The aCPS collects real-time radio frequency identification data about construction processes and resources and integrates these data into BIM-based construction models. With the use of aCPS, project statuses are tracked and aligned with project schedule in an interactive manner. This chapter can be beneficial for contractors.

Chapter 5 investigates BIM deployment within integrated construction project management information systems (PMIS) by presenting five real-world cases of BIM implementation in projects in the United States, Japan, and South Korea. The cases were analyzed using the following parameters: project delivery methods, engineering-procurement-construction (EPC) relationship, construction business functions, types of integration methods, and level of automation for BIM usage. Contractors can benefit from reading this chapter.

Chapter 6 presents the development of an integrated green BIM process model for BIM execution in green building projects. The model is based on the BIM Project Execution Planning Guidelines. This chapter can be a useful reading for architects, engineers, contractors, owners, and facility managers.

Chapter 7 explores the state of BIM deployment and execution among building owner organizations by conducting a survey of primarily higher education building owners. The chapter determines requirements for BIM deliverables and use of these deliverables post-construction for Operations and Maintenance. Building owners, facility managers, designers, and contractors can benefit from reading this chapter.

Chapter 8 presents a literature review of BIM for facility management in order to determine current practices as well as directions for future research. This chapter can be useful reading for building owners, facility managers, architects, engineers, and contractors.

Chapter 9 proposes integration of augmented reality (AR) and BIM for facility management. The chapter then discusses the technological transferability issues in the process of deploying BIM and AR in the facility management process. Building owners, facility managers, architects, engineers, and contractors can benefit from reading this chapter.

Chapter 10 investigates the use of BIM for estimating in Military Construction projects. It also looks at technological initiatives and tools that can help decrease the construction cost of these projects. This chapter can be beneficial for building owners, facility managers, and contractors.

Chapter 11 presents BIM-based model checking by reviewing the model checking principles, commercial model checking software, and model checking practices used in the state-of-art companies. This chapter can be a useful reading for building designers, contractors, and building permitting officials.

Chapter 12 presents development and validation of a domain-independent facility control framework. The framework is based on Industry Foundation Class Model View Definitions that were implemented in commercial available software and balloted within the United States National Building Information Model Standard (NBIMS-US V3). The potential readers of this chapter are facility managers, architects, engineers, contractors, and building owners.

Chapter 13 presents analysis of 57 noteworthy BIM publications (NPBs) from eight countries. NPBs are publically-available industry documents that incorporate guidelines, protocols, and requirements focusing on BIM deliverables and workflows. The chapter organizes BIM knowledge, identifies knowledge gaps, and offers directions for future research. This chapter is a useful resource for researchers in the AEC industry.

Contents

Preface iii

1 **Synthesizing Aspects and Constraints of Structural Design Using BIM and a Proposed Framework in Education** **1**
Nawari O. Nawari

2 **BIM-based Model Checking (BMC)** **33**
Eilif Hjelseth

3 **BIM and Cost Estimating: A Change in the Process for Determining Project Costs** **63**
Tamera L. McCuen

4 **MILCON in the Department of Defense: Estimating, Building Information Modeling (BIM) Based Design, and Impact on United States Army and Air Force Construction** **83**
Patrick C. Suermann and Lindsey R. Maddox

5 **BIM Inertia: Contracts and Behaviours** **107**
M. Hooper and K. Widén

6 **An Integrated Green BIM Process Model (IGBPM) for BIM Execution Planning in Green Building Projects** **135**
Wei Wu and Raja R. A. Issa

7 **Variations of BIM Deployment within Integrated Construction Project Management Information Systems (PMIS)** **167**
Youngsoo Jung

8 **An Adaptive Cyber-Physical System's Approach to Construction Progress Monitoring and Control** **195**
Oluwole Alfred Olatunji and Abiola Abosede Akanmu

9 **Building Information Modeling for Facilities Management: Current Practices and Future Prospects** **223**
Arundhati Ghosh, Allan D. Chasey, and Mark Mergenschroer

10 **BIM Use and Requirements among Building Owners** **255**
Brittany K. Giel, Glenda Mayo, and Raja R. A. Issa

11 Integrating Augmented Reality into Building Information Modeling for Facility Management Case Studies 279
Jun Wang, Lei Hou, Ying Wang, Xiangyu Wang, and Ian Simpson

12 A Domain-Independent Facility Control Framework.....305
E. William East and Chris Bogen

13 Building Information Modeling: Analyzing Noteworthy Publications of Eight Countries Using a Knowledge Content Taxonomy.....329
M. Kassem, B. Succar, and N. Dawood

Index.....373

CHAPTER 1

Synthesizing Aspects and Constraints of Structural Design Using BIM and a Proposed Framework in Education

Nawari O. Nawari*

Abstract: *Structure has always been one of the main ingredients of building design. This is ascribed to the roles and meanings of safety, economy and performance of buildings to the society at large. From early civilizations to the present, structures have provided shelter, encouraged productivity, embodied cultural history, and represented an important part of human civilization. Hence, for many, the subject of structural design is frequently marked by complexity. In contemporary domain, structure has acquired an independent personality, so that its own spatial and aesthetic qualities are highly valued. At the same time structures must obey scientific and engineering laws to be safe and sound. The separation between these aspects in practice continued since the beginning of the Industrial Revolution, when structural engineering has become a specialized field separate from architecture.*

Building Information Modeling (BIM) is one of the most promising advances in the Architecture, Engineering and Construction (AEC) industries that is significantly affecting 21st century practice. Presently, the AEC industry is actively informing their association members, stakeholders, etc., about BIM adoption. However, at the core of all this BIM evolution is education.

This chapter considers the application of Building Information Modeling (BIM) and develops a contemporary framework for synthesizing aspects and constraints of structural and architectural design in education. The framework aims to enrich the design process by advancing the understanding of the interplay between architecture and structure. This relationship between structure and architecture is fundamental to the art of building. It sets up challenges to the technical, scientific, and artistic

*Ph.D., P.E., School of Architecture, College of Design, Construction and Planning, University of Florida, 231 Arch. Bldg., P.O. Box 115702, Gainesville, FL 32611-5702, Email: nnawari@ufl.edu

realms that architects and engineers must resolve. Beauty is a subjective parameter i.e., in the eye of the beholder, whilst the mathematical and experimental sides of the structural design, controlled by norms are objective and factual. The method, in which the resolution of such challenges is carried out, is one of the most critical criteria for the success of a building design. The framework presented here focuses on the resolution of such challenges by using BIM to enhance the tie between architecture and structure as well as expanding the design vocabulary.

The framework combines various threads of knowledge; some may seem contradictory and incompatible, to arrive at structural beauty and correctness. The proposed framework will allow architects and engineers to applaud the fusion of art and science and cultivate professional qualities to meet the demands of today as well as tomorrow's integrated practice requirements.

INTRODUCTION

Students of Structural Engineering and Architecture

Building structures have always been essential components of building design. This is attributed to the roles and meanings of safety, economy and performance of buildings to the society at large. From early societies to the present, buildings have provided shelter, encouraged productivity, embodied cultural history, and definitely represented an important part of human civilization. In fact, the roles of structures are constantly changing in terms of shaping certain quantities of materials to provide efficient support to the architecture against gravity and other environmental forces (Addis, 2007). Also, from earliest times a sense of beauty has been inherent in human nature; some buildings were conceived according to certain aesthetic views, which would often impose on structures far more stringent requirements than those of strength and performance. Thus, designing structures is becoming deceptively complex as buildings today are also life support systems, communication and data terminals, centers of education, justice, health, and community, and so much more. They are expensive to build and maintain and must constantly be adjusted to function effectively over their life cycle (Prowler, 2012). Hence, for many, the subject of structural design is frequently marked by complexity.

Structural analysis courses at undergraduate level focus mostly on computation and understanding the principles of statics and strength of materials, without stressing the importance of understanding conceptual behaviors of structural systems and their aesthetic implications. Addis (1990) noted that at all times in architectural engineering history there have been some types of knowledge which have been relatively easy to store and to communicate to other people, for instance by means of diagrams or models, quantitative rules or in a mathematical form. At the same time, there are also other types of knowledge which, even today, still appear to be difficult to condense and pass on to others; they have to be learned afresh by each young engineer or architect a feeling for the structural behavior and

their aesthetic functions, for example. Currently, in the education of young structural engineers, educators have tended to concentrate particularly on that knowledge which is easy to store and communicate. Unfortunately, other types of knowledge have come to receive rather less than their fair share of attention (Addis, 1990; Rafig, 2010).

On the other hand architectural students in the design studios are concerned primarily with artistic expressions and philosophical description, independent of the building as an organism and how it is constructed. Structure is not adequately discussed and presented in their work. They apparently are not motivated by the current way of conveying structural concepts and design processes (Schueller, 2007). The purely mathematical approach of the classical engineering schools is not effective in architectural and building construction colleges (Schueller, 1995). Thus, students of these schools are driven to consider themselves as artists or contractors with less interest in scientific and engineering principles. However, all artists must acquire mastery of the technology of their chosen medium, particularly those who choose buildings as their means of expression.

The structure of a building is the framework that preserves its integrity in response to external and internal forces. It is a massive support system that must somehow be incorporated into the architectural program. It must therefore be given a form that is compatible with other aspects of the building. Many fundamental issues associated with the function and appearance of a building including its overall form, the pattern of its fenestration, the general articulation of solid and void within it, and even, possibly, the range and combination of the textures of its visible skins are affected by the nature of its structure. The structure also influences programmatic aspects of a building's design because of the ability of the structure to organize and determine the feasibility of pattern and shape of private and public spaces. Furthermore, structures can be defined to control the inflow of natural light; improve ventilation or many other functions that are needed by the architectural spaces.

The relationship between architecture and structure is therefore a fundamental aspect of the art of building. It sets up challenges to the technical, scientific, and artistic realms that architects and engineers must resolve. The method in which the resolution is carried out is one of the most tested criteria of the success of a building design. This issue has been recognized by many engineers and architects such as Khan (2004), Addis (1991), Schueller (1995, 2007), Billington (2003), Schodek (2004), and Sandaker(2008), Nawari & Kuenstle (2011), among others.

A History of Structural Engineering and Architecture Synergy

Historically speaking, one of the oldest architectural structures dates back to 2700 BC when the step pyramid for Pharaoh Djoser was built by Imhotep, who is considered the first architect and engineer at the same time in history known by name (Davidovits, 2008). Pyramids were the most common major architectural structures built by ancient civilizations due to the fact that the structural form of a pyramid is inherently stable and can almost be infinitely scaled out linearly in size

and proportion to increased loads. There is no record of any scientific or engineering knowledge employed in the construction of pyramids during that era. The physical laws that underpin structural engineering began in the 3rd century BC, when Archimedes published his work, "On the Equilibrium of Planes", in two volumes. He used the principles derived to calculate the areas and centers of gravity of various geometric figures including triangles, parabola, and half-circles. Together with Euclidean geometry, Archimedes' work on equilibrium and his work on calculus and geometry, established much of the mathematics and scientific foundation of modern structural engineering (Addis, 1992; 2007).

At the beginning of the 18th century advances in mathematics were needed to allow structural designers to apply the understanding of structures gained through the work of Galileo, Hooke and Newton during the 17th century. At that period, Leonhard Euler founded much of the mathematics and many of the principal methods, which allow structural engineers model and analyze architectural structures. Specifically, he developed the Euler-Bernoulli beam equation with Daniel Bernoulli (1700–1782) about 1750—which is one of the fundamental theories used in structural analysis and design. A few years later, Euler (1757) was able to drive the Euler buckling formula, which significantly advanced the ability of engineers and architects to design slender columns. His buckling equation is still one of the most fundamental equations used nowadays in various building codes to design columns and walls. (Schuler, 1995)

In the early 19th century, new construction materials such as iron and Portland cement played major roles in shaping the building design profession. Much of the previous century's practice tradition has had to be discontinued or radically re-conceptualized. This method did not fit well within the ancient norms of architecture and soon required a new type of training and education. By the mid-19th century, many engineering schools across Europe and the US had been founded and the modern engineering profession established. Hence, there was not a split between architecture and engineering; rather, a new discipline emerged alongside an older one. (Schuler, 1995)

In 1854 to 1872 Euqene-Emrnanuel Viollet-Le-Duc published important contributions to the field of architecture: the 'Dictionnaire raisonne de I'architecture francaise du Xle au XVle siede' (1854-68) (Dictionary of French Architecture from 11th to 16th Century (1854–1868)), and the 'Entretiens sur I'architecture' (1863). Their impacts were enormous, both in Europe and in America. Viollet-Le-Duc became the most prominent scholar to emphasis the importance of structures in architectural design. He asked the question: "*On what could one establish unity in architecture, 'if not on the structure, that is, the means of building*". He also said "*Construction is a science; it is also an art. The practice of architecture means adapting both art and science to the nature of the materials employed.*" (Nervi, 1965)

Based on Viollet-Le-Duc principles, Pier Luigi Nervi (1965), an architect and also an engineer, published his book "*Aesthetics and Technology in Building.*" in which he places his design firmly on the tradition of Viollet-Le-Duc principles, in

which architecture and structure are inseparable. In his book he insisted on that architecture cannot be based only upon pure art and explained that structure be it large or small must be stable and lasting, satisfying the needs for which it was built, and must be efficient (achieving maximum results with minimum means). He indicated that these are the criteria for good architecture. He also emphasized the idea of employing the materials "according to their nature"'. For instance, in discussing the advantages of reinforced concrete, he stated: *"Reinforced concrete beams lose the rigidity of wooden beams or of metal shapes and ask to be molded according to the line of the bending moments and the shearing stress"*. He asserts his views on the necessity for design to take account of the particular properties of each material and to form or adapt it to a particular shape. These views can be magnificently seen in his design of the Aircraft Hangers for the Italian Air Force (1940), Stadio Flaminio, Rome (1957), Palazzetto dello sport, Rome (1958), and the Cathedral of Saint Mary of the Assumption, San Francisco, California (1967).

Schueller (1995, 2007) approached the issue of the interplay between architecture and structure by emphasizing the engineering principles in architectural education alongside the application of software tools in training architects and engineers. Another viewpoint is the concept of "Structural Art" as described by Billington (2003). This perspective considers structural engineering as a new art form, which is parallel to but independent of architecture in the same way that photography, that other new art of the 19th century, is parallel to but independent of painting. Billington explored structural art in the 19th–20th century specifically in Switzerland. He thoroughly reviewed the work of Swiss structural engineers such as Wilhelm Ritter, 1847–1906) and Pierre Lardy (1903–1958) and four of their students: Robert Maillart (1872–1940) and Othmar Ammann (1879–1965) studied with Ritter, and Heinz Isler and Christian Menn with Lardy. Addis (1990, 1998, 2001) shared similar standpoints as Billington in considering structural art is a form of art that is parallel to but independent of architecture.

In the US, the work of Khan (2004) in the 70s and 80s represents a remarkable contribution to the structural art and innovation with the introduction of trussed-frames and-tubes, tube within tube, bundle tubes in high rise structural systems. Structures such as John Hancock Center, Sears Tower and One Magnificent Mile are important milestones in the history of buildings.

Sandaker (2008) considered structures as a part of architectural context. Thus, the purpose of structure is not primarily that of the support function, but also spatial harmony and enclosure organization. In his view, the main purpose of the structure is to establish architectural spaces physically. It follows that the form of structures must heavily consider the spatial functions and emphasize that an understanding and appreciation of structures thus needs to be taken into account.

The proposed SAS framework in this chapter shares some similar views as Sandaker (2008), Schueller (2007), Nervi (1965), and Viollet-Ie-Duc (1854, 1863); however, it introduces an innovative framework to enable the resolution of the challenges related to the conceptual linking and integration between architectural and structural engineering principles. The framework hinges on building information modeling (BIM) and the concepts of structural melody and poetry.

This new framework focuses on how to engage the student's imagination and to use it no less creatively than a musician or artist producing ideas while at the same time elaborates on structural analysis skills as well as on improving the ability in handling cross-disciplinary interests.

BIM IN EDUCATION

Overview

Building Information Modeling (BIM) is a comprehensive information management and analysis technology that is becoming increasingly essential for academic education. AEC schools implemented a variety of pedagogical methods for introducing BIM into their curriculums. They range from using BIM in architectural studio, sustainable design, and construction management to Civil Engineering (Önür, 2009; Sharag-Eldin et al., 2010, Barison et al., 2010; Sacks et al., 2010; Wong et al., 2011). For instance, Önür and Sharag-Eldin et.al described how BIM is integrated into architectural curriculum. Sacks et.al (2010) introduced BIM as an integral part of freshman year civil engineering education.

Several academic institutions have integrated BIM in their curricula, using different approaches; however, there is no commonly agreed upon methodology for teaching BIM in AEC programs (Barison et al, 2010). Most schools offer BIM in only one to two different courses. Many courses limit their coverage to a short period (one to two weeks) (Becerik-Gerber et al., 2011). Quite often, the BIM course is limited to a single discipline in 90% of the cases (Barison et al, 2010). The majority of schools introduce BIM on a basic level by teaching a specific software tool, limiting their perspective on BIM to viewing it simply as another CAD productivity enhancing tool for creating 2D and 3D drawings (Sacks et al., 2013). However, BIM by nature goes far beyond digital drafting (Eastman et al. 2011). A comprehensive literature review on the subject can be found in the work of Barison et al. (2010) and Sacks et al. (2013).

Since BIM is quite different from traditional CAD, it does require new ways of thinking and teaching. For example, BIM facilitates collaboration and teamwork across disciplines that must be incorporated in teaching BIM courses. Furthermore, BIM provides rich visualization of building elements and parametric modeling of behavior, which can enhance students' learning experience in virtual construction such as understanding how building elements fit together just as they must on a physical site.

BIM for Students of Structural Engineering and Architecture

With the recent technological advancements, engineers and architects have smarter tools to create and analyze artistically efficient structural forms, and demonstrate how load combinations affect the stability and behavior of a structure. Specifically, Building Information Modeling (BIM) has the potential to provide solutions to the issues addressed in the previous sections and advance

different types of structural knowledge sharing objectives without compromising their distinct requirements. BIM is a process that fundamentally changes the role of computation in structural design by creating a database of the building objects to be used for all aspects of the structure from design to construction and beyond. Based on this collaborative environment a new framework is proposed to advance structural design education. This framework is referred to as "The Structure and Architecture Synergy Framework (SAS Framework)". The framework explores structural design as an art while emphasising engineering principles and thereby provide an enhanced understanding of the influence structure can play in creating form and defining spatial order and composition.

The Proposed SAS Framework

The history of architecture intermixes with the history of mathematics, philosophy, and engineering at various levels. Designers have adopted concepts and language from these disciplines to assist in their own discourses. The term "Synergy" refers to the collaboration of multiple objects in a system to produce an effect different from or greater than the sum of their discrete effects. In the context of the proposed framework, it refers also to the essence or shape of an entity's complete form. In psychology, the term "Gestalt" is used in a similar sense referring to theories of visual perception that the human eye sees objects in their entirety (unified whole) before perceiving their individual parts. The phrase "The whole is greater than the sum of the parts" is often used when referring to synergy or Gestalt theories. Similarly, the SAS framework provides a useful language for understanding the structure as a whole in connection to its close relationship with architecture.

The Structure and Architecture Synergy Framework (SAS) focuses on the interplay between architecture and structures and emphasizes a learning process that is highly creative in nature. In this framework, the form of the structure is constrained not only by its function, the site and the designer vision, but also how it will work as a whole, and by the need to provide a rational argument and calculations to justify expectations before the structure is being built.

The proposed framework concept aims to advance other types of structural knowledge that centers on how to engage the student's imagination and to use it no less creatively than a musician or artist producing ideas. On the one hand, structural correctness emphasizes the conceptual and quantitative engineering sciences of the structural design. The framework combines various threads of knowledge (see Figure 1-1), which may seem at first glance conflicting and incompatible. These threads arise from many origins - an understanding of space and human activities, scale, proportions, engineering sciences, knowledge of the behavior of actual materials, and the construction process.

In structural design, an essential skill lies in choosing structural forms and arrangement which manages to satisfy, to varying degrees, many often incompatible constraints, for example, satisfying architectural spatial and aesthetic works in which the form substantially differs from standard structural solutions, such as the need for large open space without columns intrusion. As with musician when

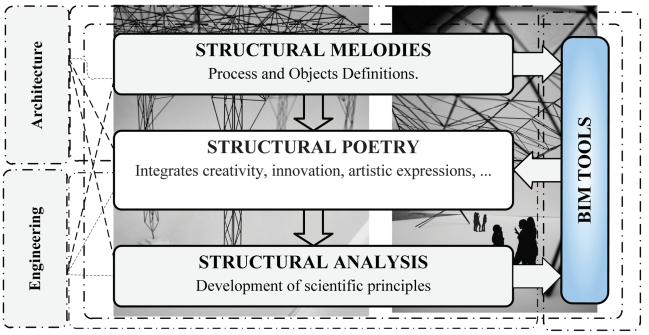


Figure 1-1. Structure and Architecture Synergy Framework (SAS Framework).

composing music, this skill relies on a mixture of precedent, experience and inspiration. For this purpose, the vocabulary and methodology will be introduced using the concepts of "Structural Melody", "Structural Poetry", and finally "Structural Analysis". These are the main components of the proposed framework along with building information modeling (BIM) as the framework enabler. Figure 1-1 depicts an overview of this framework. Without the traditional emphasis on first understanding beams, columns, footings, bearing walls, etc., two dimensionally, using the laws of statics and strength of materials, the framework emphasizes the building as a whole and create a three dimensional structural systems using building information modeling tools and then develop them further into an actual architectural solution.

BIM Concept

The structural design in education is standing on the brink of a new technology that will transform the way structures are designed and constructed. The change is more significant and more profound than the transition from hand computation and drafting to computer aided design.

Building information modeling (BIM) is a process that fundamentally changes the role of computation in the AEC industry (Autodesk, 2013). It involves new concepts and practices that are so greatly improved by innovative information technologies and business structures that they will radically reduce the multiple forms of waste and inefficiency in the building industry (NBIMS, 2007). In this concept rather than using a computer to assist producing a series of drawings that together describe a building; the computer is used to create a single, unified representation of the entire building so content-comprehensive that it can generate all necessary construction documentations. The primitives from which the BIM software composes these models are not the same ones used in traditional CAD (points, lines, curves). Instead, the BIM application models with virtual building components that hold attributed information about actual elements and systems. Examples include trusses, columns, beams, walls, doors, windows, ceilings, and floors. The software platform that implements BIM recognizes the

form and behavior of these objects, so it can ease much of the tedium of their coordination. Walls, for instance, join automatically, connecting structure layers to structure layers, and finish layers to finish layers. Many of the benefits are obvious—for instance, changes made in one view propagate automatically to every other elevation, section, callout, and rendering of the project. Other advantages include the ability to use the same model to interact with other applications such as structural and energy analysis software (Autodesk, 2013).

As a general concept modeling, BIM deals with higher-level operations than traditional CAD does. It deals with placing and modifying entire objects rather than placing drawings and modifying sets of lines and points. At the same time, BIM platforms allow one to do some standard drafting if needed. Consequently, the geometry is generated from the model and is therefore not open to direct handling (Autodesk, 2013).

Another important concept is that a BIM model encodes more than form; it encodes high-level design intent. Within the model, walls and floors are modeled not as a series of 3D solids, but as virtual walls and floors with material types and properties. That way if a level changes height or walls change width, both of the objects automatically adjust to the new values. If the wall moves, any floor that has a relationship to that wall adjusts automatically.

Students must be introduced to these basics of BIM using one of the available BIM authoring tools. This introduction can take about eight contact hours. The last phase of this introduction is an overview of platform interface along with emphasizing the comprehension of new concepts such as model element, categories, families, types and instances (see Figure 1-2). Phase 1 and 2 in Figure 1-2 cover the introduction to basics of BIM. In phase 3, a specific platform is chosen and students learn more in depth about object-oriented modeling techniques. This last phase normally takes a full semester.

Following the introduction, students can be engaged in learning about the various analysis tools that integrate with BIM platforms. Some of these tools are available as extensions to the basic versions of the software.

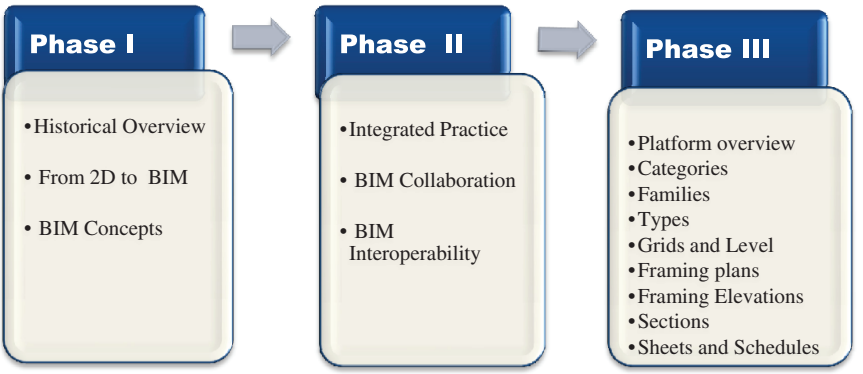


Figure 1-2. BIM Introduction Blocks (Sharag-elding & Nawari, 2010).

STRUCTURAL DESIGN FUNDAMENTALS

Common Attributes of Architecture

Throughout the US accredited schools of architecture and design are influencing and educating the future generation of architects who may go to create the next masterpiece. Their knowledge of many branches along with their judgment is the practice and theory in architecture (Waldrep et. al., 2006). It is not this issue, which is being called into question, but rather what is the current role of the architect.

To understand the role of architects it is imperative to acknowledge their focal points in design. For example, Salingaros et. al. (2006) suggests that architects may consider "order on the smallest scale that is established by paired contrasting elements, existing in a balanced visual tension; large scale order occurs when every element relates to every other element at a distance in a way that reduces entropy; the small scale is connected to the large scale through a linked hierarchy of intermediate scales with various scaling ratios" (Salingaros et. al., 2006). One of the overall objectives is to give rise to different experiences that users of a building undergo. The practical functions such as the entry and exit, and circulations are also influenced by the structural form and order.

The basic practices an architect of today would follow are appraisal, design brief, concept and design development (Chappell et.al., 2000). These actions encompass understanding the needs of the client, an outline of the preparatory work agreed upon by the architect and client, a sketch design to illustrate the external public and private space, internal public and private spaces and appearances as well as a final version showing a clear representation of the entire building including components, materials and layout.

Common Attributes of Engineering

Engineering students are trained in understanding advanced calculus and numerical methods for analyzing and designing buildings and other structures—they know how to set up the analytical model and solve equations to get solutions to verify safety and stability. However, they can lack the understanding of the overall structural behavior of the building and its connection to other architectural and construction aspects, and thus may use an abstract mathematical and analytical model that imperfectly simulates reality (Addis, 1990). Furthermore, engineers rarely have the opportunity to entertain engagement in aesthetic matters of buildings. Their focus is relative to their discipline, whether it is structural, civil or mechanical.

Also, engineers have their own set of preferred geometric forms which have their origins in the mathematical models found in structural science. A wide-flange I-section or an inverted T-shape are efficient cross-sections for a beam; depending on the material and how it is manufactured, efficient cross-sections for a column might be a solid circle, a tube, or an H-section. In order to use the

minimum amount of material, beams and columns should taper as a parabola or paraboloid from their centers to the end support points. Trusses need to be made up of triangles, sometimes of identical shape and size, sometimes changing. Suspension structures (cables and arches) feature catenaries or parabolas curves. Shells are usually made in the form of paraboloids, hyperboloids or hyperbolic paraboloids, but may also be elliptical, spherical, cylindrical or even have the form of logarithmic spirals, and epicycloids (Addis, 2001).

In nutshell, through their education structural engineers are taught fundamental understanding of applied mathematics and the knowledge of behaviour and science of materials under various loading conditions as well as theories of structural analysis, which normally guide their motives in making design decisions. However, structural design is not merely concerned with science, mathematics and techniques, but also with space enclosure, scale and proportions, nature and the environment, communication links for people and objects, circulations, and after all aesthetic values and innovation.

Differences and Oversight Between Architects and Engineers

Simply stated architects and engineers have differing goals when approached with a design. On one hand, architects are concerned with what they have been taught, space organization and order, flow, circulation, occupants comfort, cultural and social issues, and aesthetic impact. On the other hand engineers deal with structural planning, safety and economy. As can be seen there is no clear overlap or platform that would facilitate communication and coordination between the disciplines. Accordingly, if a suitable method is utilized by both professions to understand the interplay between these fields, more fluent, cohesive, and efficient design process could be achieved.

BIM along with the SAS framework will assist in minimizing the oversight between architecture and engineering due to its ability to specify the interaction of architectural forms and features, structural stresses, section properties, material strength, deformation, and performance based on type of connections and boundary conditions using a single BIM model.

Structural Melody

The initial goal of structural meldody is to understand how linear, non-linear, planar and volumetric structural elements can be orchestrated to create spatial order in architecture using BIM tools. It is also the intention to develop this idea as a holistic vehicle to introduce structural vocabulary, the hierarchy of structural members and the interplay between architectural concepts and structural systems such as exoskeleton, endoskeleton, stratification, transition, hierarch and, heart of spaces. Structural melody deals also with the structural vocabulary such as elements names and their order and hierarchy.

Structural melody introduces the language of structural design, and therein introduces students to relationships between systems and details. It aims to provide students with the basic vocabulary and grammar for expressing design

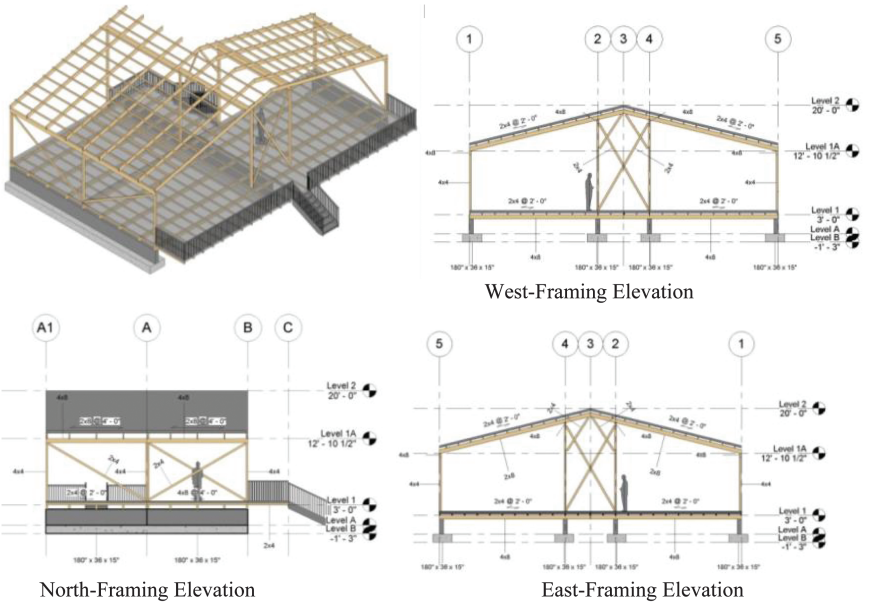


Figure 1-3. Structural Melody.

ideas. Structural meldodies start incrementally from a simple 3D system and then evolve into a whole architecural solution with lateral and vertical stratification.

Furthermore, using BIM tools, the flowing vocabularies are introduced:

- Grid lines and reference planes: Are essential lines in structural melody and they are used to define the structural layout, and boundaries. Gridlines are represented by doted lines with a buble at one end or both ends. The bubles are utlized to number grid lines using digits in one direction (y-direction) and letters in the other orthogonal direction (x-direction) (see Figure 1-3b).
- Foundation plans: This is a plan view at the foundation level.
- Framing plans: This is a plan view of the roof or floor showing the structural support system at the floor or roof level.
- Framing elevations: This is a special elevation view that depicts structural elements elevation view at a specific section line across the building.

These definitions are illustrated in Figures 1-3. This will facilitate the understanding of the relationships between the 3D models and their two dimensional representations. The hierarchy of the structural elements is also introduced using 3D models similar to those given in Figures 1-3.

Structural melody also includes understanding various suport patterns derived from basic linear, planar and non-linear elements and how these patterns respond to the functional orgainization of the buildings. For instance, columns and walls can be utlized to separate and reinforce spaces to allow for different

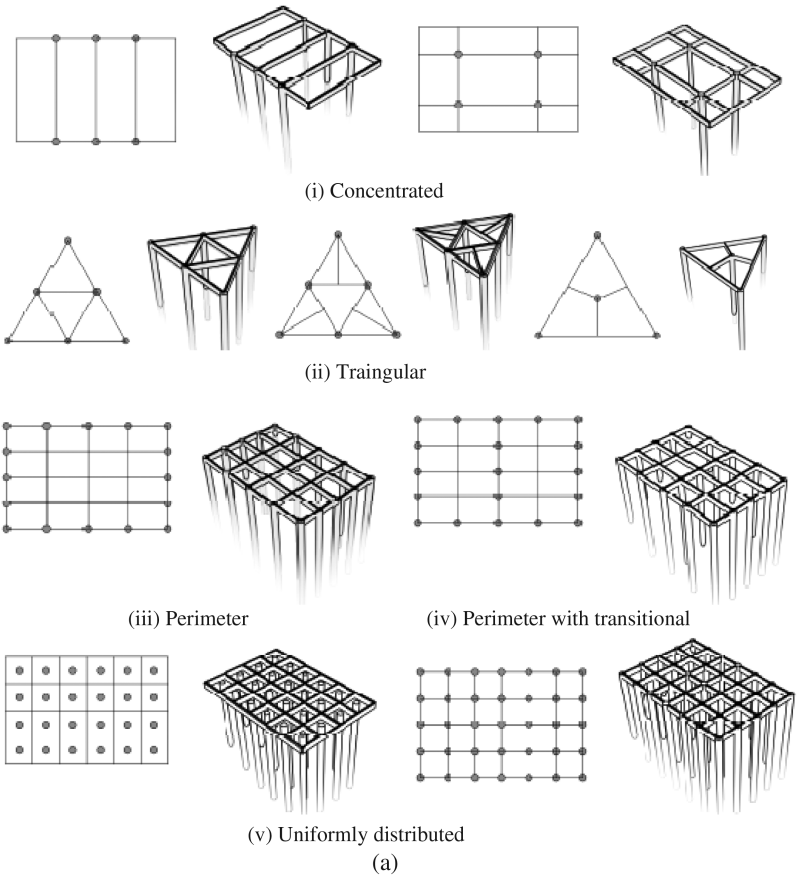


Figure 1-4. Structural Melody: (a) Linear vertical support patterns. (b) Surface support patterns. (Continued next page.)

activiites. Figures 1-4a and 1-4b illustrate some examples of structural support patterns introduced and their spacial charcatersitics. These patterns in conjunctions with the rules of thumb (defined next) provide the primary structural instrument to determine the appropriate degree of fit between the functional spaces and the structural support patterns.

Another important part of the structural melody is the rules of thumb for the relationship between the sizes the structural elements and the space they define. The followings are some examples of rules that are introduced to determine the initial sizes of linear and planar elements (Schueller, 2007): The ratio of the overall depth of a beam (d), a girder, or a planar element thickness (t) to the span of the space (L) are as follows:

$\frac{L}{d} = 10$ for a cantilever beam and trusses; $\frac{L}{t} = 30$ for a planar element

$\frac{L}{d} = 20$ for a non-cantilever roof or floor beam and trusses

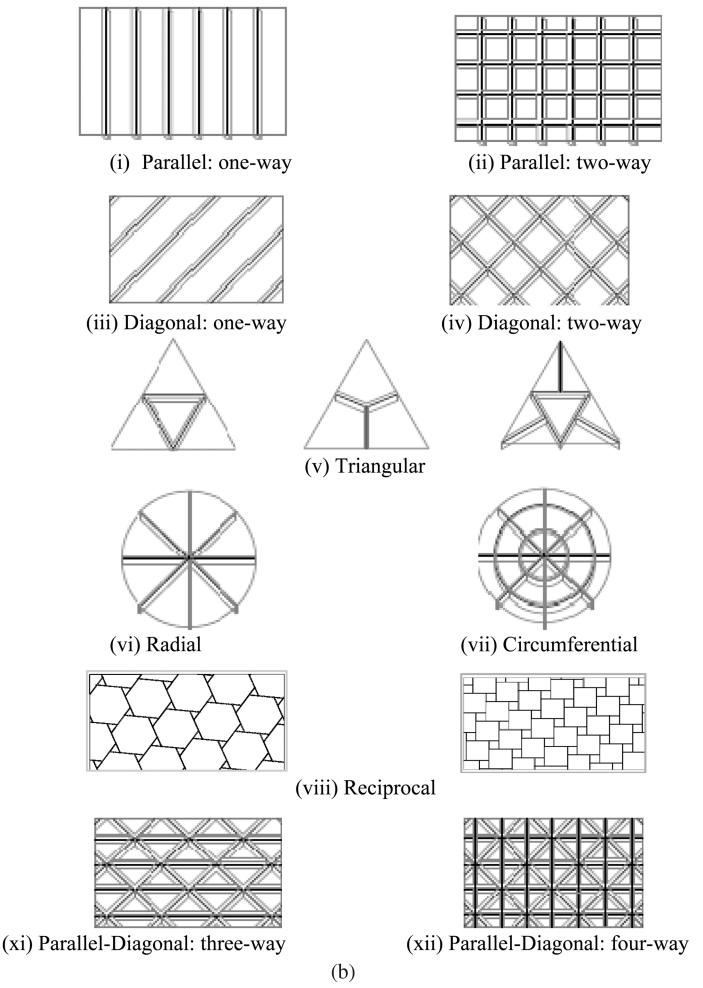


Figure 1-4. Continued.

Structural Poetry

The word poetry has its origin in Greek and means a making: forming, creating or the art in which language is used for its aesthetic and evocative qualities in addition to, or instead of, its notional and semantic content (Oxford Dictionaries, 2010). In other words, poetry is a fundamental creative act using language. Similarly, structural poetry is a creative exercise to provide structural systems using structural vocabulary and melodies in order to organize and stabilize architectural spaces.

In a more general sense, structural poetry strives to develop structural creativity and spatial thinking as well as to enhance the conceptual design abilities. This allows one to develop an imaginative complex structural system without a

thorough understanding of its individual components at the initial design stages. Without the traditional emphasis on first understanding beams, columns, bearing walls, etc., two dimensionally, using the laws of statics and strength of materials, structural poetry utilize the power of Building Information Modeling (BIM) to create three dimensional structural forms to satisfy spatial, aesthetic and other programmatic requirements.

In this approach a parallel can be drawn to language poetry to enhance student's comprehension. For instance poetry may use condensed or compressed form to convey emotion or ideas to the reader's or listener's mind or ear; structures can be formed using a few members in different form to provide certain aesthetic and framework for spaces; it may also use devices such as assonance and repetition to achieve musical or incantatory effects, similarly structures can be orchestrated by repeating the same pattern of supports to achieve simplicity and elegance. Poems frequently rely on their effect on imagery, word association, and the musical qualities of the language used. Also, structures can use its form, orientation, type and quality of materials to impact the final design. The interactive layering of all these effects to generate meaning spaces is what marks structural poetry (see Figures 1-5 to 1-10).

Figure 1-5 shows the basic structural models or simply "Buildoids". These buildoids can grow horizontally and vertically to fulfill the desired programmatic objectives using BIM tools. This process is similar to the natural growth of living objects. For example, biological forms are hierarchical structures, made of materials with elusive properties that are capable of change in response to variations in local conditions. These systems are self-assembled, using small primarily units (cells) to make whole structures. In addition, in most of these multicellular organisms, growth is not only about the volume increase of a single cell, but also about the multiplication and rearrangement of cells (Sinnott, 1960, Bard, 1990).

This process is demonstrated in Figure 1-6 by depicting buildiods'plan configurations to generate various spatial growth expressions. Figure 1-7 illustrates the manifestation of this growth concept using buildoid shown in Figure 1-5c.

Figures 1-8 to 1-10 depict the development of the basic BIM model (Buildoid) to define larger spaces by expanding progressively in the horizontal and vertical directions. This illustrates how structural poetry provides various architectural programmatic solutions using BIM tools. The ability of the BIM tools to capture and analyse various architectural and structural attributed data associated with the building components and their object-oriented modelling nature allowed structural poetry to achieve these solutions. Furthermore, in addition to using the same model data to generate numerous expansion solutions, the BIM model can also be sent to other structural and architectural analysis software platforms without having to remodel the project. These content-driven and object-oriented modelling capabilities along with the interoperability feature make BIM tools superior over traditional CAD tools in applying structural poetry. The last phase in this growth progression shows complete structural and architectural components of the building.

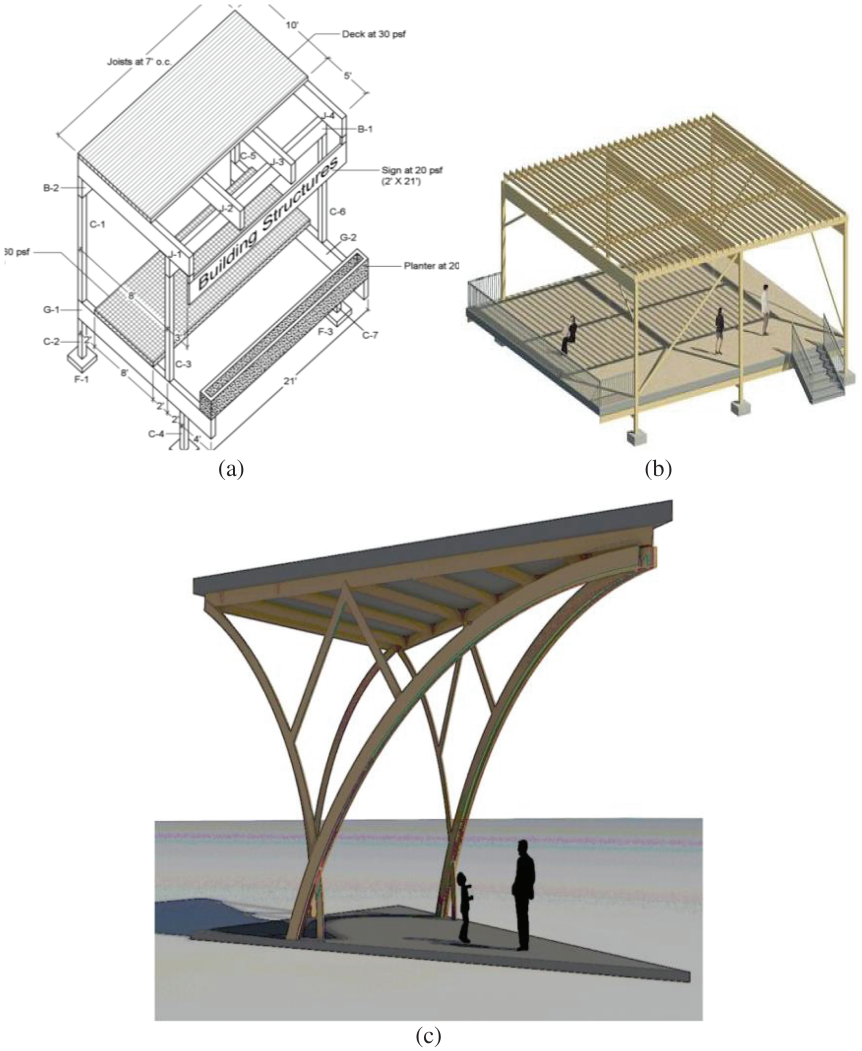


Figure 1-5. Basic units (Buildoids): Examples of Structural Poetry.

Structural poetry is thus an art that is an integral part of building design, which flourishes with engineering knowledge.

The variations of structural forms shown in Figures 1-8 to 1-10 depict various architectural and structural fundamentals such as the idea of elevated floors, cantilevers, simple trusses, frames, shear walls, bracing, two-levels of framing and three-levels of framing, linear and non-linear frames, spaces established (interior, exterior, private, and public spaces), lateral and vertical circulation, structural hierarchy and organization, spatial order and aesthetics.

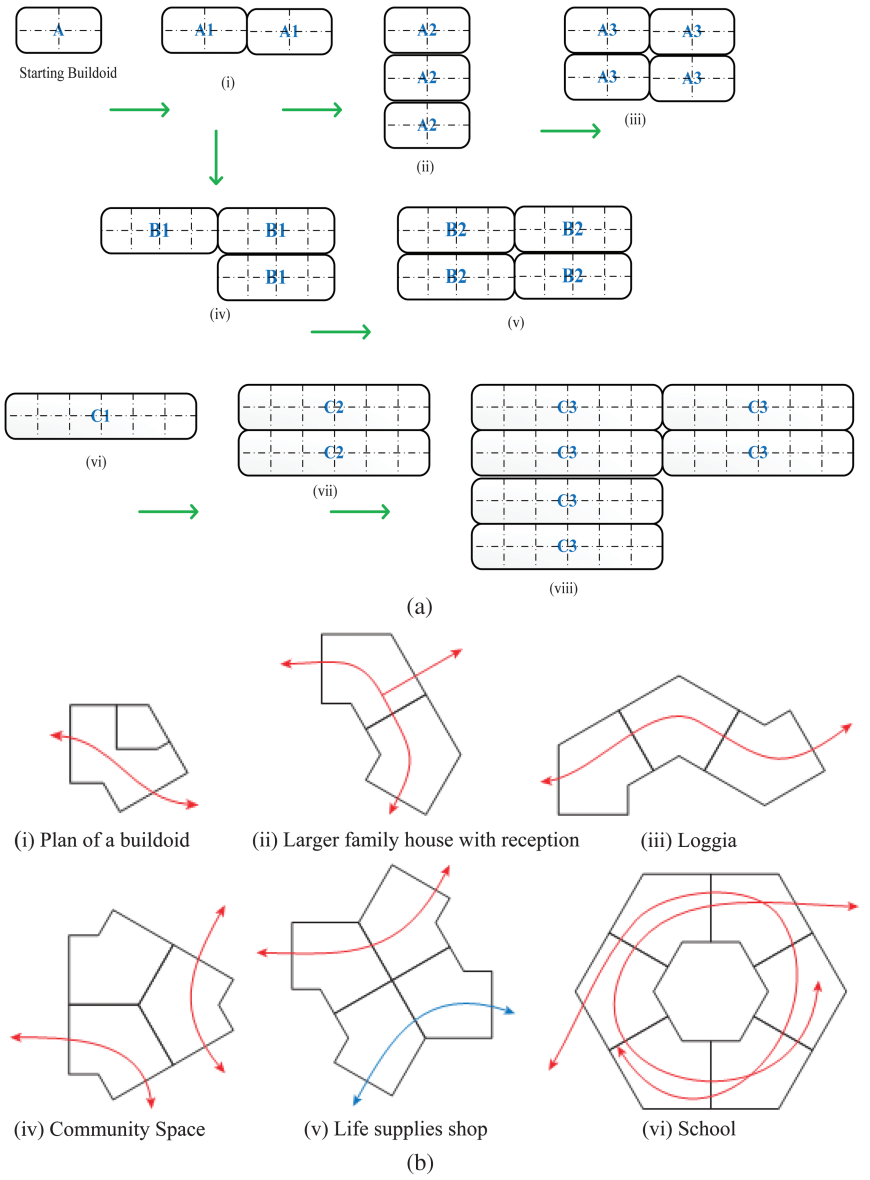


Figure 1-6. Examples of Buildiod plan organization and growth patterns.

To explore further creative activities, interaction with existing iconic structures can be conducted. Analogy is made here to musical composers who study variations on musical themes by others or for poets or philosophers who memories and learn about other great work to test their own contributions. Such creative interaction with the work of other existing creative models can be a source

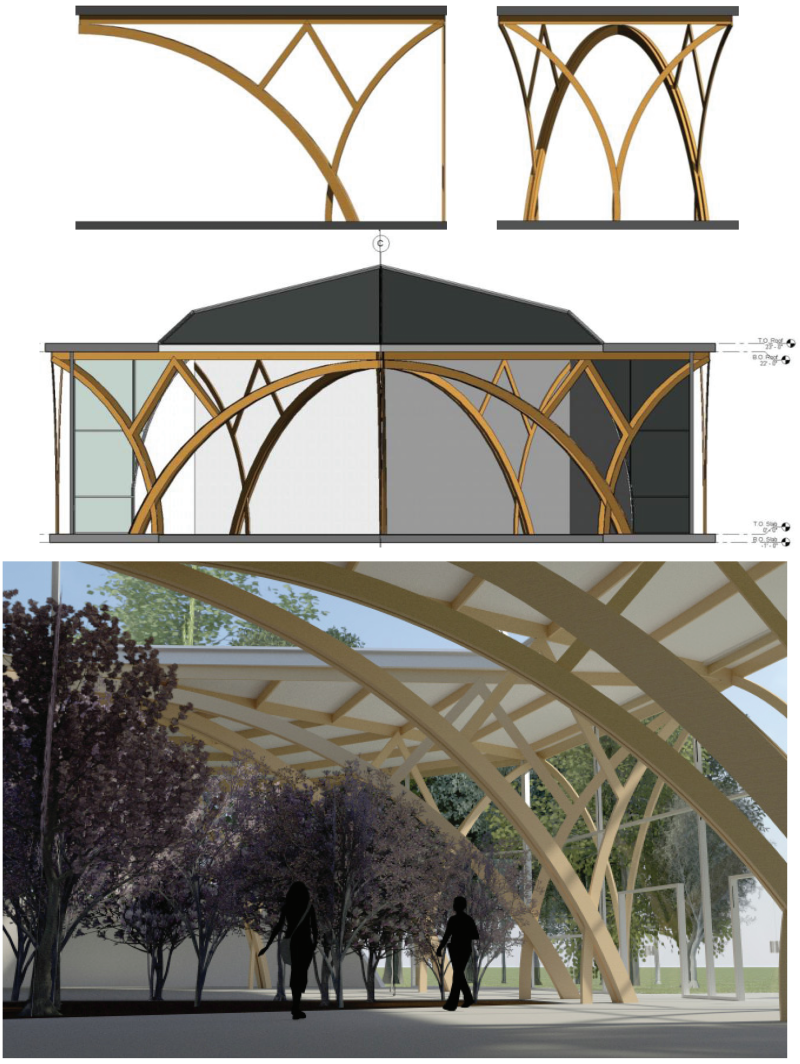


Figure 1-7. Examples of Structural Poetry.

of ideas and can develop an understanding of how architecture interacts with structural components.

Structural Analysis

After completing structural melody and poetry phases, BIM models are subjected to structural analysis. Various analysis tools within BIM platforms are introduced. BIM tools used in this phase are principally the beam, truss, frame simulation, the load takedown, and the integration with Robot Structural Analysis. The load takedown played an important role in introducing load path, load tracing,

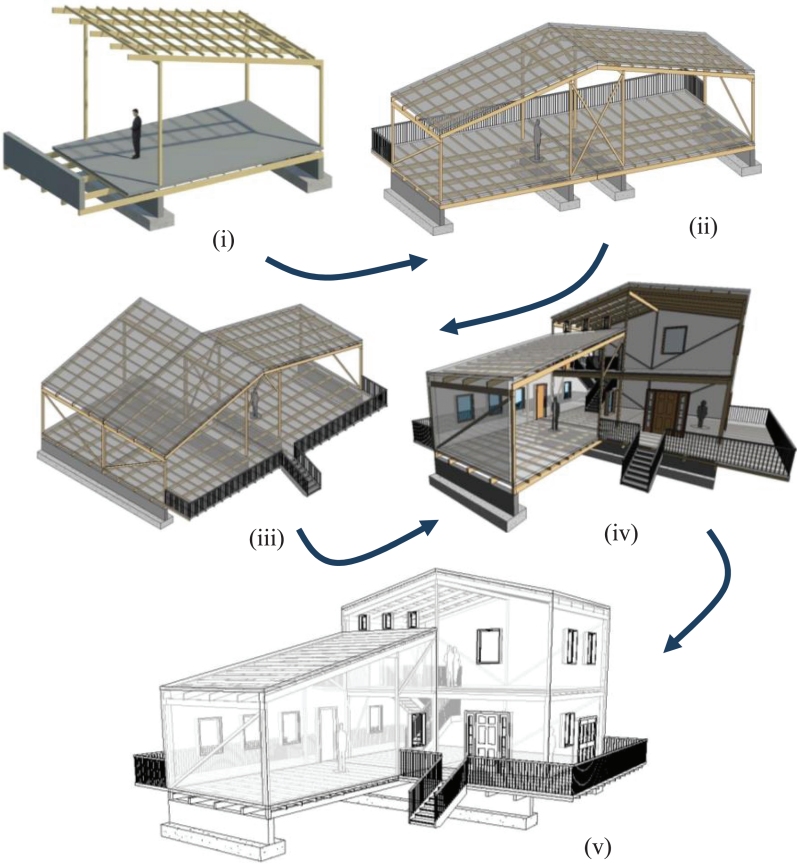


Figure 1-8. Progression in Structural Poetry.

reactions and constraints in building structures (see Figure 1-11c & 11d). Students will be able to understand concepts such as tributary areas for beams, girders and columns in visually interactive manner which can greatly stimulate the interest and motivation to explore other analysis capabilities of the tools (Nawari et al., 2011). The study can then be centered on more advanced topics such as non-linear analysis and dynamic behavior using Structural Analysis tools that are fully integrated with BIM platforms.

Teaching Methodology

To advance other types of structural knowledge, structural melodies and poetry focus on how to engage the student's imagination and to use it no less creatively than a musician or artist producing ideas. On the other hand, structural analysis concentrates on the conceptual and qualitative aspects of the structural performance. The proposed framework seeks to emphasize the value of these knowledge domains and specifically the interplay between architecture and structures as well

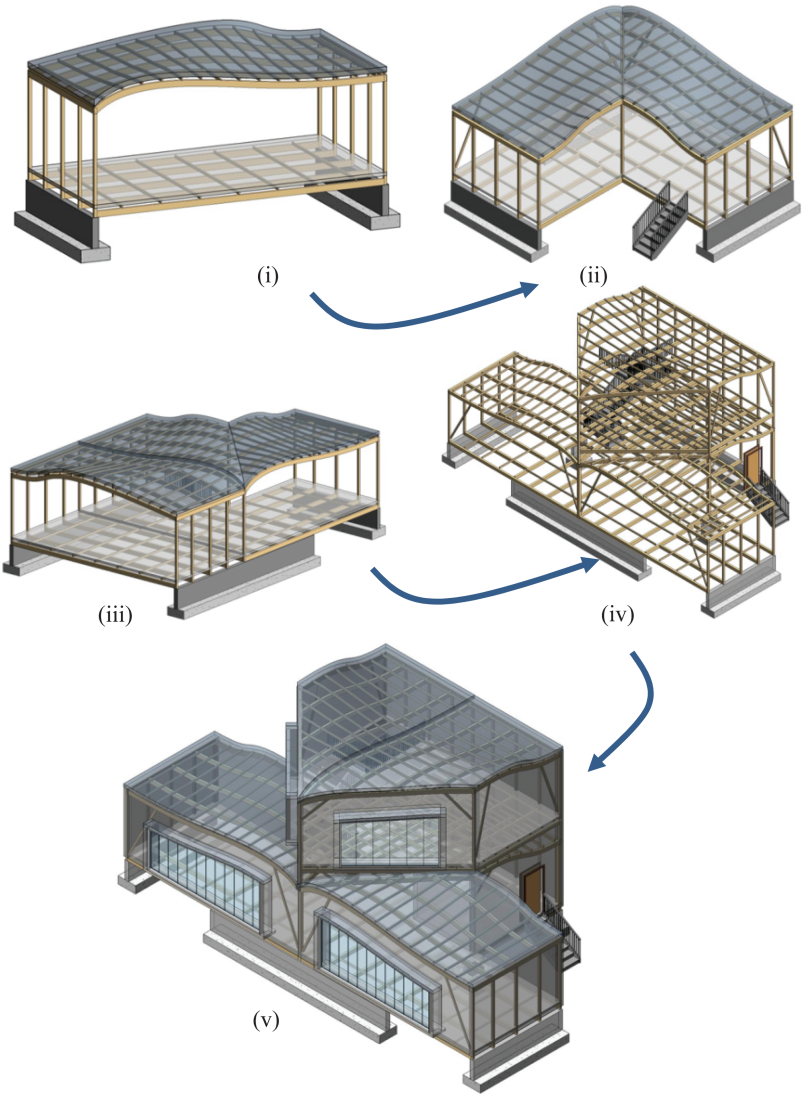


Figure 1-9. Progression in Structural Poetry.

as the qualitative understanding of structural behavior. Furthermore, the framework elaborates on improving student's ability in handling cross-disciplinary interests through use of building information modeling knowledge and other related digital tools. By approaching structural design education in this manner, several objectives can be achieved:

- First, students get exposed to the fundamentals of BIM at an earlier stage of their current core curriculum.

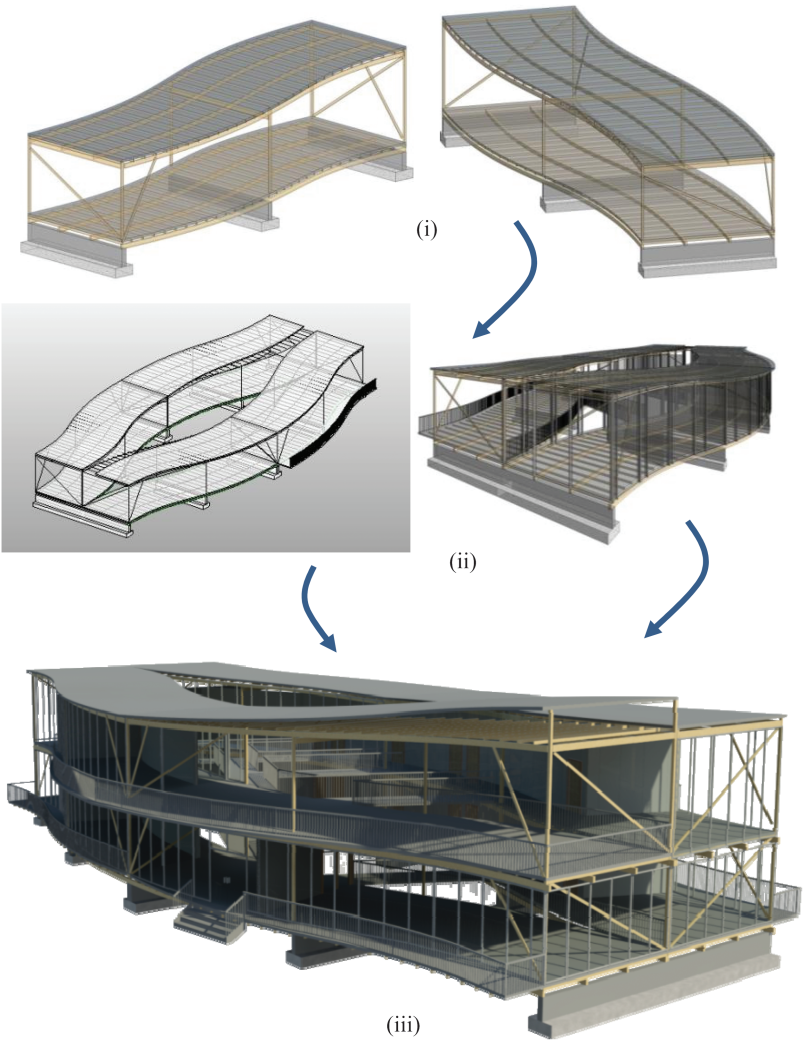


Figure 1-10. Progression in Structural Poetry.

- Second, students will explore structure as an art and thereby gain an understanding of the influence structure can play in creating form and defining spatial order and composition.
- Third, BIM introduces students to the vocabulary and hierarchy of a structural system, enabling structural decision making to be integrated early in the design thinking process.
- The proposed framework establishes the notion that structural analysis computation is primarily a tool to verify structural decisions rather than a design strategy.

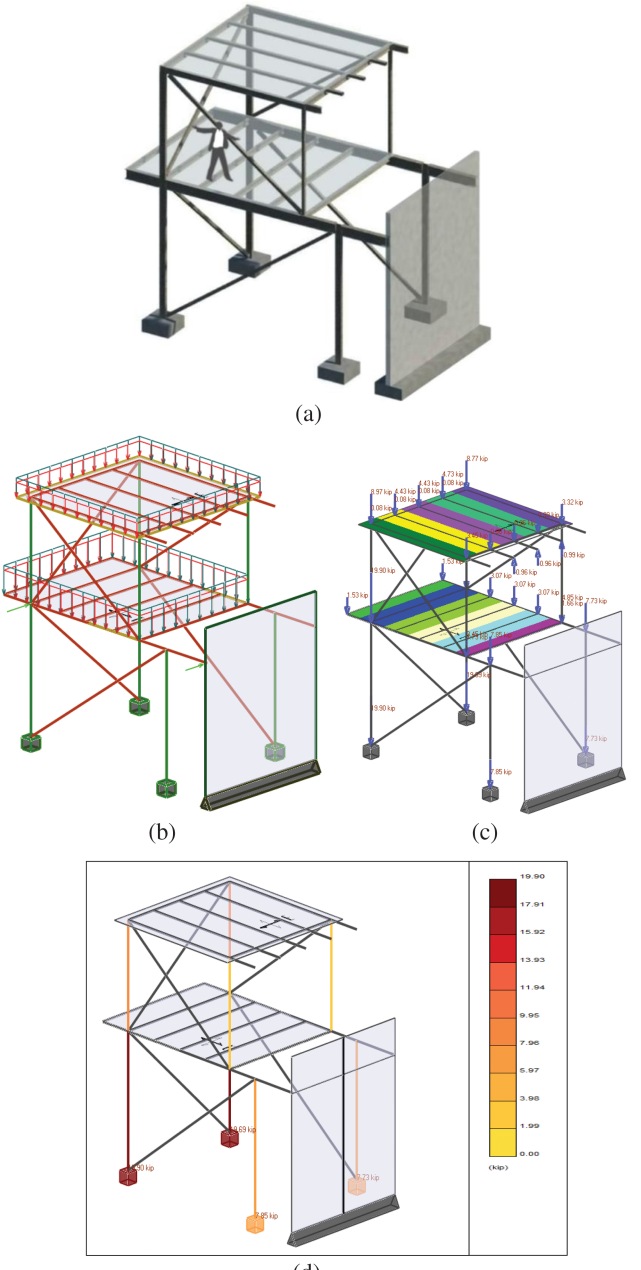


Figure 1-11. BIM Structural Analysis Tools.

- Finally, it initiates an attitude of understanding the interplay between architecture and structural systems that should continue into the students' remaining education and forward into their professional career.

TRAINING IN SAS FOR PRACTICIONER

Traditional Workflow

In a typical setting, in the US there are three types of design firms: strictly architectural firms, architecture and engineering firms, and strictly engineering firms. Quite often architectural firms specialize only in the design of buildings and outsource engineering expertise. Architecture and engineering firms' primary competency is in architectural design, but they also employ structural engineers to follow the initiation of a construction project and after approval of architectural and engineering designs. Some of these firms spend most of their time coordinating information exchanges and any additional input from owners, users, fabricators, and general contractors (see Figure 1-12). Coordination efforts start from the early phases of the project (conceptual design) to detail and fabrication phases. They mostly communicate through sending back and forth 2D or 3D CAD drawings and reports. Clearly, this current process (Figure 1-12) is highly fragmented.

The National Institute of Standards and Technology estimates billions of dollars are wasted annually due to this fragmentation (Gallaher et. al., 2004). Furthermore, this fragmentation may lead to design disputes in form of deficiencies in details, inadequate coordination, and deviations in submittals, excessive modifications, and failure of the design to meet budgetary or programmatic requirements.

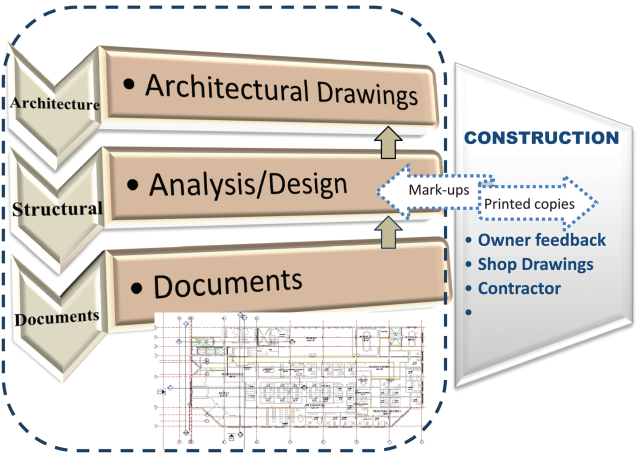


Figure 1-12. Traditional Workflow in Structural Design.

BIM Workflow and Productivity

Building Information Modeling, or BIM, utilizes cutting-edge digital technology to establish a computable representation of all the physical and functional characteristics of a facility and its related project/life-cycle information, and is intended to be a repository of information for the facility owner/operator to use and maintain throughout the lifetime of the structure (NBIM, 2007). It represents the hub of software applications that streamline the delivery process of design, detailing, manufacturing, and construction. BIM value as an integrator between the technology tools used by various AEC trades and its computational ability to manipulate the model directly, with or without human intervention is instrumental to improve productivity across the AEC industry. In a typical BIM-enabled design process, the data model serves as the principal means for communication between activities and professionals. Small and mid-size structural engineering firms find that keeping up with such technology can be overwhelming if the firm does not have a well-considered technology training and implementation plan. In addition, structural engineers are continually being asked to do more for their clients while at the same time meeting their production rate and cost.

In essence, application of BIM in the SAS framework will allow engineers to explore projects in greater depth than ever before, because a single intelligent model can be used to generate architectural models, analytical and computational models, construction documents, explore building assemblies or constructability, estimate costs, simulate building performance and even build virtual models using the latest in prototyping. Figures 1-13 to 1-14 depict examples of BIM models developed using the SAS framework to design a basic shelter for families living in extreme poverty in Latin America. In addition to aesthetics quality and overall minimum cost requirements, the design must confront the issues of heavy rain, and wind forces, as well as control heat and light. The ability of BIM tools to capture, analyze and communicate various architectural and structural details enabled the application of the SAS framework to provide a feasible and effective design solution (Figure 1-13). The successes of this design are derived from the fact that main structural and architectural constrains are examined and resolved using BIM data in conjunction with the SAS framework. The design provided also offers rapid proliferation and expansion, which manifests itself at various scales. The designed buildoid (Figure 1-13) can work on its own, or to work as a clustering pattern. Additionally, these buildoids open to extend themselves into any public spaces, while also allowing community functions (Figure 1-14).

This BIM-based design processes is fluid and collaborative. Elements of the design, such as object properties, can be created by various AEC vendors and manufacturers, and other licensed design professionals. The design may be self-modifying, and to that extent, partially self-designed as in the case of a smart truss objects that can change its member sizes in response to change in span or height. The design deliverables may be a computer model or simulation, not only paper drawings, and may be distributed between computer systems operated by different participants. The complete design may exist in a space defined by the internet,

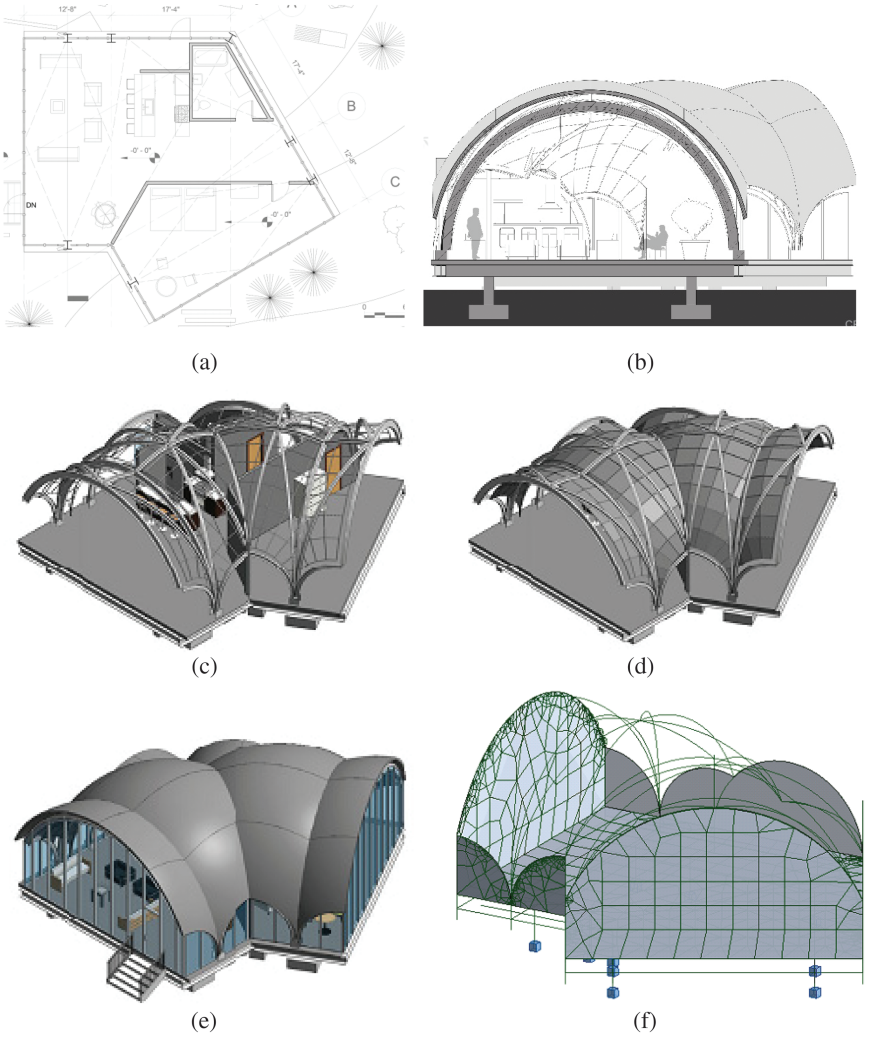


Figure 1-13. BIM model showing design results using SAS framework.

allowing concurrent access to all participants (Figure 1-15). In short, this design process is flexible, coherent and collaborative.

Some of the productivity benefits of BIM design workflow include:

- Single source of data
  - Many of the problems that are associated with the traditional workflow from the fact that various disciplines have trouble communicating with one another—particularly regarding changes in materials, approach, and scope. At its core, BIM facilitates the sharing of structural information among

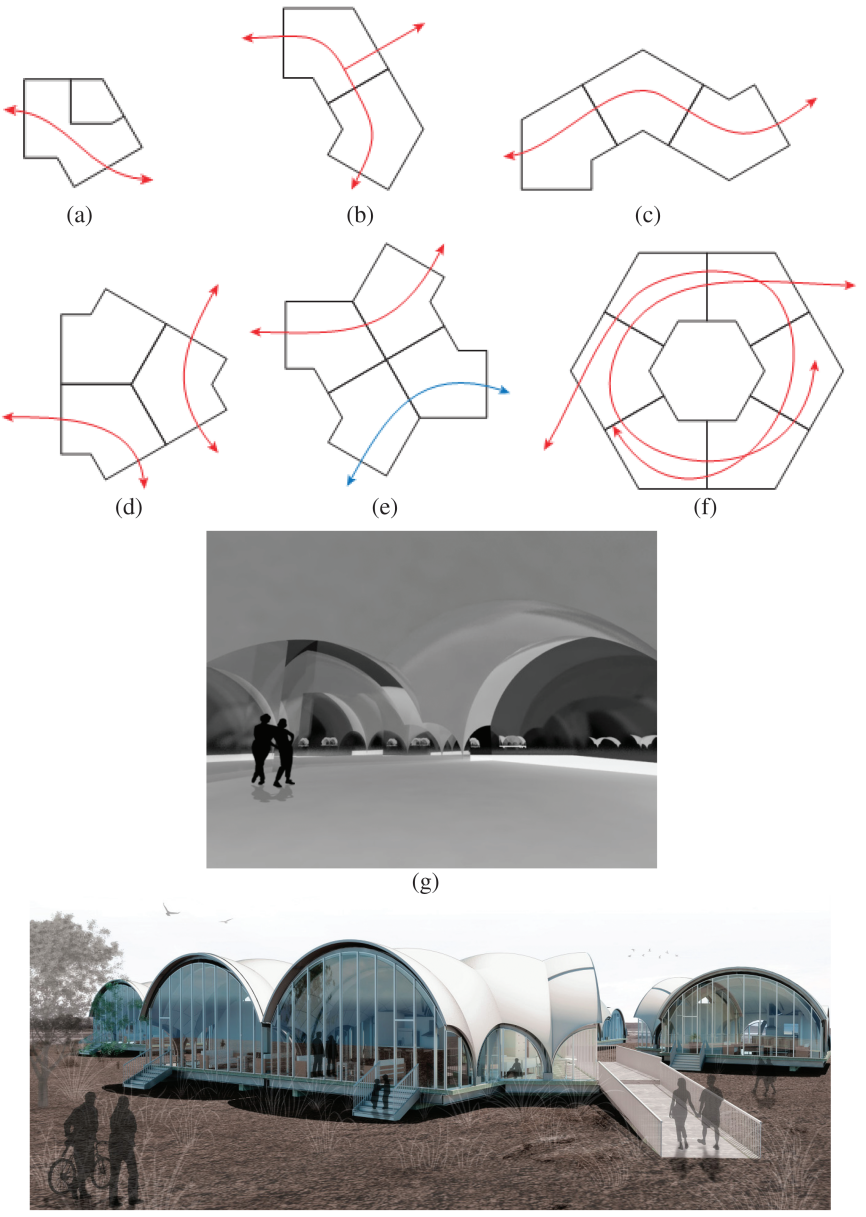


Figure 1-14. Expansion and growth using the SAS framework.

related disciplines and reduces the number of errors and omissions that flow from insufficient coordination.

– This improved coordination will allow engineers to detect clashes earlier, establish and adjust schedules more accurately and precisely and to save

precious time from work coordination and improve design coherency and productivity.

- Sharing structural details with fabricators and contractors.
- Transferring structure BIM model to the analysis software and the analysis results are delivered back into the model - keeping analysis, design, and documentation all synchronized.
- Enhanced quality of deliverables. With greater quality control of the structural design service, a higher quality product will be realized, and this will result in an encouraging experience for future clients.

The technology for exchanging information using BIM standard has now been established, but many areas require additional development before comprehensive interoperability solutions are reached. These areas include: extending the scope to include a broader range of project information, for more types of projects, and more types of information; developing the exchange mechanisms layer below the data standards and the formalized transactions level above; developing the range of software applications that implement model-based interoperability; and re-examining structural project management practices based on new integration technologies. Wood and masonry structures are examples of areas where more efforts are needed to achieve reasonable interoperability with other disciplines. Specifically, exchanging information about connections in wood, steel and masonry for structural analysis still needs extensive development.

SAS Framework in Practice

Having a command of the analytical aspects of structural engineering profession is certainly essential and fundamental, but many clients in nowadays competitive market value other skill sets, like the ability to propose elegant design alternatives, make good decisions, ability to embrace collaborative tasks, and the capability to understand a project from client's perspectives. The proposed Structure and Architecture Synergy (SAS) Framework aims to provide such skills to practicing engineers.

The proposed framework can infuse and enrich structural engineering practice in a number of ways. First, young engineers who have taken courses about the framework before graduating will have better collaborative experience in handling cross-disciplinary interests using BIM and moreover understand the interplay between architecture and structure in a more effective manner. These will result in a considerable saving for firms with respect to training cost to acquire such skills. In addition, these young professionals will have a positive impact on productivity because of their deeper appreciation of the influence structure can play in architectural tectonic, spatial composition and order, and aesthetic qualities.

Furthermore, the proposed framework can be introduced in any AEC workplace through various training options to improve creativity and productivity. These may include self-study, web-based training, video, off-site training, seminars,

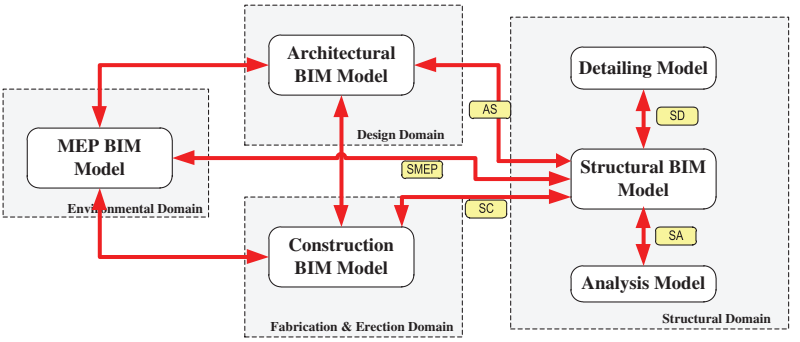


Figure 1-15. Structural BIM Workflow (Nawari. 2011).

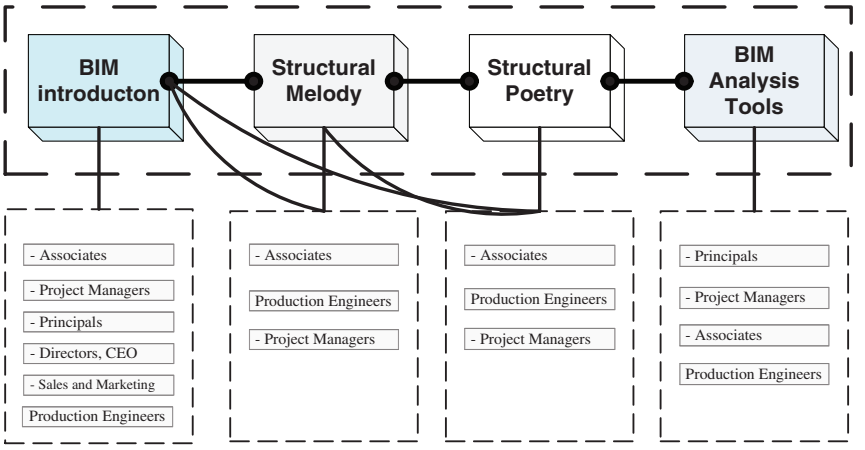


Figure 1-16. Proposed Training Modules.

on-site custom training, and in-house training. Selecting the optimum training method should be based upon the trainee background, budget, timetable, the firm culture, and workflow. Ultimately, the choice between the different training options, involves a trade-off between cost, time, realism, and other factors relative to the firm in questions. Figure 1-16 below demonstrates one method for introducing the proposed framework to AEC firms. It shows the gradual introduction of the main components of the SAS Framework to the workplace. The first course covers the introduction and BIM fundamentals. It may include, for instance, topics such as differences between drafting and modeling, the data model concept, understanding how the 3D model is built and shared in object-oriented modeling environment, comparing traditional and virtual construction techniques and identifying how virtual construction improves quality, reduces cost and enhances performance. The second and third modules cover structural melody and poetry respectively using one of BIM software platforms. The last phase of the training deals with the application of BIM structural analysis tools.

The success of the transition from engineering analytics to structural poetry and vice versa is dependent upon proper implementation of the SAS framework training. This type of training can be considered as a part of a holistic and continuous approach to productivity improvement that spans technology, processes and disciplines.

Practicing engineers and architects will benefit from the reciprocal knowledge and skills provided by the proposed framework and round out their ability to make significant contribution to their firms. Using the proposed SAS Framework in this reflective mode would advance deep understanding of the structural design, improve productivity and enrich the current practice.

CONCLUSIONS

Structural design in light of the recent advancements in object-oriented modeling requires new ways of thinking and frameworks in both education and practice. As noted by many researchers BIM education cannot be approached in a manner similar to that implemented for Computer-Aided Drafting (CAD) (Barison et al, 2010 and Sacks et al., 2013). Skill sets needed for design with current BIM technology are much different than the skill sets needed when design is done by traditional structural design workflow. In the new process, the design model developed in BIM will include all pertinent architectural and engineering design information. Data flows from the BIM to the structural analysis and design software with results coming back to update the BIM model. The AEC industry is certainly moving towards integration of information available to various disciplines. The collaborative mode is becoming standard approach in the near future. Only proper framework and training on this advanced data-sharing technology will enable effective digital practice and higher productivity.

This chapter considers the application of BIM together with the proposed Structure and Architecture Synergy (SAS) Framework to better synthesize aspects or constraints of structural and architectural design through development concepts of melodies, poetry and analysis in educational contexts. Structural melodies develop a holistic vehicle to introduce structural vocabulary, the hierarchy of structural members and the interplay between architectural concepts and structural systems such as exoskeleton, endoskeleton, stratification, transition, hierarchy and, heart of spaces. Structural melody also includes understanding the various support patterns derived from basic linear, planar and non-linear elements and how these patterns respond to the functional orgainization of the buildings.

Based on structural melodies, structural poetry strives to develop structural creativity and spatial thinking as well as enhancing the conceptual design abilities using BIM tools. At the center of this structural poetry are the concepts of buildoid and natural growth. Similar to multicellular organisms in nature, growth is not only about the volume increase of a single entity (buildoid), but also about the artistic multiplication and organization of buildoids.

BIM tools were used as the primary instruments to apply the SAS framework in structural design education for advancing other types of structural knowledge. These kinds of knowledge centers on how to engage one's imagination and to use it no less creatively than a musician or artist producing ideas. At the same time, the SAS gives emphasis to structural correctness and the quantitative engineering sciences of the structural design. In contrast to the traditional structural design education that focuses mainly on the computational aspects, the SAS framework combines various threads of knowledge; some may seem contradictory and incompatible, to arrive at structural magnificence and correctness utilizing the data management and analysis capabilities of BIM. Furthermore, the SAS framework establishes the cross-disciplinary knowledge that promotes effective collaboration between architects and engineers in a BIM design environment.

Structural engineers and architects need explicit training on this new integrated multidisciplinary design model for the era of real-time team collaborative design workflow.

The proposed SAS framework will allow engineers and architects to learn about the union of art and scientific laws, collaborative thinking, and cultivate professional qualities to meet the demands of today's as well as tomorrow's integrated practice requirements. It is a marriage in which science and aesthetic combine to fulfill some of the most basic physical and spiritual needs of humanity: safe and appealing shelters.

References

Addis, B. (2007). "Building: 3000 years of Design, Engineering and Construction." London & New York: Phaidon. 640.

Addis, W. (1990). "Structural Engineering– the nature of theory and design." Ellis Harwood, New York.

Addis, B. (2001). "Creativity and Innovation: the Structural Engineer's Contribution to Design." Oxford: Architectural Press. 138 ISBN 0-7506-4210-6.

Addis, W. (1998). "Using the history of engineering design." *Proceedings of the 20th SEED Annual Design Conference*, 97–100, Imperial College, London.

Addis, W. (1992). "Engineering History and the Formation of Design Engineers," *International Journal of Engineering Education*, 8(6), 408–412.

Autodesk (2013). "Autodesk BIM Curriculum 2013." Autodesk Inc., http://bimcurriculum.autodesk.com/structural-engineering-landing (Oct.2013).

Barison, M. B. and Santos, E. T. (2010)."BIM teaching strategies: An overview of the current approaches." *Proc., Int. Conf. on Computing in Civil and Building Engineering*, W. Tizani, ed., Nottingham University Press, Nottingham, UK, 577–584.

Bard, J. (1990). "Morphogenesis: the cellular and molecular processes of developmental Anatomy." Cambridge University Press, 1990.

Becerik-Gerber, B., Gerber, D. J., and Ku, K. (2011). "The pace of technological innovation in architecture, engineering, and construction education: Integrating recent trends into the curricula." *ITcon J. Inf. Technol. Constr.*, vol. 16, 411–432.

Billington, D. (2003). "The Art of Structural Design—A Swiss Legacy." Yale University Press.

Chappell, D. and Willis, A. (2000). "Running a Project." *The Architect in Practice*. Oxford, Blackwell Science, 98–103.

Davidovits, J. (2008). "They Build the Pyramids." Institute of Geopolymere, France. Translated by Claude James from the French Books "La nouvelle histoire des pyramides".

Gallaher, P., O'Connor, A., Dettbarn, J., and Gilday, L. (2004). "Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry," NIST GCR 04-867, U.S. Department of Commerce Technology Administration National Institute of Standards and Technology, Advanced Technology Program Information Technology and Electronics Office Gaithersburg, Maryland.

Howard, R. and Björk, Bo-C. (2008). "Building information modelling - Experts' views on standardisation and industry deployment," *Advanced Engineering Informatics*, 22(1), 271–280.

International Alliance for Interoperability (IAI), buildingSMART International, http://www.iai-international.org. (Nov. 2012).

Industry Foundation Classes (IFC), http://www.iai-tech.org (publication of the IFC specification).

Khan, Y. S. (2004). "Engineering Architecture: the vision of Fazlur R. Khan." New York, W. W. Norton & Company.

Nawari, N. O. (2011). "Standardization of Structural BIM," publication in the Proceedings of the 2011 ASCE International Workshop on Computing in Civil Engineering, 405–412, June 19–22, 2011, Miami, FL.

Nawari, N. O., Itani, L., and Gonzalez, E. (2011). "Understanding Building Structures Using BIM Tools," *Proceedings of the 2011 ASCE International Workshop on Computing in Civil Engineering*, 478–485, June 19–22, 2011, Miami, FL.

NBIMS (National Building Information Modeling Standard), Version 1, Part 1 (2007). "Overview, Principles, and Methodologies," National Institute of Building Sciences. 12/2007. http://www.nationalcadstandard.org/

Nervi, P. L. (1965). "Aesthetics and Technology in Building." Harvard University Press.

Önür, S. (2009). "IDS for ideas in higher education reform." *Proc., 1st Int. Conf. on Improving Construction and Use through Integrated Design Solutions*, VTT-Techniocal Research Centre of Finland, Espoo, Finland, 52–71.

Oxford Dictionaries (2010). "New Oxford American Dictionary," Oxford University Press. 2010.

Salingaros, Nikos Angelos and Mehaffy, Michael W. (2006). "Rules of Beauty and Order in Past Times." *A Theory of Architecture. Solingen: Umbau-Verlag*, 2006, 29–30.

Prowler, D. (2012). "Whole Building Design." The Whole Building Design Guide (WBDG), The National Building Institute, http://www.wbdg.org/wbdg_approach.php

Rafiq, Y. (2010). "A Radical Rethink in Educating Engineering Students." *Proceeding of the 19th Analysis & Computation Specialty Conference*, ASCE, 366–376, 2010, Orlando Florida.

Sacks, R. and Barak, R. (2010). "Teaching building information modeling as an integral part of freshman year civil engineering education." *J. Prof. Issues Eng. Educ. Pract.*, 136(1), 30–38.

Sacks, R. and Pikas, E. (2013). "Building Information Modeling Education for Construction Engineering and Management. I: Industry Requirements, State of the Art, and Gap Analysis," *J. Constr. Eng. Manage. ASCE*, 139(11), 04013016.

Sandaker, B. N. (2008). "On Span and Space: exploring structures in architecture," Routledge, Taylor & Francis Group.

Schueller, W. (1995). "The Design of Building Structures," Prentice-Hall.

Schueller, W. (2007). "Building Support Structures: Analysis and Design with SAP200 Software," Computer and Structures Inc.

Sharag-Eldin, A. and Nawari, N. O. (2010). "BIM in AEC Education" *2010 Structures Congress joint with the North American Steel Construction Conference in Orlando*, Florida, May 12-15, 2010, 1676–1688.

Sinnott, E. W. (1960). "Plant Morphogenesis." McGraw-Hill Book Company, New York, Toronto, London.

Viollet-Le-Duc, Eugène-Emmanuel. ([1854] 1990). "The foundations of architecture." New York: George Braziller Inc. (Translated by Kenneth D. Whitehead from the original French.)

Viollet-Le-Duc, Eugene-Emmanuel (1990). "The Architectural Theory of Viollet-Le-Duc: Readings and Commentary." M. F. Hearn (editor), The MIT Press.

Waldrep, Lee W. (2006). "The Education of an Architect." *Becoming an Architect: A Guide to Careers in Design*. Hoboken, NJ: J. Wiley & Sons.

Wong, K. A., Wong, K. F., and Nadeem, A. (2011). "Building information modelling for tertiary construction education in Hong Kong." *ITcon J. Inf. Technol. Constr.*, vol. 16, 467–476.

CHAPTER 2

BIM-based Model Checking (BMC)

Eilif Hjelseth*

Abstract: *This chapter presents Building Information Model (BIM)-based model checking (BMC). BMC is often referred to as one of the major benefits in utilizing BIM, where everyone can perform compliance checking and design coordinating. Wide use of BMC software in BIM-based projects should therefore be expected. This study is based on a broad approach, ranging from exploring principles of model checking to practices in state-of-the-art companies, in addition to reviewing commercial software. Outcomes indicate that functionality in commercial software covers requirements for model checking in projects based on the use of simple rules and unspecified content of information in the BIM-file. Improved collaboration based on coordinating merged BIM-files and automatic clash detection was regarded as the main benefit. BMC was regarded as a part of company quality assurance systems for model coordination. Wide use was not observed, and the use of BMC software was regarded as a specialist tool operated by a limited number of users. This study indicates a potential for the further development of rule sets and procedures for trustworthy compliance checking. In this respect, BMC can be regarded as a catalyst for the exchange of high-quality BIM for cross-disciplinary collaboration. Utilization of BMC can be an indicator of BIM-maturity.*

INTRODUCTION

BIM-based Model Checking (BMC)

BMC is the process which processes the content of information in BIM-files according to rules specified as pre-defined procedures. The components in BMC consist of three components: software, rule sets, and BIM-files. This division into the components enables to focus and improve each of the components – and the

*Department of Mathematical Sciences and Technology, Norwegian University of Life Sciences (NMBU), P.O. Box 5003. NO-1432 Aas, Norway; Phone (+47) 64 96 54 00; Fax (+47) 64 96 54 01; email: eilif.hjelseth@nmbu.no

relation between the components. BMC is therefore not only solved by buying software and hit the 'checking' button.

BMC is perhaps one of the best ways to illustrate the power of relevant information in BIM-files. Model checking explores the content of information in BIM-files in a transparent way. Statements like improving the BIM by enriching the model and increasing the amount of information are not valuable unless the information is relevant for the information required to process the rule. The rule must also be relevant for what one intend to check. The development of new rules, or adaptation of existing rules, is often required.

This aspect can also be used to illustrate the distinction between BM (Building Model/3-D model) and BIM with a focus on the '*I in BIM*', where I stand for information. The BIM community is in its expansive phase, and proponents are claiming that BIM in general, and model checking in particular, will be a game changer. The approach in this chapter tries to be more balanced. The opportunities are great, but this requires a high degree of input of relevant information from BIM-files and advanced, precise rules for processing. The maturity level in exchanging BIM-files with a highly specific content of information is currently low.

Structure of This Chapter

This chapter has a broad scope and is structured into several parts. The first part provides examples of BMC. The importance of BMC is documented with reference to several studies. This part also intends to give the use of BMC a position as something more than being skilled in use of software. Organizational aspects must be taken into account. The second part introduces principles and classification in the use of BMC. The close relation to BIM is included in this part. The third part gives an overview of commercial BMC software. BMC has a number of aspects, and the final part explores what can be checked – and what cannot be checked. This part focuses on the important development of rule sets for enabling advanced model checking. It includes a study of state-of-the-art companies in Norway as well as their experiences and suggests future development.

EXAMPLES OF BMC

Clash Detection

Use of BMC, or model checking, is often used synonymously with clash detection. Clash detection is a useful way to demonstrate the benefits of BIM in model checking software, such as Navisworks from Autodesk or Solibri Model Checker from Solibri. Clash detection in the BIM is one of the most common ways to demonstrate the practical uses of BMC. BMC replaces or supports the traditional quality assessment of drawings. Quality assurance (QA) is a key aspect in BMC. Figure 2-1 shows an example of a conflict between a structural beam and a ventilation duct.

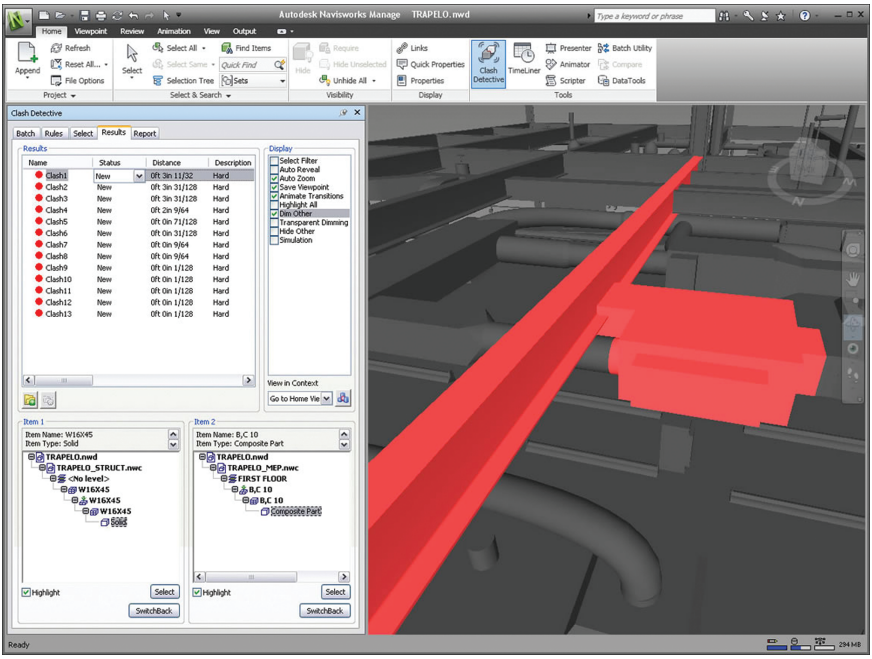


Figure 2-1. Clash detection by use of Navisworks software (Courtesy: Navisworks 2013).

This important issue would probably have been detected by visual checking. The benefit from BMC is often more significant if the issues are many, small, and hard to visually identify. BMC testing gives identical results every time it is processed and has a higher reliability (quality) than visual inspection.

One practical problem of automatic clash detection is that it can provide too many false issues. The QA responsible must then spend time sorting relevant issues from non-relevant issues. BMC software has features to handle this in an efficient way. The background for this over-reporting is the attitude that it is better to report ten times too many issues than miss one issue. The technical background is that the rules for clash detection are coarse, and the precision of information in BIM files is not specific enough.

However, BMC can be used in a large number of tasks. The 'BMC = clash detection level' can be more like a plateau – a comfortable level to stay within without seeking solutions above that level. BMC has an unrealized potential for solving new types of problems in new ways. This future-based aspect is covered later in this Chapter.

Smart BMC

The general challenge for BMC, and particularly clash detection, is massive reporting of non-real issues – which has to be dismissed manually. Model-checking

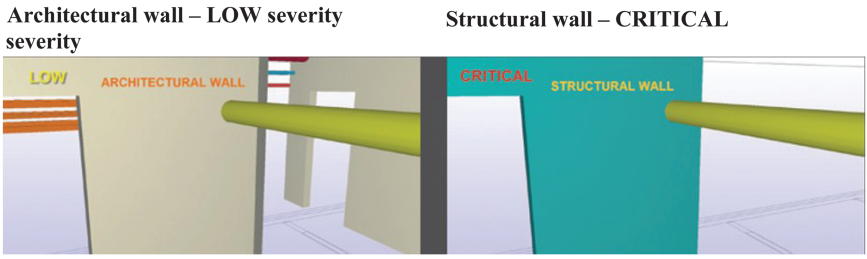


Figure 2-2. Rule-based reasoning used to assess impact of rule violation, case: wall-pipes interference (Courtesy: Solibri 2010).

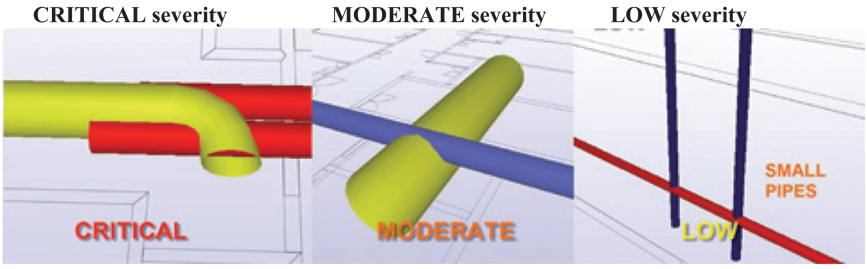


Figure 2-3. Rule-based reasoning used to assess the impact of rule violation, case: pipes of different diameter (Courtesy: Solibri 2010).

software has a function for marking the issues as not relevant. Severities of issues are often graded by degree of deviation from the rule constraints, not from technical or economic impact. The information in the BIM file enables BMC software to grade the issues by other criteria, like the type of wall. Figure 2-2 illustrates reasoning to assess the impact of rule violation. Interception of a structural wall may be critical while an architectural wall may be cut without severe impact. In a proper object model, the wall type will be derived from the class of the wall object.

Figure 2-3 shows examples of 'Critical', 'Moderate' and 'Low' severity issues. Interference between small pipes is considered low severity since that is possible to fix on site. Rule-based reasoning contributes significantly in addressing the most relevant issues first and when required. However, it is not always obvious that small pipes are easy to move. An example is pneumatic dispatches in hospitals, for which bends are to be avoided. Rule-based reasoning can improve model checking.

BMC Software as Coordination and Reporting Tools

Coordination of models from different disciplines in the design and construction process is an important feature of BMC. BMC software such as Navisworks and Solibri have features for merging BIM-files into a single common coordinated

model. Reports can be exported in PDF, XLS, or BCF format. The BIM collaboration format (BMC) introduces a workflow communication capability connected to IFC models. The idea is to separate communication from the actual model. The BCF format is based on XML (Stangeland 2011).

ADOPTION OF BMC IN THE CONSTRUCTION INDUSTRY

High Expectations in the Construction Industry

Eastman stated in the status report from McGraw-Hill Construction (2012) that model checking is the most important current BIM requirement to effectively advance the industry, followed by improved interoperability. Increased model quality with correct solutions is a great motivation for using BMC. Another rationale for model checking is to provide models free of issues so that data can be trusted when used in other software and processes.

A study from the AutoCodes project (Fiatech 2012) in the International Code Council (ICC) illustrates that manual checking gave uncertain answers. The number of issues flagged by various jurisdictions differed widely. When one jurisdiction raised one single issue, another raised 43 issues. A lesson from this study is that what is manually checked or not checked is actually undefined. Sawyer (2012) expressed that analysts only know what they found in a manual review, but did not really know what they actually looked at in the review. BMC processes pre-defined rules, so the scope of review is determined by the selected rule set. One consequence is that a situation which lacks rules will not be checked. Knowing the scope of all rules in a rule set is important for a trustworthy review. A survey of 139 projects indicates that design issues increased direct costs by 6.9% and indirect costs by 7.4% of the total contract value (Lopez and Love 2012). A study by Conover (2007) showed that on average, 3% to 5% of the design time of a construction project is currently devoted to code-checking, and even then, not everything is checked.

Status reports from McGraw-Hill Construction (2012) point out more clearly defined BIM deliverables between parties as one of the five top-rated areas for improvement. High-quality BMC can be a deliverable. A more pervasive benefit of BMC is presented in a video from the AutoCode project by Fiatech (2013). This video illustrates that time spent on code checking can be reduced from months to minutes. ICC board president Ronald Piester says that automated code checking helps reviewers focus on the core tasks of code compliance and speeds up the permitting process. Piester says that this innovative technology will provide comprehensive and consistent results from project to project across jurisdictions and allow code officials to dedicate more time to safety issues, inspections, and other important duties (Fiatech 2012). Architects on average spend almost 50 hours per project on code checking, and 11% spend more than 100 hours. Approximately 85% of architects are positive about working with model checking software to support the code checking process (McGraw-Hill Construction 2007).

Public Services and BMC

Building authorities look at BMC as a concept for the automatic processing of applications. This type of validation requires transforming regulations into computable rules for processing building permit applications. So far, only a limited number of projects have been completed, but this is expected to change significantly in the near future. An international state-of-the-art survey by Refvik (2013) identified projects in Korea, Japan, and further development of existing solutions in Singapore, the UK, and Norway. BMC was reported to be included in future solutions but was currently not a part of the verification of applications. The existing solutions were based on verification of application forms filled in manually. This chapter does not focus on software solutions for public purposes since most countries will develop their own software solution for processing based on national requirements. These types of software solutions will also include a large number of administrative services in addition to compliance checking based on input from BIM-files and other sources. Use of commercial software will therefore not be relevant for these types of solutions. BMC was intended to be solved by use of model server technology.

According to Shih et al. (2013), public authority provides a foundation for the development of code-checking systems using BIM to assess compliance with building codes. Not only do code checking systems have the potential to enhance designers' awareness of building codes, but they also have the potential to improve collaboration and communication among project stakeholders.

PRINCIPLES OF BIM-BASED MODEL CHECKING (BMC)

The Components of BMC Systems

A BMC system consists of three parts: software, BIM files, and rule sets. Figure 2-4 illustrates the integrated relationship between logic in a rule set, the content of information in a BIM file and functions in model checking software.

- Software includes the service and function enabling import of BIM files, processing of rules, visualization and reporting of issues. An overview of software is presented later in this chapter.
- The quality of the BIM file, measured as the structure and content of relevant information, is of high importance for reliable model checking. This must comply with requirements in the rule to avoid the 'garbage in-garbage out' syndrome. BIM guidance and similar specification of content in the BIM file can be used to address the specification of information.
- Rule sets are collections of rules within one topic, such as BIM validation (clash detection), space validation, identifying updates between different versions of the design, comparing the structural versus architectural model, MEP solutions, and content in BIM file (Statsbygg BIM guidance). Today, the rule-set is a part of the commercial software package. It is often possible to

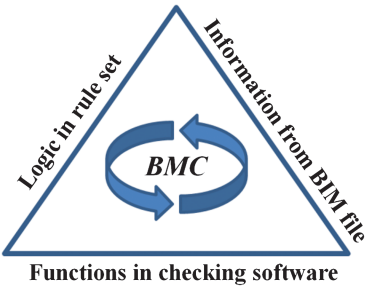


Figure 2-4. Development of BMC solutions illustrated as interactions between rule set, BIM file and checking software.

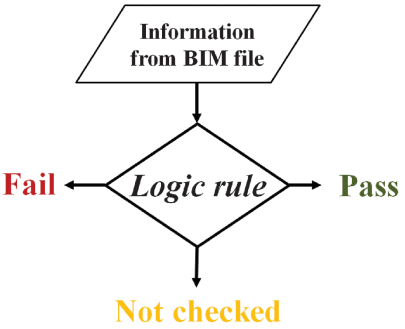


Figure 2-5. Principle of BMC.

update and change the embedded rule set to adapt to requirements in the project. A separate study of rule set for content checking is presented in the 'Survey of automatic checking of Statsbygg's BIM requirements' section. The AutoCode project from Fiatech (2012) can be regarded as an example of the separate development of rule sets.

Logic in BMC

A rule is basically a simple logic question answered with 'Yes', 'No', or 'Not checked' if not activated due to missing information. The flow is illustrated in Figure 2-5. BMC uses information (geometry, text, numbers, and relations) from the BIM file as input for processing the rules. An example of checking would be: 'Check if the door width is equal to or more than 800 mm'. If the BIM file contains information about a 'door object' with a property named 'door_opening_width' (also used in the rule) with the value '800 mm', then the result is 'Pass'. If the value is '750 mm', the result is 'Fail'. If the BIM file does not contain information about the property 'door opening width', or this is specified as 'width-of-door', then the outcome is 'Not checked'. Exact correspondence between content of information in the BIM file and required information in the rule is essential.

BMC in Authoring (Design) Software

BMC does not have to be done in separate software. Object-based or BIM-based software has embedded rules for model-checking. These rules are, for example, that a door or window must be placed in a wall, or that a wall cannot start or end in a door or a window. However, further development of design rules can be regarded as part of the BMC concept.

Modelling Practice—Content and Structure in BIM Files

Another example of poor modelling is a stair modelled as a number of small slabs. This influences quantity-take-off and model checking, but not necessarily the visualization. The quality of information, regarded as correspondence between the BIM file and rule, is addressed in this chapter. Information in BIM can be adjusted by the classification functionality in the model checking software or by adding objects and/or attributes in the BIM authoring tool (e.g., Revit, ArchiCAD, and others), and then redoing the BMC.

CLASSIFICATION OF BMC

Harmonized Understanding of BMC

BMC can be used as a wide and inclusive term, enabling BIM to cover both simple clash detection and the advanced code compliance verification processes. Compliance checking, rule checking, code checking, clash detection, collision control, and validation control are used as synonymous terms for model checking, but without further specification, precise and joint understanding can be hard to achieve.

To support joint understanding, the following two frameworks are introduced:

- **Framework: The four types of model checking concepts**
  Model checking is not a clearly defined term. It is primarily understood as clash detection or compliance checking, but this understanding limits the scope of model checking. Table 2-1 from Hjelseth and Nisbet (2010) presents a framework, which extends the use of model checking into four main categories based on intention and type of result.

  A) *Compliance model checking.* This is the "default" understanding of BMC (and therefore important to be aware that this is not the only one). This type of checking is based on comparing the model with pre-defined criteria. An example of this type of rule says that a minimum acceptable door width is 800 mm or more. Compliance is reached if the minimum width is larger than required width.

  B) *Guidance.* The intention of this concept is to guide the designer to consider a larger range of most-used solutions according to best practice rules. This is particularly relevant in spheres where the designer is not an expert. The checking is based on two elements: rules which identify the

Table 2-1. Framework for model checking concepts (modified version based on Hjelseth and Nisbet 2010)

Intention with model checking	*Checking*	*Result*
A) validating compliance	Compliance	pass/fail
B) guidance to technical solutions	Guidance	proposal
C) adaptation of objects	Intelligent objects	adapted object
D) validating content of information	Content	present/missing

situations where problems occur, and a presentation of a list of possible solutions. This type of checking is closely related to best practice a decision-support systems, but so far this concept has not been implemented within the construction industry.

C) *Adaptive model checking.* Active objects or intelligent objects are an alternative description for this type of checking. The intention is to let the object itself register its environment and then adapt automatically by following embedded behavior rules. Adaptive model checking can be divided into object adaption and system adaption. One example at object level implemented in most BIM authoring tools can be a rule that says you must always place doors or windows in a wall. This, and likewise features, are implemented in most BIM authoring software. One example at the system level could be if the building shall comply with accessibility regulations, all door widths have to be adjusted to be a minimum of 800 mm.

D) *Content checking of information in BIM file.* Content checking can be regarded as a declaration of delivered information. The intention here is to examine the BIM model for a specific purpose. The filtering rules can be used for reporting relevant information. The information can be further analyzed in BMC software, spreadsheets, word processors, and databases in flexible ways. The use of Construction Operations Building Information Exchange, COBie (East 2013), can be regarded as a light variant of this type of model checking. An example of implementation is presented in the 'Study of degree of automatic processing of Statsbygg's BIM requirements' section later in this chapter.

- **Framework: Taxonomy for classification of BMC maturity**
  BIM based model checking can be from simple clash detection as supplement for manual checking, to checking of multiple integrated models who replace manual checking. However, it is so far not established a joint terminology that states level of model checking, and this make it difficult to understand the extent in use of BMC. This chapter presents a framework to determine level of BMC. Research by Succar (2009) about BIM maturity has been used as framework for development for the five level BMC maturity model. An overview of the five levels and corresponding description is presented in Table 2-2.

Table 2-2. Levels of BMC maturity

Level	*Description*
Level 5	pervasive model checking
Level 4	integrated model checking
Level 3	specific purpose checking
Level 2	adjusted model checking
Level 1	clash detection checking

Note: This framework for BIM maturity covers type A) validating compliance checking and checking of type D) validating content of information from previous section.

These five levels are used as label for classification of BMC maturity. The taxonomy for classification of levels of BMC maturity is based on two criteria (taxa):

- content of information in the BIM file (increased 'the I in the BIM')
- complexity in the rules/rule set (increased intelligence in the rules)

The relation between these two criteria is illustrated in matrix in Figure 2-6.

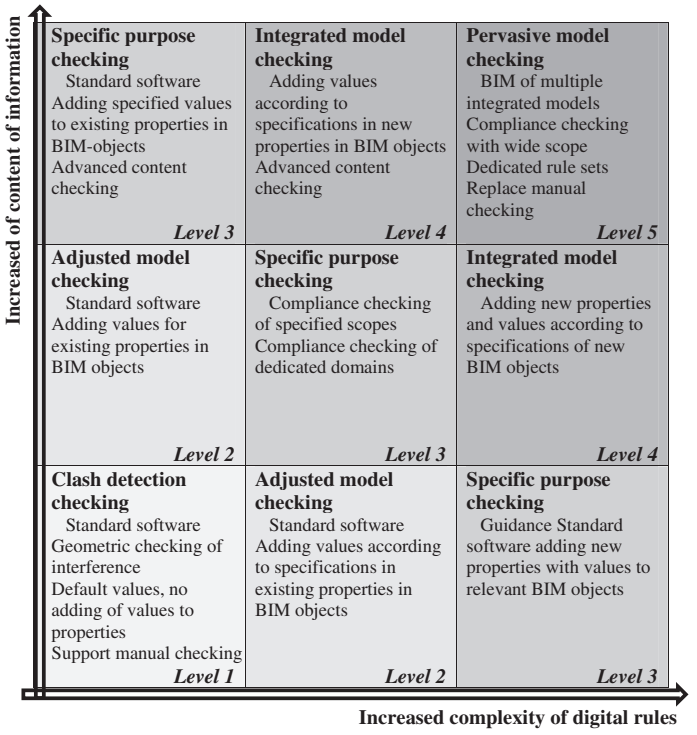


Figure 2-6. Classification of levels of BMC maturity.

Table 2-3. Overview of BIM-based model checking software

Software		*Link for more information*
Commercial	Autodesk Navisworks Manager	http://www.autodesk.com/products/autodesk-navisworks-family/overview
	Bentley Projectwise Navigator	http://www.bentley.com/en-US/Products/ProjectWise+Navigator/
	Commercial BIM-servers	more developers–no one listed
	dRofus – Nosyko	http://www.nosyko.no
	Solibri Model Checker	http://www.solibri.com
Free	BIM-viewers	http://www.ifcwiki.org/index.php/Free_Software
	Open source BIMserver	http://bimserver.org
	Tekla BIMsight	http://www.teklabimsight.com

The level of BIM can be classified based on content of information and complexity in the rules. Classification into middle levels; 2, 3 and 4, of maturity can be achieved by with variation of the two criteria. Which of the criteria is highest will be related to the use in projects. Benefit from use of BMC can be achieved from level 1.

BMC SOFTWARE

Overview of Software in the Study

The history of BMC is closely related to the development of BIM in general and specially to openBIM using the IFC format. The development of BMC software is therefore fairly new, with an increasing number of software developers. The Autodesk product that Navisworks has used for over ten years for clash detection uses input from various formats. Solibri can be regarded as the first true openBIM-based model checking commercial software accepted in the market. Table 2-3 gives an overview of some BIM-based model checking software.

Overview of Functions in BMC Software

Table 2-4 gives an overview of functions in BMC software. The overview does not test the quality or user friendliness for the software functions. This is not a test ranking the best software, as this depends on the purpose of checking.

SURVEY ON AUTOMATIC CHECKING OF RULE SET

Content and Development of Rule Sets

Khemlani (2011) points out that rule sets are the cornerstone of BMC. The International Code Council (ICC 2009) presented SMARTcodes as the 'Tools of Today and Tomorrow' in 2009. The concept of intelligent codes (SMARTcodes) is an initiative of the ICC in coordination with the buildingSMART Alliance. The objective was to automate a code compliance check, which takes the building plan as represented by a building information model (BIM) and instantly checks for code compliance via model checking software. This project ended in 2010 due to lack of funding (Refvik 2013).

The proof-of-concept report from the AutoCode project in March 2012 by Fiatech indicates that this aim is still relevant. 'ICC and Fiatech are committed to completing this long-term project', said ICC CEO Dominic Sims. Using technology for code checking is a win-win for the jurisdiction, designer, and property owner, according to Fiatech (2012). This project was highlighted in the study by Refvik (2013) as an important contribution for the development of computable rules. Projects like AutoCodes can therefore have significant importance for the development and implementation of digital rule sets in BMC software. The market for rule-set is currently limited as it was with BIM objects (windows, doors, and furniture) some years ago.

Developers of BMC software offer different packages adapted to design and professional disciplines. There are a number of barriers, such as no standardized procedure for converting design rules and regulations into digital rules. BIM guidelines are mainly developed by national organizations like GSA (2007) and NBIMS (2012) in the US, BSI (2013) in the UK, Senate (2012) in Finland, CRC (2009) in Australia, and Statsbygg (2011) in Norway.

BuildingSMART International has developed a number of specifications for content in BIM files called Information Delivery Manuals (IDM 2013). The American Institute of Architects has established the 'Level of Development' (LOD) as a useful framework for specifying required information (AIA 2012). Due to their focus on specific information, these types of specifications act as a foundation for developing rule sets. Statsbygg has also taken the initiative to develop a rule set in the Solibri Model Checker based on their BIM guidance version 1.2. This initiative is presented in the next section.

The following ISO standards can be used for advice or as guidance in the development of digital rules. ISO 29481-1:2010 Building information modelling – 'Information delivery manual – Part 1: Methodology and format' (ISO29481-1: 2010) presents principles for business rules and validation rules in Clause 5. ISO TS12911:2012, 'Framework for building information modelling (BIM) guidance' (ISO TS 12911: 2012) points out control as one of three key elements for specification of information. As this selection of highly relevant resources illustrates, model checking has a strong focus on BIM guidance and standards.

Table 2-4. Overview of functions in BMC software

	Software						
Functions	*Solibri Model Checker*[2)]	*Autodesk Navisworks Manager*	*Bentley Projectwise Navigator*	*Tekla BIMsight*	*dRofus Nosyko*	*Open source BIMserver*[4)]	*Free IFC viewers*[5)]
Functions							
Clash detection	x	x	x	x		x	
Compliance checking	x				x	x	
Content checking	x				x	x	
Search function	x	x	x	x	x	x	x
Reporting	x	x	x	x	x	x	
Quantity take off	x	x	x		x	x	
Time liner		x					
Animations		x					
Exchange formats							
Import of BIM file	IFC, DWG	Almost all formats	DGN, DWG, PDF,[3)]	IFC	IFC	IFC	IFC, DWG, others
Direct link Revit		x			x		
Direct link ArchiCAD	x						
Export of reports	PDF, XLS	PDF, HTML, XLS	PDF			IFC, others	

(Continued)

Table 2-4. Overview of functions in BMC software (Continued)

	Software						
Functions	*Solibri Model Checker*[2)]	*Autodesk Navisworks Manager*	*Bentley Projectwise Navigator*	*Tekla BIMsight*	*dRofus Nosyko*	*Open source BIMserver*[4)]	*Free IFC viewers*[5)]
Rule sets							
Separate rule sets	x				x	x	x
Modify existing rules	x	x		x	x	x	
Combine rules to new rule sets	x				x	x	
Develop new rule sets					x	x	–
Cost							
License cost[1)]	Pro	Pro	Pro	Free	Pro	Free	Free

Notes:
[1)]Software license may vary depending on local/national market. Pro indicates that the cost of license is high and for permanent use in the company, not for use in only one (small/limited) project.
[2)]Solibri has developed integration with COBie (AECMAGAZINE 2013).
[3)]Bentley Projectwise Navigator can import point cloud data (Bentley 2012).
[4)]Services have to be programmed as database queries.
[5)]Viewers are free and can be used for viewing the BIM. Viewers are easy to use and can reduce the need for drawings on site. The viewing model is also possible on tablets.

Automatic Processing of Statsbygg's BIM Requirements

This study focused on the degree of automatic processing of digital rule sets based on the BIM guidance from Statsbygg, Norwegian Public Construction and Property Management Agency. Statsbygg has developed BIM guidelines since 2008, and the current version, 1.2, is their third edition. It is available in both Norwegian and English versions (Statsbygg 2011). BIM guidance is used as a mandatory requirement for BIM projects. The BIM guidance document contains 131 requirements for the specification of information in the IFC file. These requirements were implemented as a separate rule set by Solibri Model Checker, and are included in Version 7 and newer. After first glance in Solibri Model Checker, it is easy to believe that all requirements in the BIM manual version 1.2 from Norwegian Statsbygg are implemented and can be checked automatically. However, it is quite demanding to develop computable rules, and it is therefore too optimistic to expect that all requirements are directly computable.

To determine the degree of processing, all rules in this rule set in Solibri Model Checker explored and classified whether the requirement was able to be:

- *Automatically processed*. The requirement in the BIM guidance corresponds directly with IFC data model. The rule can be processed automatically to fulfil the requirement.
- *Partly automatically processed.* The requirement in the BIM guidance corresponds partly with IFC data model. The rule is processed, but fulfilment of the requirement must be verified manually.
- *Suggested to be processed manually*. The requirement is not implemented as a processable rule but only as information in the rule set. The requirement requires either information that is not specified in the IFC data model (e.g., Norwegian specifications) or is too complicated (or expensive) to be implemented as a rule. The requirement must be verified by manual inspection of the building information model (e.g., by looking at the file in an IFC viewer).
- *Requirements was not specified or documented*. There was no information about the requirement, just missing from the rule set. The user must find the BIM guidance document and interpret the requirement, whether this is relevant in the project and where it can be verified manually.

The results from this study are presented in Figure 2-7.

This rule set is based on input of information in an IFC 3x2 file IFC file. The outcome identified that 35% of requirements could be automatically checked, 13% partly automatic/manual, 33% could only be checked manually, while 19% of the requirements were not implemented as digital rules at all. This indicates that approximately half of the requirements can be checked automatically and verified, while the other half of the requirements have to be checked manually. It is therefore important to be aware that only parts of the requirements can be checked automatically. This type of model checking

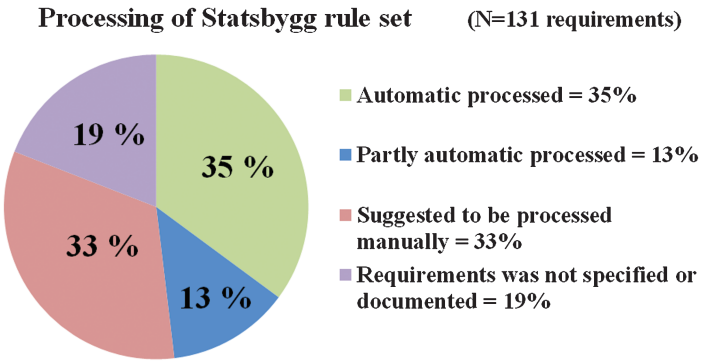


Figure 2-7. Distribution of processing of BIM requirements in Norwegian Statsbygg BIM guidance Version 1.2.

can be regarded as an example of 'content checking of BIM file' previously presented in this Chapter.

Degree of Automatic Checking of Regulations

Hjelseth (2012) performed a study of the ISO21542:2011 accessibility and usability standard (ISO21542:2011), which identified 720 rules within the 152 pages. The study showed that 57% of the rules were prescriptive and could be directly converted into computable rules. Of the remaining rules, it was possible to transform about half of them into computable rules for automatic processing. The transformation was done by a mapping method. The conclusion of this test was that 17% of the total number of rules had to be interpreted manually, while 83% were applicable for BMC. The result indicates that performance-based regulation is not a barrier for BMC.

Practical use of this type of checking can be illustrated by the Solibri Model Checker, which has implemented Clauses 8, 10, 11, 12, 13, 18, 19, 26, and 33 from the ISO/DIS 21542 version (DIS stands for Draft International Standard and is a version of the standard, which is under development). The result from the check is shown as a list of red, orange, and yellow triangles in Solibri Model Checker in Figure 2-8. Looking into one of the issues by clicking on the line with a triangle, the 'Results' and 'Info' windows become activated. Clicking on the clause '18.1 Door and doors furniture' (related to the clause in the ISO standard), only door and belonging wall objects are displayed. All other elements are removed. This situation is illustrated in Figure 2-8. This contributes to identifying, for example, the issue, 'Revolving door is not accompanied by swing door', in a visual way. How this issue can be solved in practice must of course be discussed in the design team meeting or in coordination meeting. Solibri Model Checker only identifies possible issues – it does not propose possible solutions; professional skills are therefore still needed.

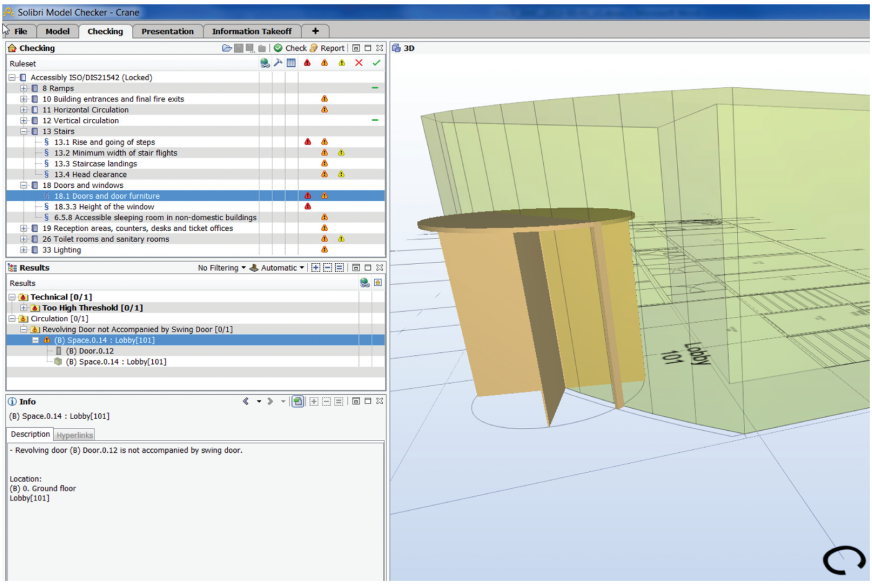


Figure 2-8. Checking of accessibility in Solibri Model Checker (Hjelseth 2012).

USE OF BMC SOFTWARE AND PROCESSES IN NORWAY

Motivation for the Case Study

The intention of this study was to explore experiences – 'Best practice' – and to identify suggestions for the further development of BMC solutions. The outcome can be regarded as an indication of how the leading-edge companies (in Norway) are utilizing BMC in today's projects (possibilities/challenges/ problems) and what they regard as opportunities of tomorrow. The study does not focus on exploring a specific project in each company; instead, it focuses on the general use of BIM and BMC. It does not cover constraints like the type of contract, split of risk and profit, number of involved partners, or number of subcontractors. All companies' feedback was based on experience from 'real BIM projects', which had a high focus on both process and utilization of BIM-based software. The respondents were regarded as the most experienced BIM experts in their companies.

The Norwegian construction industry has a high focus on the use of BIM, especially openBIM-based exchange of IFC files. Public builders like Statsbygg (Norwegian Public Construction and Property Management Agency), Forsvarsbygg (The Norwegian Defense Estates Agency) and Helsebygg (Norwegian Hospital Development Project Agency) have demanded BIM in selected projects since 2007 (Statsbygg 2007). Statsbygg announced in spring of 2013 that they had signed a 'Joint Statement' about the use of openBIM (IFC) in all projects from 1 June 2016 (BuildingSMART 2013).

Table 2-5. Overview of commercial and public companies in the survey

Category	*Commercial/public companies*
Public serial owners/builders	Statsbygg
	Forsvarsbygg
	Sykehuset Østfold
Architects	Link Arkitektur
	Nordic
Consulting engineers	COWI
	Multiconsult
	SWECO
Contractors/property developers	AF-Gruppen
	NCC
	Skanska

Research Method

This study intends to identify best practices for the utilization of BMC. Table 2-5 presents an overview of the selected companies in this study. All companies are representing the-state-of-the-art in utilization of BIM and BMC. They are among the largest companies in their branch of the construction industry in Norway.

A questionnaire was sent by e-mail one week in advance of the telephone interview. This qualitative approach tries to extract understanding, experiences and common elements, rather than quantifiable statistical data. Anonymity was granted to motivate open feedback on problems and challenges.

RESULTS OF THE INTERVIEWS WITH THE BMC COORDINATORS

Qualitative Approach: Expert Experiences

This is a qualitative study with a focus on extracting experiences from the most skilled users of BMC in Norway. Highlights from the interviews are therefore presented to give an understanding of how BMC is utilized on demanding projects. The questionnaire was structured into six themes, with separate questions, and used as a framework during the interviews.

Questionnaire Theme 1: Type of Company and Projects

The survey included most disciplines involved in construction projects. An overview of the interviewed companies was presented in Table 2-5. It was expected to get clear differences between the disciplines, but the survey did not indicate this effect. All companies were large and with high profile in use of BIM, and in this respect heterogeneous. On the other hand, it did identify a change in roles, and

especially that building owners were very active. This can be explained by model checking done by professionals in the company with long experience and high competency. This was especially clear for the building owners having an active role in demanding BIM-based deliverables. Limited competency in the company, both BIM and BMC, was pointed out as a barrier for collaboration and increased level of use.

Questionnaire Theme 2: Use of BIM and BMC Software

All companies had experiences of five or more years with BIM-based projects, varying in levels. The share of BIM projects is increasing, from use of BIM only on special projects to its use on most projects by default. All companies in this survey work mainly with large projects with more than $10 million USD. However, most projects were done in collaboration with ordinary companies without a high focus on BIM beyond the use of commercial BIM-based software as drawing tools. An overview of software is presented in Table 2-6.

The focus in this study was on advanced use, development, or adaption of rule set and future perspectives from the BMC coordinators in state-of-the-art projects. It did not focus to determine extent or combinations in use of different software. Use of IFC – or openBIM – has in general a very high standing in Norway. Use of IFC-based software, such as Solibri Model Checker, is therefore regarded as a default file format in multidisciplinary projects. All 11 companies used Solibri Model Checker but also other software like Autodesk Navisworks. Navisworks was dominant on the infrastructure project due to its capacity to import a large number of file formats. Free versions of IFC viewers were used when the project management wanted to distribute the BIM file for individual presentations.

One very interesting observation was that the number of Solibri Model Checker and NavisWorks licenses was very limited compared to use of other licenses. Model checking and model coordination was generally performed by one to three participants, utilizing one or two licenses. This was also the situation in large projects with multiple disciplines from architecture, engineering, and contractors, counting over 100 professionals. This was not an expected result regarding the high BIM profile in all of these projects. Traditional organization and low awareness in utilization of BIM and BMC were mentioned by the respondents as possible explanations.

Questionnaire Theme 3: What is BMC Used For?

This theme focuses on identifiable deliverables related to the use of BMC. BMC was used in all phases where BIM was used and not only as a check of final design. Clash detection and coordination of different model files (disciplines) was the default use reported by all respondents. The companies confirmed that merging different IFC files into one presentation of the project was quite common (multi-disciplinary coordination). The outcome was a coordination report, which illustrated identified issues based on screenshot functionality, and included a description of the problem, possible solutions, responsibility for following up, and

Table 2-6. Use of BMC software in the Norwegian study

	Category of software								
	BIM-based model checking software					*BIM-authoring (design) software*			
Type of company/ organization	*Solibri M C*[1)]	*NavisWorks*[2)]	*Tekla BIM Sight*[3)]	*dRofus*[4)]	*IFC viewers*[5)]	*Revit*[6)]	*Archicad*[7)]	*Tekla Structures*[8)]	*AutoCAD Civil 3D*[9)]
Public serial owners/builders (N = 3)	3			3	3				
Architects (N = 2)	2					1	1		
Consulting engineers (N = 3)	3	2		1	3	3	1	2	2
Contractors/property developers (N = 3)	3	2	2		3	3		2	1
All respondents (N =11)	11	4		4	11	7	2	4	3

Notes:
BIM-based model checking software:
[1)]Solibri Model Checker All use based on IFC import
[2)]NavisWorks Used only on infrastructure projects
[3)]Tekla BIM Sight Used as supplement to Solibri MC, and as a 'free IFC viewer'
[4)]dRofus Only used by public builders on large projects, and consulting engineers in hospital projects,
[5)]IFC viewers
BIM-authoring (design) software:
[6)]Revit Includes both Architecture and Structure versions
[7)]Archicad Only used by architect
[8)]Tekla Structures For structural constructions
[9)]AutoCAD Civil 3D Used only on infrastructure projects
Mostly free versions of Solibri Model Checker and Data Design IFC viewer (Norwegian)

deadline. All respondents that used Solibri Model Checker highlighted that the reporting functions replaced traditional minutes. These types of reports were very useful for collaboration and saved time in reporting and discussion afterwards. BMC was regarded as a part of the QA package. Some companies used the information take-off functions, e.g., in Solibri Model Checker, for quantity take-off (QTO) and the further calculation of material and works.

Utilization is related to traditional quality assurance and not to new digital services. The checking software itself is easy to use, and the license cost could be saved by avoiding one single construction mistake. However, it was reported that it was hard to get directly paid for BMC. Even if the benefits from savings were very significant and positive for the overall project, the contracts were separate for each discipline. Type and design of the construction contracts plays a major role for collaboration and how changes become solved. National differences may influence the method of collaborating. In Norway, a contract for construction is often split up among a number of sub-contractors, who in turn use other sub-contractors. This is also the situation when one large contractor has won the entire contract. The attitude was: 'I do my job and get paid for that – not for what happens afterwards'.

Another interesting piece of feedback from one respondent was that there were very few practitioners who took their own BIM and merged it with others in order to explore coordination and content. Lack of 'curiosity' should perhaps line up as a barrier, or can the business model be blamed?

Questionnaire Theme 4: Procedures for BMC

BMC was regarded a part of the quality assurance (QA) system of the model and of the project. QA traditionally uses written procedures, and this approval was applied to BMC procedures as well. The extent of using this practice had some variations, but all companies used written procedures in combination with best practice experiences.

BMC was not included in contracts, while the mandatory use of BIM guidelines was. BIM guidance had references to BMC regarding when and what should, or must, be BIM deliverables. BMC was not regarded as a separate deliverable but as a part of the process and a way of utilizing BIM. The procedure executing a BMC procedure can be divided into the following three parts:

- *Quality of BIM deliverables*. These specifications were covered by the company's BIM-guidance.
- *Procedures for QA*. BMC is following established QA procedures. Best practice for coordination meetings is included in these procedures.
- *Scope and content in rule set*. This was not documented as the company reports. This development was done by the BIM coordinator, BIM manager, or participants with experience with BMC. This development was based on experience and best practice.

The close connection between BIM and BMC was expressed by the following type of statement from one company: 'Use of BMC can be regarded as an indicator for BIM-maturity'.

Projects using BMC (in Norway) are regarded as real BIM projects because everyone has to deliver BIM files in IFC format to be merged into the model checker (based on Solibri Model Checker). There are no needs of drawings for coordination of design – this was done by use of models.

Processing of BMC was done by a very limited number of participants in the project. Even in very large projects – over $100 million USD –operating the BMC software was normally limited to 1–3 participants working on the project management team. The software, like Solibri or Navisworks, is easy to operate. Arguments for limited use are related to contracts and responsibility for coordination.

Presentation of the issues after a clash detection check always need some time – 2–4 hours – of preparation by an experienced operator. Too high a sensibility in the rule sets results in an excessive reporting of non-relevant issues. This makes it hard to know which issues are relevant or not. Preparation was therefore a mandatory part before presentations of the outcome.

One interesting observation was some changes in the scope of disciplines. The building owner – in this case, the public builder of hospitals – took a very active role in the use of BIM and coordinating the BIM models. Closer collaboration among all roles was also a general feedback given from the use of BMC.

Questionnaire Theme 5: Use of Adapted Rule Sets from Solibri Model Checker

This survey was not focused on testing specific software, such as Solibri Model Checker. On the other hand, Solibri Model Checker can be used to illustrate the concept of separate rule sets in the checking software. Rule sets can be regarded as commercial goods, such as objects of building parts. So far, they are only an embedded part of Solibri Model Checker. Users can modify existing rule sets and save these separately for their own use. No companies, except Statsbygg, have developed a rule set from the ground up. Statsbygg have developed a digital rule set in Solibri Model checker for compliance checking with their BIM guidance. This was previously presented as 'Study of degree of automatic processing of Statsbygg's BIM requirements' in this chapter. The respondents explained that the need for development of new customized rules was solved by modification and adaptation of existing rule sets. This did the job at low cost and in a short amount of time – and was often "good enough". Another reason was that development of new rules required a lot of skills and the fact that the technical implementation had to be performed by Solibri Model Checker.

All respondents had modified the embedded rule set to minor or major degrees. The modification was done as a selection of separate rules into a new rule set more adapted to the need in the project. In addition, some constraints were

modified, e.g., distances to be longer or shorter than in the embedded rule set. Dedicated rule sets, such as accessibility based on ISO/US requirements and other rule sets based on regulations, were not regarded as relevant for Norwegian projects, and were therefore not in use.

This study identified that it was mainly following rule sets in Solibri Model Checker, which were modified and adapted to company/project related rules:

- 'General Intersection Rule' for checking collisions between technical subjects, architectural, and structural models
- 'Components are filled' for checking consistency between architectural and structural models
- 'Components fit in architectural ones' for checking consistency between architectural, engineering and MEP models
- 'Comparison' for checking changes in a revised model

As the titles of the above rule sets indicate, these rule sets are based on variations of clash detections for making this type of verification more relevant for Norwegian requirements. Another motivation for adapted rule sets was to reduce the amount of feedback from of non-relevant issues.

Questionnaire Theme 6: Highlights – Open Questions and Free Answers

The two main overall questions asked in the interviews were:

a) What is the most positive effect of using the model checking software?

b) What is the most challenging aspect of using the model checking software?

a) What is the most positive effect of using model-checking software? This question focuses on positive experiences from real projects.

All respondents stated that BMC is a very useful collaboration tool merging different model into one joint model – visualization was very important. Use of BMC gathered the project team to a joint presentation of the project. It was the combination of process and program which made the power for the participants in the project. The outcome of the validation – the model checking in itself – was regarded as 'guidance' for identifying issues.

The respondents said that BMC makes them focused on solutions – issues are identified at a stage where they can be solved without redoing work. All involved in the project see the same 3D model or building information model; this is far easier to understand in a short time than drawings. It was reported by some respondents that the volume of traditional 2D drawings has been dramatically reduced. A combination of drawings and models are often used on the construction site. As one respondent expressed, 'BMC makes a new daily routine for the project coordinator'.

The feature to produce issue reports or coordination minutes was regarded as a very important function of the BMC software. This feature was used for collaboration and management of who shall follow-up which issue by deadline. Some of the respondents thought that BMC had the effect of a learning tool. It

gave feedback on correct modelling and structuring of information in the authoring BIM software.

b) What is the most challenging use of model checking software? This question focused on both experiences from real projects and obstacles aiming for increased ambitions in future projects.

The most important drawback was that Solibri Model Checker identified too many false issues. It takes time to prepare and eliminate non-relevant issues before presentations. It contributes to reducing the impression of reliable verifications. An aspect of this is that 'BIM is not always BIM' as one respondent expressed it. There is a large variation in how the IFC implementation is done in different software and software libraries – and also how the designer is modelling and structuring (entering) information in the BIM software. This makes more advanced testing unreliable and confirms the 'garbage in/garbage out' principle. One respondent stated: 'Solibri Model Checker rule sets are powerful tools that identify almost everything in an assembled model of more BIM files (e.g., in multidisciplinary project). If you are sloppy with putting limits in what to be checked, it soon becomes a mess about what the rule set include of rules (that in principle can be checked), the content of object with relevant information in then BIM files (what can be checked in practice), and how this is reported by the checking software (priority of actions). The procedures of rule checking are critical for the outcome.

Multidisciplinary coordination requires that BIM from the different disciplines are at same level of development (LOD) or are in the same phase to perform BMC. Often, one discipline will start designing when other disciplines have reached a stated level. This requires dedicated rule sets, because rule sets are normally based on the final design.

Lack of flexibility was mentioned by some respondents as a challenge. It was reported that it was not possible to check only specified parts of a model ('zone of control'), specific disciplines, or other partial elements without preparing the BIM file in advance. Better tools for management of information were wanted. The classification function in Solibri was useful and easy to use, but a good and joint system for classification was often hard to develop.

Some respondents reported that a collision (issue)-free model often was regarded as a good solution, and stopped further development. A model free of issues can, at its best, be verified as 'not bad', but never as good. This can only, with BMC of today, be done by skilled practitioners. The required effort for closing the chasm between the level of today and higher-level BMC was expressed by some respondents as a leap in level, i.e., more than incremental development. To reach the BMC level where one trusts the outcome of a check 100% without visual control requires full control of all steps, both in process and program. One of the respondents expressed this as going from tricycle to bicycle – this requires a number of new skills. However, the companies in this study use BMC at a level far above the general use of BIM and clash detection.

Many respondents reported a lack of design objects or object libraries with joint and missing comprehensive content of information as a critical

problem for multidisciplinary coordination. This was in projects solved by 'bypasses' and a high focus on discipline and joint manual input. Specific building parts were identified by type number, ID-codes, and similar solutions of manual input. This was hard to maintain for all parts in the project, but easy to violate.

Highlights from the Survey

All respondents stated that clash detection was the most frequent use of BMC. Reporting on many irrelevant issues was a challenge and involved time to prepare the presentation of the outcome of clash detection for the design or coordination teams. Clash detection was very useful – almost mandatory – in the coordination of multidisciplinary projects. The capacity to produce issue and coordination reports in the coordination meeting was regarded as one of the most useful functions in the checking software. Clash detection was used to support collaboration, and BMC was regarded as a very useful collaboration tool. This finding is supporting 'Developing internal collaborative BIM procedures' as the top forecast for 2014 in the status report from McGraw-Hill Construction (2012). The level of BMC can be regarded as a maturity index for the utilization of BIM. Most advanced BIM projects also had the most advanced utilization of BMC. All respondents supported the view that BMC must be regarded as a 'mandatory tool' for the coordination of BIM projects.

Clash detection and multidisciplinary coordination represented the most typical uses of BMC. Solibri Model Checker was the most-used software for BIM files in IFC format. Autodesk Navisworks was the second most-used software, but in infrastructure projects, Navisworks was the most used on infrastructure projects due to its ability to import different file formats. All companies in the survey had modified the embedded rule sets in Solibri Model Checker and adapted them into company-specific rule sets. The benefit was better precision on what was actually checked, in addition to a reduced number of non-relevant issues. The development of digital rule sets was regarded as a challenge.

LIMITATIONS FOR THE INTERVIEWS

The interviews of BMC experts in Norway are based on a limited selection in the forefront companies. Suggestions for future solutions have particularly been influenced by technology optimism. This is of course not representative for the construction industry. A survey contrasting these companies could be useful. This study could have focused on why companies are not using BMC, and what the decisive moment is for these companies to start using BMC in their projects.

All interviews were documented and a questionnaire was used, but the answers were mostly based on personal experiences and attitudes related to the pervasive use of BIM and BMC. Reliability is in principle ensured, but due

to time and project dependency, it can be hard to repeat with identical results. On the other hand, the variation within the group was low and the main findings should be repeatable.

CONCLUSIONS

BIM-based model checking (BMC) can be regarded as one of the best ways to illustrate the benefit of the relevant content of information in BIM files. It is a cross-disciplinary way for the coordination of BIM deliverables from different disciplines. Commercial software solutions for BMC are easy to operate and offer more functions than most users will need. Software is not delimiting the implementation of BMC in the construction industry. Implementation of BMC is highly related to the use of BIM in general and the use of openBIM based on IFC specifically. BMC requires files with relevant information to process the rules of checking. More information in the file enables more rules and exchange of information in a common format like IFC enables concentration of efforts in the development of solutions. BMC can have a high impact for development of high-quality content of information in BIM files and the use of open BIM. The level of utilizing BMC can therefore be used as an indicator for the maturity of BIM.

However, use of BMC is not a mainstream method of workflow today. Even in large companies, keeping tabs on BIM-based projects through the use of BMC software is limited to a few dedicated users (coordinators). This is a paradox since the software is easy to operate and the detection of issues is best done by experienced professionals rather than by coordinators. Lack of relevant information in BIM files, in addition to low and variable BIM-maturity in companies involved in the project, is pointed to as the main reason for limited use of BMC.

BMC is therefore mostly used as a coordination tool for clash detection, and in this way, it has a large impact on the process by identifying issues, assigning responsibility, and following up with changes. In this respect, BMC is playing an important part in the quality assurance of digital models.

Development of rule sets is a general obstacle for wider use; this is especially the case for missing rule sets of mandatory regulations and standards where BMC has the potential to replace manual and time-consuming work. The modification of existing rule sets in commercial software will cover the need in most projects. This must be supported with specification of information in BIM files.

BIM-based model checking (BMC) is a type of software solution, which has the capacity of becoming a game-changer for utilizing BIM. BMC provides a close interaction with the content of information in the BIM model and can be used as a catalyst for increased utilization of copious BIM and for sharing relevant information among all partners in a construction project.

ACKNOWLEDGMENTS

The author would like to thank all BMC experts who participated in the interview for their openness in sharing experiences and thoughts. A special thanks to Professor Tor G. Syvertsen at The Norwegian University of Science and Technology (NTNU) and to Master of Architecture Lars Aasness for his useful comments.

References

AECMAGAZINE (2013). "Solibri Model Checker V8." *Building Information Modelling (BIM) for Architecture, Engineering and Construction*, <http://aecmag.com/software-mainmenu-32/527-solibri-model-checker-v8> (June 9, 2014).

AIA (2012). "Document E202™ – 2008 Building Information Modeling Protocol Exhibit, Contract Documents." *The American Institute of Architects* <http://www.aia.org/contractdocs/training/bim/aias078742> (June 9, 2014).

Bentley (2012). "Bentley Navigator V8i." *Product Data Sheet*, <http://ftp2.bentley.com/dist/collateral/docs/projectwise/PDS_ProjectWise_Navigator_V8i.pdf> (June 9, 2014).

BSI (2013). "New standard for BIM to help meet 2016 Government savings target." *British Standards Institution* <http://www.bsigroup.com/en-GB/about-bsi/media-centre/press-releases/2013/3/new-standard-for-bim-to-help-meet-2016-government-savings-target/> (June 9, 2014).

buildingSMART (2013). "Joint Statement – openBIM." *buildigSMART Norway*. <http://www.buildingsmart.no/nyhetsbrev/2013-06/joint-statement-openbim-vil-gi-bedre-bim-leveranser> (June 9, 2014).

Conover, D. (2007)."Development and Implementation of Automated Code Compliance Checking in the U.S.," International Code Council, 2007.

CRC (2009). "National Guidelines for Digital Modelling." *Cooperative Research Centre for Construction Innovation*. <http://eprints.qut.edu.au/30341/> and <http://www.bim.natspec.org/index.php/resources/bim-guidelines/13-bim-documents-completed/56-rd-3> (June 9, 2014).

East, E. W. (2013). "Construction Operations Building Information Exchange (COBie)." *National Institute of Building Sciences*. <http://www.wbdg.org/resources/cobie.php> (June 9, 2014).

Fiatech (2012). "AutoCodes Project: Phase 1, Proof-of-Concept Final Report," *Element 6 Project management, Fiatech Regulatory Streamlining Committee, March 2012*. <http://www.fiatech.org/images/stories/techprojects/project_deliverables/Updated_project_deliverables/AutoCodesPOCFINALREPORT.pdf> (June 9, 2014).

Fiatech (2013). "The AutoCodes Project." Fiatech, Video presentation, length 9:30, available at: <http://fiatech.org/the-autocodes-project> (June 9, 2014).

Sawyer, T. (2012). "Making the Case for Automated BIM Review." Engineering News-Redord, <http://enr.construction.com/technology/bim/2012/0528-Making-the-Case-for-Automated-BIM-Review.asp> (June 9, 2014).

GSA (2007). "GSA BIM Guide For Spatial Program Validation GSA BIM Guide Series 02." The U.S. General Service Administration (GSA). <http://www.gsa.gov/graphics/pbs/BIM_Guide_Series_02_v096.pdf> (June 9, 2014).

Hjelseth, E. and Nisbet, N. (2010). "Overview of concepts for model checking." Presented at the CIB-W078 conference in Cairo, Egypt, 16th–19th October 2010. <https://www.academia.edu/873824/Overview_of_ concepts_for_model_checking> (June 9, 2014).

Hjelseth, E. (2012). "Experiences from converting interpretative regulations into computable rules." Presented at the CIB-W078 conference in Beirut, Lebanon, 17th – 19th October 2012, <http://itc.scix.net/data/works/ att/w78-2012-Paper-2.pdf> (June 9, 2014).

ICC (2009). "Building Technology: Then and Now." International Code Council (ICC). <http://www.iccsafe.org/safety/Documents/BSW-Technology.pdf> (June 9, 2014).

IDM (2013). "Overview of Information Delivery Manuals independent of their status." International User Group (IUG), buildingSMART International. <http://iug.buildingsmart.com/idms/overview> (June 9, 2014).

ISO 16739:2013. "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries." ISO - International Organization for Standardization. <http://www.iso.org/iso/ catalogue_detail.htm?csnumber=51622> and <http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc4-release/ifc4-release-summary> (June 9, 2014).

ISO 21542:2011. "Building construction - Accessibility and usability of the built environment." ISO - International Organization for Standardization. <http://www.iso.org/iso/ catalogue_detail?csnumber=50498> (June 9, 2014).

ISO 29481-1:2010. "ISO 29481-1:2010 Building information modelling - Information delivery manual - Part 1: Methodology and format." ISO - International Organization for Standardization. <http://www.iso.org/iso/ catalogue_detail.htm?csnumber=45501> (June 9, 2014).

ISO TS12911 (2012). "ISO TS12911:2012 "Framework for building information modelling (BIM) guidance." ISO - International Organization for Standardization. <http://www.iso.org/iso/catalogue_detail.htm? csnumber=52155> (June 9, 2014).

Khemlani, L. (2011). "AECbytes Product Review." November 17, 2011, Solibri Model Checker v7, AECbytes. <http://aecbytes.com/review/2011/ SolibriModelCheckerv7.html> (June 9, 2014).

Lopez, R. and Love, P. (2012). "Design Error Costs in Construction Projects." *J. Constr. Eng. Manage.*, **138**(5), 585–593. American Society of Civil Engineers, ISSN (print): 0733-9364, ISSN (online): 1943-7862 Permalink: <http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000454> (June 9, 2014).

McGraw-Hill Construction (2007). "Interoperability in the Construction Industry." Smart-Market Report, McGraw-Hill Construction, The report can be downloaded from: <http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aias077485.pdf> (June 9, 2014).

McGraw-Hill Construction (2012). "The Business Value of North America: Multy-Year Trend Analysis and User Ratings." SmartMarket Report, McGraw-Hill Construction. The report can be downloaded from: <http://images.autodesk.com/adsk/files/mhc_business_value_of_bim_in_north_america_2007-2012_smr.pdf> (June 9, 2014).

Navisworks (2013). "Features for Navisworks Manage, Simulate." Auotdesk, <http://www.autodesk.co.uk/products/autodesk-navisworks-family/ features> (June 9, 2014).

NBIMS, (2012). "National BIM Standard-United States™ Version 2" National BIM Standard-United States™ (NBIMS-US™), <http://www.nationalbimstandard.org/> (June 9, 2014).

Refvik, R. (2013). "ByggNett Status Survey," International survey on status of use of systems for automatic of processing of building applications. Norwegian Building Authority. <http://www.dibk.no/globalassets/ byggnett/ byggnett_rapporter/byggnett-status-survey.pdf> (June 9, 2014).

Sawyer, T. (2012). "Making the case for automated BIM review." Engineering News-Record, Dodge Data & Analytics. <http://enr.construction.com/technology/bim/2012/0528-making-the-case-for-automated-bim-review.asp> (June 9, 2014).

Senate (2012). "Common BIM Requirements 2012." Senate Properties. <http://www.en.buildingsmart.kotisivukone.com/3> (June 9, 2014).

Shih, S., Sher, W., and Giggins, H. (2013). "Assessment of the Building Code of Australia to Inform the Development of BIM-enabled Codechecking Systems" School of Architecture and Built Environment; University of Newcastle, Australia. <http://www.conference.net.au/cibwbc13/papers/ cibwbc2013_submission_370.pdf> (June 9, 2014).

Solibri (2010). "Solibri Model Checker: The Leading BIM Quality Assurance and Analysis Tool Enables Superior Spatial Coordination." Solibri Magazine 1/2010, page 20. <http://www.solibri.com/old/news/solibri-magazine-1-2010-published-read-interesting-case-studies-of-full-scale-openbim-projects.html> (June 9, 2014).

Stangeland, B. (2011). "BIM Collaboration Format (BCF)." BuildingSMART International User Group, <http://iug.buildingsmart.org/ resources/abu-dhabi-iug-meeting/IDMC_017_1.pdf>

Statsbygg (2007). "Statsbygg goes for BIM," The Norwegian Directorate of Public Construction and Property – Statsbygg. <http://statsbygg.no/en/Aktuelt/ Nyheter/Statsbygg-goes-for-BIM/> (June 9, 2014).

Statsbygg (2011). "Statsbygg Building Information Modelling Manual," Version 1.2 – English version, dated 2011-10-24, Statbygg. <http://www.statsbygg.no/FilSystem/files/prosjekter/BIM/StatsbyggBIMmanualV1-2Eng2011-10-24.pdf> (June 9, 2014).

Succar, B. (2009). Building information modelling framework: A research and delivery foundation for insutry stake holders. Automation in Construction, 357-375. <http://www.sciencedirect.com/science/article/pii/ S0926580508001568> (June 9, 2014).

This page intentionally left blank

CHAPTER 3

BIM and Cost Estimating: A Change in the Process for Determining Project Costs

Tamera L. McCuen*

Abstract: *Using BIM for the cost estimating process is evolving and the cost estimator's responsibilities are changing. As a result of these changes professional estimators from industry organizations have dedicated time to be actively involved in advancing the state of estimating in BIM. This chapter discusses the cost estimating process in detail and compares the traditional methods with BIM methods. The chapter also provides an overview of the constraints, variables, and opportunities for the BIM cost estimating process. A critical step in the BIM process is in generating a quantity take-off for which the cost estimator can trust that the information is reliable and accurate based on the project scope and level of development. Examples for proposed standards that define the information exchange needed between the design model and cost estimator is included in this chapter.*

INTRODUCTION

The simulation of alternate factors and parameters that can affect project costs is an important step in the cost estimating process. An analysis of such alternates requires time and reliable information about a project, however performing these cost analyses and simulations is often limited during the estimating process due to the compressed time allocated for such activities. The discussion in this chapter focuses on building information modeling (BIM) for cost estimating and how the use of BIM may facilitate cost estimators in their simulation and analysis for optimizing project costs in the future. The expectation is that as the adoption and implementation of BIM in the Architecture/Engineering/Construction (AEC) industry increases the design and construction processes will evolve and so will the technology used to create a building information model. As a consequence of

*Associate Professor, Construction Science Division, College of Architecture University of Oklahoma, Norman, OK

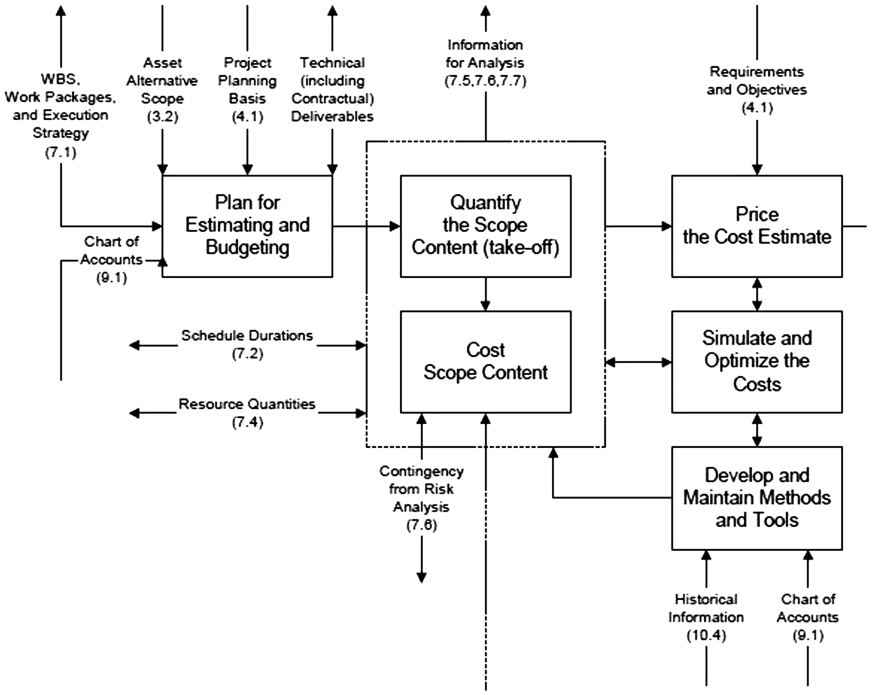


Figure 3-1. Cost estimating process map (Hollman, 2006).

evolving processes and technology the methods stakeholders use to fulfill their responsibilities on a project team will change. The future of the cost estimator's role and responsibilities will change to include more value added activities to support cost management decisions.

BACKGROUND

Cost estimating is a complex activity that requires knowledge beyond quantification and pricing of materials and labor. Although the topic of this chapter is BIM and cost estimating, the process map shown in Figure 3-1 is an excerpt of the process map for cost estimating and budgeting from the Total Cost Management (TCM) Framework (Hollman 2006) in which the traditional process is depicted. Figure 3-1clearly shows the relationships between creating a plan to estimate a project's cost, the quantity take-off (QTO), pricing the quantity takeoff, costing the scope content, and simulation and optimization of project costs. The TCM framework (Hollman 2006) is used as a reference for the discussion in this chapter and it describes the following five activities: 1) The first activity is to create a plan based on the assessment of the documented scope basis and required deliverables

for the purpose of defining the cost estimating effort required for the specific project; 2) The output from the planning activities becomes the input to the QTO activity as the basis for determining assemblies and component quantities based on the project's scope from the technical documents; 3) The output from the QTO becomes input to cost the scope content at which time the scope QTO is translated into expressions of the financial expenditure required for the project; 4) Costing scope content is a basic algorithm in which a unit cost is applied to each scope item in the QTO; 5) Pricing the cost estimate is a separate activity from costing the scope and is distinct in that pricing the estimate includes overhead, profit, contingencies, and other techniques applied to costs for meeting business interests. As shown in Figure 3-1 the simulate and optimize costs activities are useful for value analysis and engineering to optimize scope decisions in addition to evaluating cost risks. Simulating and optimizing costs are done concurrently with the costing and pricing steps to identify possible outcomes and evaluate possible trade-offs between scope elements. Although the TCM is based in the context of traditional methods for cost estimating, the relevance of each activity and its outputs is transferrable to the BIM cost estimating process.

In the past each activity box in the cost estimating process map was completed by quantity surveyors and cost estimators. Technological advances have increased the productivity of cost estimators over the years with computerized methods for quantity take-off and cost modeling tools, but the process still required interaction between the cost estimator and project information to complete each activity. With advances in the BIM tools generating a QTO no longer requires actions by the cost estimator. Historically the QTO was a time intensive step that required the estimator to dedicate hours reviewing, measuring, and counting items in the construction documents. As with any change there are factors, such as constraints and variables that can affect the successful implementation of BIM for cost estimating. The first factor is technology, which in its current state can be a constraint due to the lack of interoperability between software applications. Another factor in BIM implementation is the variability associated with humans and their willingness to collaborate and share project information in a way that renders the information useful for other project stakeholders. The final factor to consider is the fact that using BIM for cost estimating provides an opportunity to redistribute the estimator's time to focus on more value added activities instead of performing tasks that can be automated.

This chapter provides an overview of BIM, cost estimating, and a detailed discussion about the constraints, variables, and opportunities that impact the current and future use of BIM to generate accurate and reliable cost estimates. An important thing to remember when reading this chapter is that it focuses on BIM as a tool that has the potential to improve the cost estimating process and add value to a project only if there is an agreement about the information exchange required between the design team and estimators. Emphasis is placed on using BIM to improve an estimator's productivity, facilitate progressive analysis, and add value through enhanced decision making during the cost estimating process. Great opportunity exists for BIM to reverse the typical

estimator's time distribution from 80% QTO and 20% analysis, to 20% QTO and 80% analysis. Reversing the distributed effort though will require industry standards to guide the input and sharing of information, which will ultimately improve the quality of information about the project in the building information model.

To add context this chapter includes several comparisons between the traditional methods and BIM methods for estimating. The chapter is organized into three main sections. The first section focuses on the important terms and descriptions related to BIM and cost estimating. The next section presents a detailed discussion about the estimating process including its variables, constraints, and opportunities associated with using BIM to determine project costs. The section begins with a discussion about the difference between the 'science' of QTO and the 'art' of cost estimating, and how the unique aspects of each transfer to BIM. A clear distinction is made about QTO and estimating as interdependent activities and it emphasizes the fact that the two are not synonymous. There is a clear distinction made about how the inputs and outputs during the quantity take-off differ greatly from the inputs and outputs of a cost estimate. The chapter concludes with a discussion about the current state of using BIM for cost estimating and offers a glimpse into future possibilities.

VOCABULARY IN THE CONTEXT OF BIM AND ESTIMATING

BIM

In this section the focus is on the vocabulary used in the context of BIM and estimating germane to the discussion in this chapter. Granted the terms in this section are not new however it is important to establish a mutual understanding about the terms and descriptions. Because the definition of BIM varies slightly between stakeholders depending on the industry perspective it is essential to clarify the term BIM and its definition as used in this chapter. The National BIM Standard (NBIMS) defines BIM as a technology enabled collaborative process and facility life cycle management tool. Specifically the NBIMS definition is (NIBS, 2012):

> Building Information Modeling (BIM) is 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.

The NBIMS definition addresses the idea that there are two different aspects to BIM. The first aspect specifically addresses the machine side, or BIM as a

technology and a tool. The second addresses the collaborative process, which is the human side of BIM. Collaboration is a process and can only be achieved when people work together to achieve a common solution. To summarize, BIM is not a stand-alone technology or software, but instead it is a process for the design, construction, and operations of a building centered on collaboration that is enabled by the technology and software. It is important to also understand that not all modeling software produces a BIM. Three-dimensional (3D) models **without** 1) data about the objects, 2) parametric intelligence, and 3) features supporting automatic updates between model views do not meet the capabilities required to be considered a BIM technology (Eastman et al., 2008; Smith and Tardif 2009). Three-dimensional models that do not contain data or parametric intelligence about model objects are used primarily for visualization in the early stages of a project for planning and developing purposes and may provide the basis for developing the building information model. A 3D model of this type does not provide ongoing support of stakeholders' activities across the life cycle of a facility and is limited in its use for cost estimating.

Information

Next in the BIM vocabulary is the term information, which in the context of BIM it is described as data that has been collected and analyzed so it can be used to reason about something, make a decision, or draw conclusions (Smith and Tardif 2009). In essence, information is data that has been acted upon. What makes BIM unique compared to all the other uses of 3D modeling is the fact that the model contains data about model elements that becomes information when it is shared with other project stakeholders. One way that may help with understanding the importance of project information is to look at it in terms of its reliability and in terms of how it is used and by whom. All project information has an author and a consumer. Information must be accurate, accessible, complete, and transparent for it to be considered reliable and useful to stakeholders through the life cycle of a building (Smith and Tardif 2009). In addition to the content, the format of information in BIM impacts its usefulness to the end consumer. To ensure the information is useful the author needs to know what information the consumer needs to know to accomplish their responsibilities for the project.

Interoperability

Interoperability in the context of BIM means that the multiple software applications used by building information stakeholders have the capability to function as part of an integrated system (Smith and Tardif 2009; NBIMS 2012). The benefits of interoperability as identified in industry reports include (Young et al. 2007; Bernstein and Fitch 2012):

- Increased speed of overall project delivery
- Reduced infrastructure vulnerability
- Greater reliability of information through the life cycle

- Expanded markets for companies
- Decreased supply-chain communication
- Improved value to customers

Interoperable applications support information exchange for activities between stakeholders in the building industry. To date one of the greatest challenges to the adoption of BIM industry wide is the lack of interoperability between applications and platforms. For example, if the design model is created in an application that is not compatible with the application for cost estimating then the material list must be manually entered by the estimator. Manually re-entering data from one application to another is redundant and adds no value to a project, only cost for the time allocated to re-enter the data. Therefore the value of an automated QTO is negated if the software generating the QTO is not interoperable.

Project Costs

Project cost is the third term germane to the topic of this chapter. The cost to construct a project is more than the unit price of multiple items extended and summed at the bottom of a spreadsheet. The construction cost of a project is the amalgamation of three elements: resources, time, and cost. Resources in this context refer to the material, human, and financial inputs necessary to complete the project. The element of time may be measured based on the overall, weekly, daily, or hourly amount of time. The cost element is the cost of a single resource given a particular unit price. The complexity determining the estimated cost for a project lies in the fact that it is contingent on decisions about how to allocate each element to a project such that the requirements in the construction document are met. For example, a project owner may have a deadline for completion of construction that requires additional labor resources achievable by adding another shift, crew, or by paying for hourly overtime. Obviously either way, the increase in labor resources will increase the project cost compared to the same project without a tight schedule requiring additional resources. In addition to labor productivity, the estimator must also consider external factors such as market conditions and material availability when determining the projected total cost of a project. It is at this point that the pricing and simulation activities as discussed in the background section of this chapter add value to the cost estimating process.

The Estimator

There is little doubt about the importance of an accurate estimate in the design and construction of a new building or the renovation of an existing building. The responsibility of an accurate estimate belongs solely to the cost estimator. Given that the estimator's responsibility is to provide a complete and accurate estimate, the question to ask is "What are the characteristics, skills and knowledge necessary to achieve a complete and accurate estimate?" The TCM framework (Hollman 2006) outlines these characteristics beginning with the ability to visualize how the

project will be built. Once the estimator has a mental image of the entire proposed project, then the estimator can begin to analyze the design and determine the best means and methods for completing the project. The entire project includes more than just visualizing the building. The estimator must also understand job phasing, site layout, and sequencing of the construction to complete the analysis and identify potential costs. With the analysis complete only then can the estimator actually determine the cost for the proposed project. Ultimately the estimator must understand the construction process, means and methods, and management of the work to be completed. The cost estimator that can visualize, analyze, and identify costs associated with these characteristics is critical to any project (Hollman 2006; Dagastino and Peterson 2011; Eastman et al. 2008).

Success as a cost estimator also requires a distinct set of skills and knowledge beyond the characteristics discussed in the preceding paragraph. The estimator needs to be able to expand upon the costs identified in the project analysis to knowledge about a variety of cost elements. Examples of cost elements are cost types, cost classifications, and pricing. Estimators must also have skills and knowledge about a variety of analytical methods including statistics, probabilities, and cost models. Furthermore cost estimating relies on skills and knowledge in the areas of information management, quality management, and value management (AACE 2006). The accuracy of estimated cost compared to actual cost of a project depends on how the estimator uses his skills and judgment across these aspects of estimating (Dagastino and Peterson 2011). The accuracy of estimated cost compared to actual cost also depends on the information exchange between stakeholders using BIM.

THE ESTIMATING PROCESS

In this section the estimating process is discussed from both the traditional and the BIM perspective. This section also includes several comparisons between the two perspectives. In this chapter, any method of cost estimating that does not use BIM is referred to as a traditional method. Examples of the traditional method include: 1) paper, pencil, and calculator, 2) quantity take-off software for electronic drawings paired with a separate spreadsheet application for inputting the quantities and 3) any combination of these two examples. In addition to categorizing based on the tools used as traditional or BIM generated estimates, cost estimates are also categorized based on the methodology used for estimating. The two estimating methods are: 1) stochastic and 2) deterministic. Stochastic methods use algorithms in which the independent variables are generally something other than a direct measure of the material item being estimated and are subject to the estimator's judgment. Stochastic methods typically involve modeling based on inferred or statistical relationships between costs and programmatic and/or technical parameters. Deterministic methods include counts or measure of units of items multiplied by the unit costs or factors (AACE 2003).

Science of Quantity Take-off

In general the cost estimating process involves multiple steps which can be divided into two overarching steps. The first step is the quantity take-off which is the quantification of materials, or as it is sometimes referred to, the 'science' of estimating. One definition for the quantity take-off process describes it as a systematic approach that is grounded in an effective strategy for dividing up and managing the process in an organized manner (Pratt, 1995). To accomplish the quantity take-off the cost estimator must have a disciplined method for the review of project documents and drawings, measuring, calculating, and extending line items. The following is a simplified example of steps in the traditional quantity take-off process. First the estimator divides the project into parts, such as building, phase, or level. After the project is divided up the estimator begins identifying assemblies within each part of the project. Once the assemblies are identified, the estimator will take-off all the material items within the assembly. The output from a quantity takeoff is generally a list of materials with quantities assigned to each line item.

Art of Estimating

The second step in the estimating process is often referred to as the 'art' of estimating because it is more subjective than quantifying items and it requires experience in construction to facilitate good judgment at this step in the process (Dagastino and Peterson 2011). The term art is used to describe the act of cost estimating because it requires estimators use their talent to evaluate factors and alternates then use their judgment to simulate and optimize costs (Hollman 2006). Although these two steps originated in the traditional estimating process they are not lost when using BIM. There are differences however in the process that can impact the outcome of a cost estimate and must be addressed prior to the quantity takeoff. The differences in the BIM process that must be addressed are discussed later in this section as variables and constraints.

Traditional Estimating and BIM Estimating

Differences between the traditional methods and BIM methods exist in both the quantity take-off and estimating steps. Traditionally the quantity take-off for a commercial construction project in the United States is the responsibility of an estimator. The quantity take-off process is a time consuming task that begins with a thorough review of the contract documents including the general conditions, working drawings, and specifications. The format of output from a traditional quantity take-off is typically in the form of a spreadsheet, or bill of quantity, that either lists work assemblies and systems by the ASTM Uniformat II classification or the output may list may be more detailed lists of materials organized by the Construction Specifications Institute's Masterformat. In contrast, a BIM generated QTO differs from the traditional method in the amount of effort and time required from the cost estimator because BIM automatically generates a quantified list of materials. As a result of the automatic QTO the labor intensive task of QTO is no longer the responsibility of the estimator. Details about the materials

contained in the BIM generated list may vary widely depending on the level of project definition and subsequent information about the materials for objects in the model, however a BIM generated QTO will have a line item for every object in the model. It is important however to point out that although the QTO will include all the model objects, the QTO may not be a reliable source of information about the model elements. In its current state of development the lack of reliability will require additional work by the estimator to validate the QTO. The level of project definition and level of development will be discussed in detail in the BIM for estimating section of this chapter. The ultimate benefit of using BIM is that it eliminates the quantity take-off activity from the cost estimator's project responsibilities. As a result, the estimator has more time to complete value added tasks such as risk analysis and project simulations.

It is at this point in the estimating process that the quality of the BIM information has the greatest impact on the accuracy of a project's estimate. Quality of information in this context refers to the accuracy and reliability of the information exchanged from the design team to the estimator. Professional estimators classify estimates based on the level of project definition. A project's level of definition is based on the amount of information known about a project which increases simultaneously with the progression of the project's design. Traditionally the design process progresses through the following phases: 1) predesign, 2) schematic design, 3) design development, 4) construction documents, 5) agency permit/bidding, 6) construction, and 7) closeout. As the design process progresses estimates are needed by the owner and design team to check costs and verify the project is within owner's budget. Cost estimates during the design process are categorized as: 1) feasibility/range of magnitude, 2) conceptual/schematic, 3) budget/design development, 4) bid/construction document, and 5) tender/final cost (AACE 2003; ASPE 2011).

In the traditional method of estimating costs, the estimator reviews the QTO to identify any obvious missed items and confirms the accuracy of the quantification in general. After reviewing the QTO the estimator begins to look at project specific conditions, constraints, and external factors. It is at this point that construction experience and judgment is applied to perform the 'art' of estimating. It is also at this point where the traditional process and BIM process are most similar because both processes rely on the human estimator's experience and judgment to actually complete the estimate. To replicate the estimator, BIM would need artificial intelligence capabilities that are not probable in the near future.

Variables

By definition a variable means that something is inconsistent. In the context of BIM and cost estimating the variables referred to are the building information stakeholders and the integrity of the information exchange. Ultimately the list of stakeholders for a facility includes participants from every stage in the life cycle (Smith and Tardif 2009; NBIMS 2007). The owner, planner, environmentalist, realtor, appraiser and mortgage banker are examples of stakeholders in the early stages of a project. Typical stakeholders during the design and construction stage

are designers, architects, cost estimators, specifiers, general contractors, subcontractors, fabricators, suppliers, and code officials. The operation and maintenance stage includes facility managers, maintenance, safety and occupational health, plant operator, security manager, and even the insurer. Building information stakeholders in the closure stage are those responsible for disposal, recycling, and archiving (Smith and Tardif 2009).

Ideally the capability to exchange information between stakeholders is a benefit of using BIM however in some instances the opposite can be true and it can actually be a problem. How could sharing information possibly be a problem? From the cost estimator's perspective it can be a problem if the information author in the design phase inputs information that is not complete or accurate in accordance with the project's level of development. As a consequence the information is not reliable and therefore it becomes a problem for the consumer of the information, the estimator. This can be a significant problem for the estimator that relies on the information in the design model as the basis of an accurate QTO. Essentially the design model must contain reliable information required at every phase to complete the appropriate category of estimate. For example, a design model at the construction documents stage should contain the information necessary for the cost estimator to complete a bid estimate based on deterministic method of estimating.

Based on the discussion in this section the importance of building information to the estimator is apparent. Remember that in the estimating process the quantity take-off is the first step and that in the traditional estimating method the cost estimator is responsible for the time consuming task of quantifying materials. In contrast is the BIM method of estimating in which the QTO is automatically generated by the design model. This is a change in the process which shifts the responsibility of generating the QTO from the cost estimator to the design team, but leaves the estimator with the responsibility of validating the QTO.

The change in the estimator's role associated with a BIM generated QTO along with recommended practices to bridge the gap from the current state of BIM and estimating to the future of BIM and estimating is discussed in the BIM for estimating section of this chapter. It is a complicated topic that requires an understanding of the role and responsibilities of designers and estimators and the information each role requires to complete their responsibilities on a building project.

Constraints

The project delivery method selected by the facility owner for design and construction services can be a constraint on using BIM to prepare a cost estimate. A collaborative project delivery method such as the AIA Integrated Project Delivery (IPD) method or the DBIA Design-Build (DB) method aligns best with the collaborative intent of BIM. While there are examples of Construction Manager at-Risk (CM at-Risk) and Design-Bid-Build (DBB) projects using BIM, the contractual relationship between the owner, architect, and contractor act as constraints on the communication between parties in a way that may limit the open exchange of information. It is not uncommon in CM at-Risk and DBB to

find that the design team may not share their model with the contractor, or if they do share the model it is noted for design purposes only and may be completely void of useful information about object properties and materials so critical for cost estimating.

Through the collaborative methods in IPD and DB the project team works together and creates a BIM as the team progresses through the stages of defining the project and inputting project information. The less collaborative method of CM at-Risk and the completely linear method of DBB require an understanding about the information needed by an estimator to determine the project costs. The professional estimating associations are working to define the information needed at different phases in the design and construction process and they are working within the NBIMS framework to further awareness about the information exchange requirement for estimating using BIM in all project delivery methods. Some details about this effort are discussed in the BIM for estimating section of this chapter.

Opportunities

The number one opportunity for estimators is that the detailed BIM generated QTO may reduce uncertainty about material quantities and increase time available for the estimator to analyze the project and its alternatives. To this point in the chapter the discussion has focused on cost estimating at the project level however the benefits of using BIM for estimating extends farther to include the organizational level. At the organizational level the use of BIM for estimating can increase productivity for the architect, engineer, and contractors by eliminating redundant work and increasing the exchange of information across a project life cycle. The use of BIM for estimating can also provide the facility owner with information to use at various stages of strategic decision making, rather than just being used on in the late stages of project development (Smith and Tardiff 2009).

BIM FOR ESTIMATING: A LOOK EXISTING AND FUTURE USE

Existing Use

An exploratory study investigating the process used by cost estimators to validate a BIM generated QTO revealed a basic manual process (McCuen 2013). The cost estimators interviewed for the study reported the current validation process as time consuming, but necessary due to the gaps in the content of information available from the design model. Table 3-1 lists the steps reported to validate a BIM generated QTO in 2013.

Based on the process shown in Table 3-1, it reasonable to conclude that the effort expended by the estimator is extreme and it adds no real value to the project. In 2012 an industry survey revealed that 5D models for the integration of schedule and cost data will be a value proposition of BIM in the future however due to its level of difficulty 5D models ranked behind spatial coordination, quantity take-off, preliminary design phase budgeting, and 4D models in its frequency of use for

Table 3-1. Current steps in the BIM QTO validation process.

1. Manually check the design model against the traditional 2D set of drawings for the project.
2. Utilize a 'shadow' project to compare quantities from BIM with quantities from a traditional set of drawings.
3. Compare the design model with historical information from similar projects (traditional or BIM projects).
4. Ensure dataset is output in a usable format.
5. Review the QTO dataset for 'global' holes using Uniformat as a guide.
6. Focus on each level in Uniformat relevant to the project Level of Development.
7. Verify the integrity of the data from the design model and that the model elements used are appropriate based on the element's properties.
8. Confirm accurate use of model elements, such as correct slab element based on its location (e.g. slab on grade or elevated slab).
9. Map elements from the model to a complete data assembly that includes items specific for construction means and methods that are not typically in the BIM (e.g. formwork).
10. Select key items in the model for query about additions and/or deductions (e.g. deduct volume of concrete for embedded pipe in slab).
11. Verify that complete dimensional data is exported.
12. Manually spot check dataset against model content.

preconstruction activities (Bernstein and Fitch 2012). Integrating costs into BIM models today requires extreme effort on the estimator's part. For example even if the estimator receives an accurate QTO from the model elements, the model will not include information about construction means, methods, or sequencing. The cost estimator must therefore expend time to manually input this supplemental information. As a result, the additional time required to supplement the QTO with construction information adds overhead to thecost estimating task which then offsets the time savings gained in the automated QTO. The value proposition for automated cost estimating is one for the future. While BIM may be a standard business practice for many architects and contractors, it has yet to be fully defined, fully automated, or entrenched in the estimating community. Following is a brief list of user related resistance and limitations to the use of BIM by cost estimators (Young et al 2008):

- Down market – limited investment from large companies. Smaller companies adapt to survive.
- People too busy doing what they are doing to use new tools or change process
- Lack of training/understanding to use new tools
- Modeling to correct level of detail and for intended purpose

The last point of modeling to the correct level of detail addresses the issue of information exchange. Information exchange between stakeholders is an issue in which cost estimators should be actively involved and contribute to improving the process. Professional estimators realize this need and as a result on December 10, 2008 eight organizations in the construction industry signed a buildingSMART alliance memorandum of agreement (MOA) to define the information exchange requirements for cost estimating in BIM. The MOA describes the collaborating organizations' collective goal as being to develop best business processes, practices and open standards that can be used by all software vendors to develop applications with the capabilities to produce reliable and predictable estimation results. Resulting from the MOA was a collaborative effort, otherwise known as the Estimating in BIM Workgroup, comprised of interested members from Association for the Advancement of Cost Engineering International, American Society of Professional Estimators (ASPE), and the Royal Institute of Chartered Surveyors (RICS). The group agreed that their work would focus on developing items within the framework of the National BIM Standard. The workgroup agreed that it would focus on producing items firmly grounded in standard practices for cost estimating and results based on the concepts of stakeholder collaboration and interoperability of technology.

Early in the workgroup's process the decision was made to align the information exchange requirements from the design model to the estimator using the American Institute of Architects (AIA) level of development (LOD) framework. The AIA LOD describes building information model elements progressing through phases of building design. In particular the LOD of a BIM describes the level of completeness to which an element in a BIM is developed. Elements may represent a component, system or assembly of the building or building site (AIA 2008). Further development is underway by AIA to refine the definition of LOD so that it would include specific dimensional, spatial, quantitative, or qualitative data about a model element. The AIA E202 (AIA 2008) includes prescribes LOD categories based on the model content requirements and the authorized uses of each category. Cost estimating is one of the authorized uses for four of the five LOD categories. The LOD, design model content requirements, and authorized use for cost estimating are displayed in Table 3-2.

The AIA E-202 (AIA 2008) framework was selected by the workgroup to guide the estimator's exchange requirement based on its clear outline and alignment with estimate classifications. As a result the building projects for which the AIA BIM Protocol is used to define the model development currently impacts the building information exchange from the designer to the estimator. Therefore it is important that the design team and the estimator have a mutual understanding about the BIM data content at each level. To accomplish this, exchange requirements should be clearly articulated and adopted as a standard to meet the expectations of all stakeholders. A recent industry survey reported that QTO is a fast-growing activity that will accelerate in use with the adoption of better modeling standards (Bernstein and Fitch 2012).

Table 3-2. Level of development and estimating (adapted from AIA (2008)).

LOD	*Model Content Requirements*	*Authorized Use for Cost Estimating*
100	Overall building massing to indicate area, height, volume, location, and orientation may be modeled in three dimensions or represented by other data.	Authorized to develop a cost estimate based on current area, volume or similar conceptual estimating techniques
200	Model elements are modeled as generalized systems or assemblies with approximate quantities, size, shape, location, and orientation. Non-geometric information may also be included.	Authorized to develop a cost estimate based on the approximate data provided.
300	Model elements are accurate and specific assemblies in terms of quantity, size, shape, location, and orientation. Non-geometric information may also be included.	Authorized to develop cost estimates based on the specific data provided.
400	Model elements are accurate and specific as in LOD 300 with complete fabrication, assembly, and detailing information added. Non-geometric information may also be included.	Authorized to develop actual cost of specific elements at buyout

Information Required by LOD

In an effort to establish a standard, the estimators' workgroup created the following list of information needed at LOD 100 to complete a conceptual estimate using stochastic methods (McCuen and Bredehoeft, 2012). Given the high level of information necessary and the model content requirements at this LOD, most technology and design teams are capable of providing this information. The information required is as follows:

- Project location (geographic)
- New or existing building
- Remodel of existing
- Addition to existing
- Alternates
- Breakdown of requirements

- Square Foot/Square Meter of building by level
- Number of floors
- Overall height
- Building use type
- Structure type
- Exterior enclosure type(s)
- Special systems
- Overall building codes
- Anti-terrorism force protection
- Level of cost of finishes
- Location of existing site conditions
- Site constraints
- Site considerations – e.g. associated with the building
- Existing environmental conditions
- Zoning
- Building performance requirements – LEED, sustainability
- Construction, Operation and Reciprocal Easement Agreement (COREA)
- Allowances
- General Project Schedule

Meeting the estimator's exchange requirements at LOD 400 however requires much more information from the design team. The following is a partial list of information needed in the design model at LOD 400 to complete a deterministic construction documents estimate for bid (McCuen and Bredehoeft 2012):

- Standard Foundations
- Special Foundations
- Slab on Grade
- Basement Excavation
- Basement Walls
- Floor Construction
- Roof Construction
- Exterior Walls
- Exterior Windows
- Exterior Doors
- Roof Coverings
- Roof Openings

- Partitions
- Interior Doors
- Wall Finishes
- Floor Finishes
- Ceiling Finishes
- Elevators & Lifts
- Escalators & Moving Walks
- Other Conveying Systems
- Plumbing Fixtures
- Domestic Water Distribution
- Sanitary Waste
- Rain Water Drainage
- Other Plumbing Systems
- Elevators & Lifts
- Energy Supply
- Heat Generating Systems
- Site Lighting
- Site Communications & Security

The importance of modeling accurate building information by the design team means more than simply modeling the building. The actual level to which the information about the model elements are accurate and complete dictates the reliability of the information used to determine costs. The next section outlines a guide for defining exchange requirements in terms of factors and categories recommended for use by stakeholder and by the purpose for which the information is used in a building project.

Guide for Exchange Requirements

The discussion at this point presents the framework as a guide for defining information exchange requirements between project stakeholders. According to NBIMS (NIBS, 2007), three factors need to be in place to allow for interoperability in the computerized information exchange between project stakeholders. These three factors are:

1. The format for information exchange
2. Specification of the information to be exchanged and when to exchange the information
3. Standardized understanding between stakeholders of the information to be exchanged.

In addition to the three factors necessary for interoperability, the information needed to support an exchange can be categorized into seven groups (NIBS 2007).

1. WHO? This category defines who is requesting the information. For instance in the current process for cost estimating in BIM, the owner or architect may be requesting a cost for the design.
2. WHY? This category answers the question why is the activity happening and correlates with the stakeholder (who?).
3. WHEN? In this category the project phase is defined by design development phase.
4. WHAT? To answer this question the entities, objects, and properties of objects are defined along with the expectation that it is to be delivered between stakeholders.
5. To WHOM? In this category the stakeholder being asked to complete the task is identified.
6. HOW? This category specifies how resources are to be used to develop the design and construction of a project.
7. INPUTS & OUTCOMES? This category references the data utilized during the process of the creation of a facility. And the legacy documents used as references such as Masterformat, Uniformat, and OmniClass. It also includes data created by a model such as the quantity takeoff.

Future Use

Using BIM to determine costs for a project presents an opportunity for estimators to complete more analysis for informed decision making about cost alternatives. According to a recent industry report the adoption rate of BIM has steadily increased since 2007 when 28% of the industry reported using BIM compared to 71% in 2012. Furthermore the report indicated that the future of estimating in BIM appears to rely on the adoption of standards and the interoperability of technology (Bernstein and Fitch 2012). Until estimators can trust that the BIM data is accurate and comprehensive, skepticism will prevail and estimators will resist BIM and continue to use traditional methods for determining project costs.

The most promising aspect of BIM for estimators is the opportunity to increase the value added to a project by automating the QTO to generate an accurate bill of quantities that is a reliable source of information for input into the cost estimate process. Ultimately a BIM generated QTO that is accurate and comprehensive will facilitate improved productivity with less effort dedicated to measuring, counting and price loading. As a result the estimator can spend more time evaluating alternatives and complete analyses of the project. In the end estimators can expect that their role and level of contribution to a project's success will change when using BIM. Is the estimating community ready to change and adopt BIM?

CONCLUSIONS

The focus of this chapter was the cost estimating process and its evolution from the traditional non-BIM methods to the current state of cost estimating and BIM. For example, BIM replaces the time consuming quantity take-off with its capability to generate an automated QTO based on a model's level of development. While advances in technology have enabled shifts in responsibility BIM has yet to be accepted as a trusted source of data for the purpose of cost estimating. The reason estimators do not trust the BIM QTO is because there is no automatic method for validating the information contained in a model. A method for model checking the information is one of the most important BIM needs to most effectively advance the industry (Bernstein and Fitch 2012). Before a method for validating model information can be developed there must first be a standard for the information required for input by stakeholders at each level of model development. This chapter discussed in detail the cost estimating process in terms of both traditional and BIM methods as a basis for comparison. The chapter also discussed the early work being done in this area by professional cost estimators to establish standards for the exchange of reliable information so that the QTO can be trusted. Throughout the chapter there is a focus on the future for BIM and cost estimating. A future in which a building information model will provide estimators with the opportunity to devote more time for more analysis about project factors and increase the level of informed decision making about cost alternatives.

References

American Institute of Architects. (2007). *Integrated Project Delivery Guide*, Downloaded from http://www.aia.org/ip_default.

American Institute of Architects. (2008). *AIA Document E202™ - 2008*. <http://www.aia.org/contractdocs/AIAB095933>.

Association for the Advancement of Cost Engineering International. (2003). *Cost Estimate Classification System: TCM Framework 7.3 – Cost Estimating and Budgeting* (AACE International Recommended Practice No. 17R-97). Morgantown, WV.

Association for the Advancement of Cost Engineering International. (2006). *Required Skills and Knowledge of Cost Engineering: TCM Framework General Reference* (AACE International Recommended Practice No. 11R-88). Morgantown, WV.

American Society of Professional Estimators. (2011). *Standard Estimating Practice* 8th Edition, Vista, CA: BNI Building News.

Bernstein, H. and Fitch, E. (2012). The Business Value of BIM in North America: Trend Analysis and User Ratings (2007–2012), SmartMarket Report. Bedford, MA: McGraw-Hill Construction Research & Analytics.

Dagastino, F. and Peterson, S. (2011). *Estimating in Building Construction*. 7th Edition. Upper Saddle River, NJ: Prentice Hall.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2008). *BIM Handbook*, Hoboken, NJ: John Wiley & Sons, Inc.

Hollman, J. (2006). *Total Cost Management Framework 1st Edition*, Morgantown, WV: Association for the Advancement of Cost Engineering International.

McCuen, T. and Bredehoeft, P. (2012). *Cost Estimating in Building Information Modeling: Process Development Report*, *Association for the Advancement of Cost Engineering International, Transactions of the 56th Annual Meeting*, San Antonio, Texas, July, 2012.

McCuen, T., *Validating a Quantity Takeoff Generated by a Building Information Model*, *Association for the Advancement of Cost Engineering International, Transactions of the 57th Annual Meeting*, Washington, DC, *July, 2013.*

National Institute of Building Sciences (2007), *National Building Information Modeling Standard, Version 1- Part 1: Overview, Principles, and Methodologies*. Downloaded from http://www.wbdg.org/pdfs/NBIMSv1_p1.pdf

National Institute of Building Sciences (2012), *National Building Information Modeling Standard, Version 2*. Downloaded from http://www.nationalbimstandard.org/

Pratt, D. (1995). *Fundamentals of construction estimating*. Albany, NY: Delmar Publishers.

Smith, D. and Tardiff, M. (2009). Building Information Modeling:A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers. Hoboken, NJ: John Wiley & Sons, Inc.

Young, N., Jones, S., and Bernstein, H. (2007). *Interoperability (SmartMarket Report)*. New York, NY: McGraw-Hill Construction.

Young, N., Jones, S., and Bernstein, H. (2008). *Building Information Modeling (BIM) (SmartMarket Report)*. New York, NY: McGraw-Hill Construction.

This page intentionally left blank

CHAPTER 4

MILCON in the Department of Defense: Estimating, Building Information Modeling (BIM) Based Design, and Impact on United States Army and Air Force Construction

Patrick C. Suermann*
Lindsey R. Maddox†

Abstract: *The U.S. Army was one of the original Building Information Modeling (BIM) pioneers in the federal government, having published the Army "BIM Road Map" in October of 2006. The Air Force followed suit and required BIM on vertical construction projects starting in October of 2009. This chapter will review the particulars of the Military Construction (MILCON) arena and provide updates on the latest strategies for the Army and Air Force. Additionally, it investigates programming and design phase technological initiatives aimed at helping decrease cost growth in the construction phase. These tools include the Parametric Cost Estimating System (PACES™) software, BIM-based projects' statistical analysis, and BIM-based dynamic prototypes to optimize and standardize facility scope. Analysis resulted in inconclusive results with some BIM-based project types costing less per square meter to build and some costing more. For the category codes that were less expensive on the average (training facilities, hangars, and fitness/youth centers), researchers could speculate or infer that there was possibly less rework and greater design certainty, leading to less overall cost per square meter. Administration or*

*PhD, P.E., LEED AP, Assistant Professor, Department of Civil and Environmental Engineering, United States Air Force Academy, 2354 Fairchild Dr. USAFA, CO 80840; PH (719) 333-2444; email: patrick.suermann@usafa.edu

†P.E., Program Manager, Air Force Civil Engineer Center, 2261 Hughes Ave, JBSA Lackland, TX 78236-9853; PH (210) 969-8782; email: lindsey.maddox@us.af.mil

headquarters projects cost more per square meter for BIM-based projects. As the results were inconclusive, more research is required in this area.

INTRODUCTION

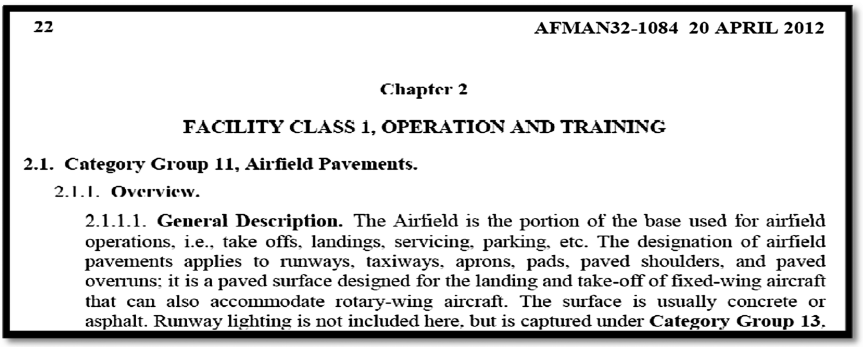
The United States military is the largest real property owner in the world (Carter 2012). Additionally, the Department of Defense (DoD) is frequently the largest single source/owner for construction annually. Consequently, since World War II, the DoD has been a source of standardization and innovation for billions of dollars of facility construction in the last 70 years. Many fundamentals of the construction industry came from the Army Corps of Engineers, Naval Facilities Command, or Air Force engineers. Examples include value engineering, lifecycle cost analysis, quality control/assurance, earned value calculations, and "ribbon cutter metrics" (Whole Building Design Guide 2013).

As the largest federal land owner and one of the top construction owners, the DoD plays a large role in the construction industry and is responsible for documenting standard procedures for many innovations. The DoD has regulations, manuals, handbooks, codes, and instructions for standard operating procedures for nearly every step of the construction process. However, it is also widely known that Military Construction (MILCON) projects are plagued by cost and time growth. This chapter will present three technological initiatives aimed at improving MILCON cost growth: parametric estimating, BIM-based design, and dynamic prototypes for optimized and standardized design. In order to properly describe the possibly foreign arena of MILCON, some background information will be provided on how the original, programmed amounts are determined for projects. Because these initial programmed amounts are the benchmark for final cost growth comparisons, the process for determining the initial programmed amount is worthy of scrutiny.

The military has a long history of implementing information technology software to help improve MILCON processes. The first portion of this chapter will describe how the military employs guides and software to support certainty in the estimating phase of the facility acquisition lifecycle. Later sections will outline how BIM helps to improve certainty in the design phase of the lifecycle. Lastly, BIM applications (e.g. dynamic prototypes) will be reviewed. As Shen and Issa demonstrated (2010), BIM improves estimating accuracy. However, this chapter will provide a more targeted focus and look solely at BIM's impact on the estimating and design for MILCON projects in the Department of Defense.

MILCON ESTIMATING

When developing the scope and a general cost estimate for a new MILCON project, the "old way to do it" (and it is still often done now) is that DoD estimators (programmers) reference several published documents that detail the



22 AFMAN32-1084 20 APRIL 2012

Chapter 2

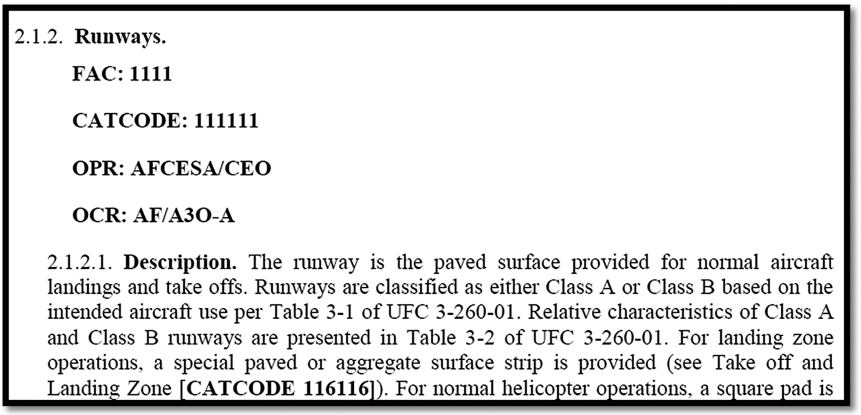
FACILITY CLASS 1, OPERATION AND TRAINING

2.1. Category Group 11, Airfield Pavements.

2.1.1. **Overview.**

2.1.1.1. **General Description.** The Airfield is the portion of the base used for airfield operations, i.e., take offs, landings, servicing, parking, etc. The designation of airfield pavements applies to runways, taxiways, aprons, pads, paved shoulders, and paved overruns; it is a paved surface designed for the landing and take-off of fixed-wing aircraft that can also accommodate rotary-wing aircraft. The surface is usually concrete or asphalt. Runway lighting is not included here, but is captured under **Category Group 13.**

Figure 4-1. Excerpt from air force manual 32-1084.



2.1.2. **Runways.**

FAC: 1111

CATCODE: 111111

OPR: AFCESA/CEO

OCR: AF/A3O-A

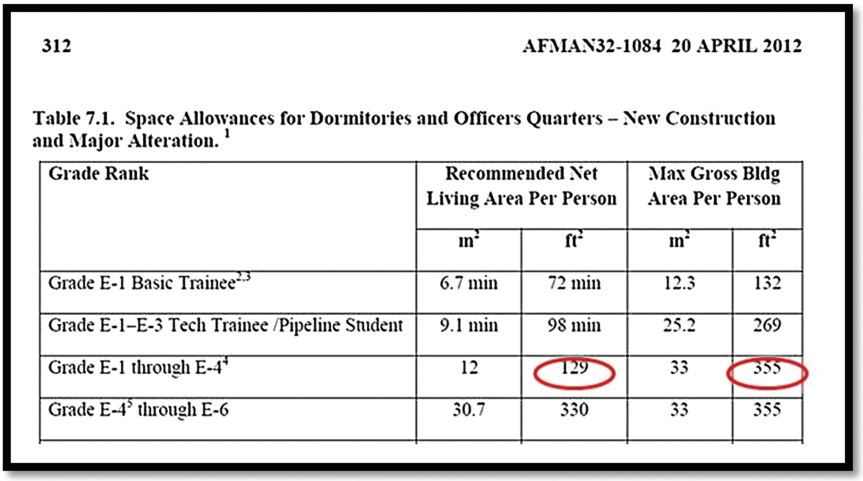
2.1.2.1. **Description.** The runway is the paved surface provided for normal aircraft landings and take offs. Runways are classified as either Class A or Class B based on the intended aircraft use per Table 3-1 of UFC 3-260-01. Relative characteristics of Class A and Class B runways are presented in Table 3-2 of UFC 3-260-01. For landing zone operations, a special paved or aggregate surface strip is provided (see Take off and Landing Zone [**CATCODE 116116**]). For normal helicopter operations, a square pad is

Figure 4-2. Excerpt from category code 111111 description.

standard size of each building type, functional areas included within the space, average cost per unit of area, and historical size, location, and inflation factors.

The first document that an Air Force programmer might reference is Air Force Manual (AFMAN) 32-1084 (See Figure 4-1).

AFMAN 32-1084 is an Air Force specific document that provides guidance on space allocations for new and existing Air Force facilities based on their Category Code (CATCODE) and the Real Property Classification System (RPCS). RPCS is a hierarchical numbering system that is used to identify what a facility is and how it is used. For example, all runways are classified in Category Group 11, Airfield Pavements, with a Facility Code (FAC) of 1111, and a CATCODE of 111111 (See Figure 4-2). A composite medical facility would be in Category Group 51 for Medical Centers and Hospitals, and have a FAC of 5100, and a CATCODE of 510001. These numbers form the framework for managing all Department of Defense property and facilities. They allow programmers to quickly sift through massive amounts of data to isolate buildings/facilities of a particular type.



312 AFMAN32-1084 20 APRIL 2012

Table 7.1. Space Allowances for Dormitories and Officers Quarters – New Construction and Major Alteration. [1]

Grade Rank	Recommended Net Living Area Per Person		Max Gross Bldg Area Per Person	
	m^2	ft^2	m^2	ft^2
Grade E-1 Basic Trainee[2,3]	6.7 min	72 min	12.3	132
Grade E-1–E-3 Tech Trainee /Pipeline Student	9.1 min	98 min	25.2	269
Grade E-1 through E-4[4]	12	129	33	355
Grade E-4[5] through E-6	30.7	330	33	355

Figure 4-3. Air force manual 32-1084 planning factors for sizing dormitories.

The ultimate goal of AFMAN 32-1084 is to enable the timely acquisition of facilities, expedited project design, equitable space allocations, and standardization of facility designs across the Air Force. If a new dorm for unaccompanied personnel between the ranks of E-1 and E-4 was to be built on any Air Force installation, AFMAN 32-1084 states that each member should be authorized 129 SF of individual living area, and the building should have a max gross area per person of 355 SF (See Figure 4-3). In other words, if the dorm was being built for 100 personnel, it should be no larger than 35,500 SF including all common rooms, bathrooms, and circulation. Additional information on the requirements of the building would be found in the Air Force Unaccompanied Housing Design Guide or the individual base or Major Command (MAJCOM) standards.

After the initial scope is determined, programmers use Unified Facilities Criteria (UFC) 3-730-01 and 3-701-01 to develop an order of magnitude cost estimate for the new construction. UFCs are similar to the AFMAN previously discussed in that they provide planning, design, and construction guidelines; however they apply to all military departments. UFC 3-730-01 specifically addresses Programming Cost Estimates for MILCON Projects, and UFC 3-701-01 is the DoD Facilities Pricing Guide. These documents are created by Headquarters, U.S. Army Corps of Engineers (HQUSACE), Naval Facilities Command (NAVFAC), and the Air Force Civil Engineering Center (AFCEC–previously the Air Force Center for Engineering and the Environment and Air Force Civil Engineer Support Agency before combining to form AFCEC on October 1, 2012). The size and cost data in the UFCs are based on historical averages of similar MILCON projects. They are periodically reviewed and updated to provide more accurate data. The current version of UFC 3-730-01 was published on June 6, 2011, replacing the previous guidance published on March 1, 2005. UFC 3-701-01 was most recently updated in September of 2012.

Table 2: Facility Unit Costs for Military Construction

Unit Costs for Military Construction FACILITY TYPE	Reference size (gross m2)	Oct 2011 unit cost (GUC) ($/m2)	Reference Size (gross SF)	Oct 2011 unit cost (GUC) ($/SF)	Standard Deviation ($/SF)	Standard Deviation /GUC pct (%)	Number of Projects
BARRACKS / DORMITORY (does not include kitchenette equipment)	7,989	2,075	86,000	193	39	20	93
BARRACKS - OPEN BAY, TRAINING	15,793	1,851	170,000	172	26	15	7
BARRACKS - STUDENT DORMS, ADVANCE TRAINING	15,793	1,644	170,000	153	15	10	11
OFFICERS QUARTERS (does not include kitchenette equipment)		**		**			
DINING FACILITY (includes kitchen equipment and installation)							

Figure 4-4. Excerpt from UFC 3-701-01, $193/SF for historical dormitory cost.

Table 4-1: Area Cost Factors	MILCON	Sustainment	1 Oct 2011 Currency Exchange Rate
COLORADO SPRINGS	1.07	1.10	
DENVER	1.02	1.00	
FORT CARSON	1.07	1.05	
PETERSON AIR FORCE BASE	1.07	1.05	
PUEBLO ARMY DEPOT	0.97	0.95	
SCHRIEVER AIR FORCE BASE	1.07	1.05	
ROCKY MOUNTAIN ARSENAL	DROPPED	DROPPED	
CONNECTICUT AVERAGE	**1.16**	**1.20**	
BRIDGEPORT	1.13	1.16	

Figure 4-5. Excerpt from UFC 3-730-01, area cost factors for Colorado.

Given the example of the new dorm for 100 personnel between the ranks of E-1 through E-4, a programmer would use these documents to find that the historical unit cost of a dormitory is $193/SF (See Figure 4-4).

The cost given in UFC 3-701-01 is an average, and it does not account for variations based on location or the size of the building, so a few more steps are required to get a more accurate cost estimate.

First, the programmer will look up the location modifier. Assuming the dorm is being built on Peterson AFB, the appropriate modifier for a MILCON project would be 1.07 (See Figure 4-5).

Next, the programmer will adjust the cost for the actual size of the building compared to the reference size that the historical unit cost is based upon. For a dormitory designed for 100-149 personnel, the project size factor is 1.03 (See Figure 4-6).

Lastly, the unit cost will be adjusted to address inflation based on the midpoint of construction. According to Table 4-2 of UFC 3-701-01 if the hypothetical midpoint of construction was October of 2015, a programmer would

Table 2 BARRACKS/DORMITORIES PROJECT SIZE ADJUSTMENT FACTORS

Numbers of Soldiers in the Project	Project Size Factor
1-99	1.07
100-149	1.03
150-199	1.00
200-299	0.97
300+	0.95

Figure 4-6. Excerpt from UFC 3-701-01, project size factors.

Historical			Budget Guidance		Projected	
Month-Year	ENR Indices (raw) (Note 1)	DoD SPI (Note 2)	FY	Annual escalation rate (Note 3)	Midpoint of constr (Note 4)	Escalation factor (Note 5)
Oct-03	3745					
Oct-04	4129					
Oct-05	4265					
Oct-06	4431					
Oct-07	4535	100.00				
Oct-08		104.89				
Oct-09		98.32				
Oct-10		96.83				
Oct-11		99.30			Oct-11	**1.0000**
			2012	1.70%	Oct-12	**1.0170**
			2013	1.70%	Oct-13	**1.0343**
			2014	1.80%	Oct-14	**1.0529**
			2015	1.80%	Oct-15	**1.0719**
			2016	1.80%	Oct-16	**1.0912**
			2017	1.80%	Oct-17	**1.1108**

Figure 4-7. Excerpt from UFC 3-701-01, military construction escalation rates.

use an escalation factor of 1.0719 to account for the fact that the UFC is based on data from 2011 (See Figure 4-7).

Now that location and size variations as well as inflation have been taken into consideration, the final step in determining the estimated cost of the new dorm facility is simple multiplication using all of the factors that the programmer found in UFC 3-701-01 and UFC 3-730-01 (See Figure 4-8).

Given that this is only a rough order of magnitude cost estimate the cost would most likely be rounded to 8 or 8.5 million dollars.

This section was intentionally laborious to show how pedestrian this process is for arriving at a cost that is still likely rounded to the nearest 6-10% for cost data.

$$Cost = Building\ Size \times Unit\ Cost \times Location\ Modifier \times Size\ Modifier \times Inflation$$

$$Cost = 35{,}500\ SF \times \frac{\$193}{SF} \times 1.07 \times 1.03 \times 1.0719$$

$$\boldsymbol{Cost = \$8,093,957.79}$$

Figure 4-8. Cost calculations using the factors provided in UFC 3-701-01.

The military knew that surely, there was a technological tool to help them make more accurate estimates more quickly than their existing process of "hand-jamming" order of magnitude costs for conceptual estimates.

PARAMETRIC COST ESTIMATING SYSTEM SOFTWARE™

Once the scope of the project is more clearly defined and a conceptual design has been completed, engineers have additional resources to develop more detailed cost estimates. One type of estimate that can be particularly helpful and is fairly easy to complete is a parametric cost estimate. A parametric cost estimate breaks the facility down into major systems and typically offers more accuracy than an order of magnitude cost estimate, without going as in depth as a detailed, line by line cost estimate. Air Force programmers typically use a PC-based software program like the Parametric Cost Engineering System (PACES™) to develop parametric cost estimates. PACES™ uses pre-built models to predict the cost of new construction and renovation projects given only basic design information from the user. Just like other cost estimating resources, the pre-built models are based off of historical averages for similar projects, and architectural and engineering assumptions.

To start a new estimate in PACES™, the user would first create a new project and define some of the basic project details such as location, client, construction start date, duration, etc. Users also have the ability to adjust markups like profit margins, taxes, contingency costs, and other percentages (See graphics in Figure 4-9).

Once those details have been established, a primary facility is created. Creating the primary facility is as simple as clicking a button, and searching for the facility type that matches the desired project. As seen in Figure 4-10, using the example of the dorm at Peterson AFB, the user may search for "dorm" and select an "AF Enlisted/1+1 dorm" (two single rooms that share a bathroom).

If the user has questions regarding the model facility type, PACES™ has descriptions of what is included in each building type or system (See Figure 4-11).

After defining the building type and size (See Figure 4-12), the user can edit additional details such as the number of floors, construction materials, HVAC systems, and additional amenities.

Common rooms, entryways, stairwells, elevators, hallways, etc. can all be added and adjusted to the appropriate size (See Figure 4-13).

In addition to the primary facility, PACES™ is also capable of incorporating the costs of any supporting facilities such as parking lots, sidewalks,

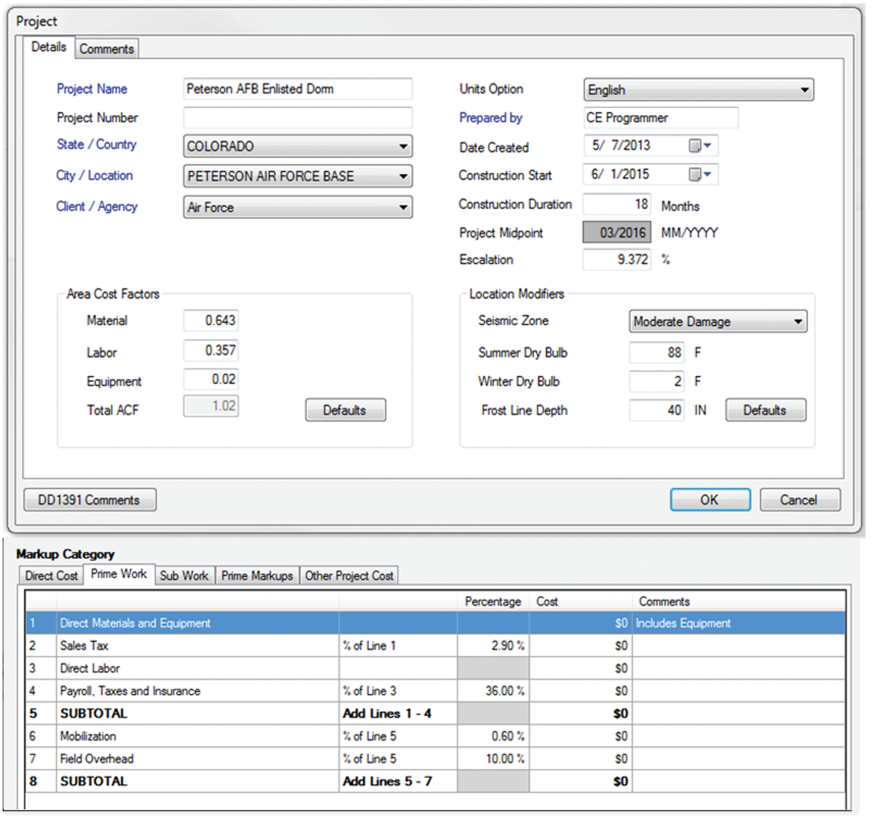


Figure 4-9. PACES™ graphical user interfaces for project and markups.

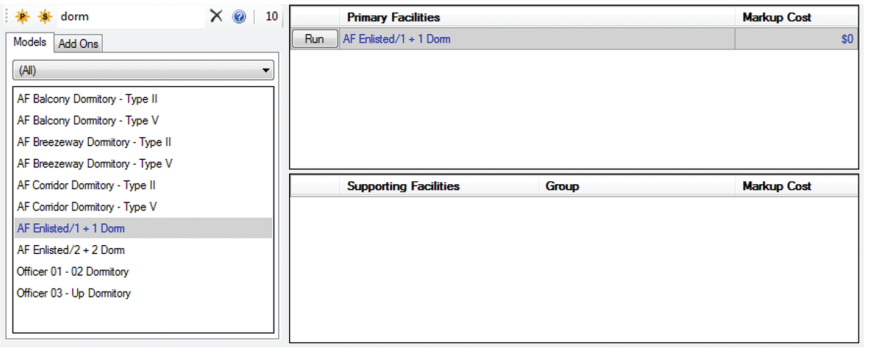


Figure 4-10. Query ability for facility types in PACES™.

and landscaping (See Figure 4-14). Just like when creating the primary facility, the user will add a secondary/supporting facility, search for and select the appropriate facility type, and edit the details and quantities as necessary.

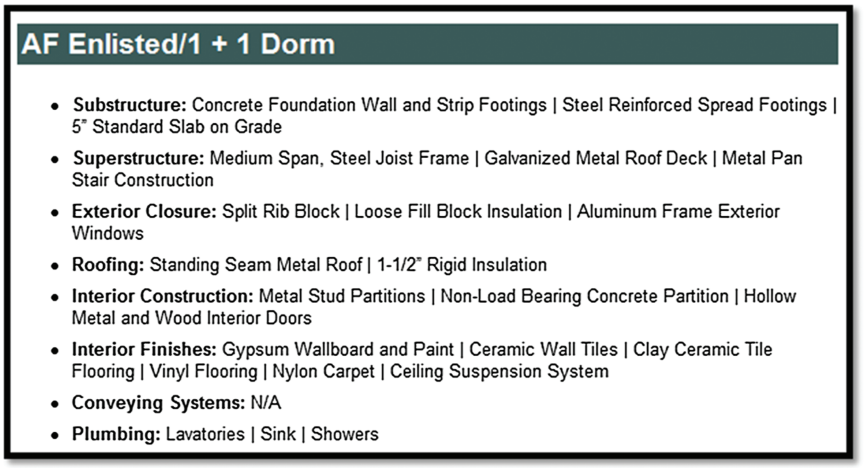


Figure 4-11. Building descriptions embedded in PACES™.

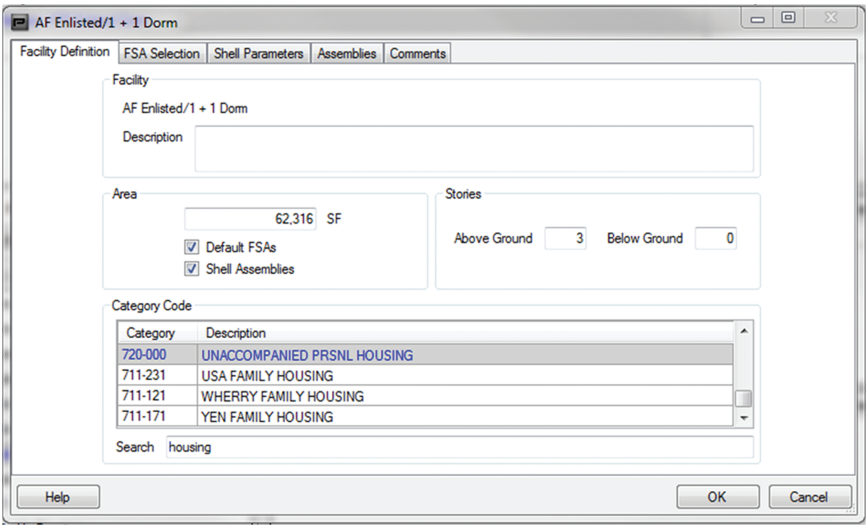


Figure 4-12. Facility definition interface for unaccompanied personnel housing.

Creating a parametric cost estimate usually results in a more accurate cost estimate, and also allows the programmer to compare alternatives quickly. For example, they could see what the cost difference would be if they added an elevator to the building or only used stairs, or what the cost difference would be between a brick veneer and stucco. Parametric cost estimates and programs like PACES™ are powerful decision making tools that can save owners and engineers time by providing an added level of clarity on construction costs.

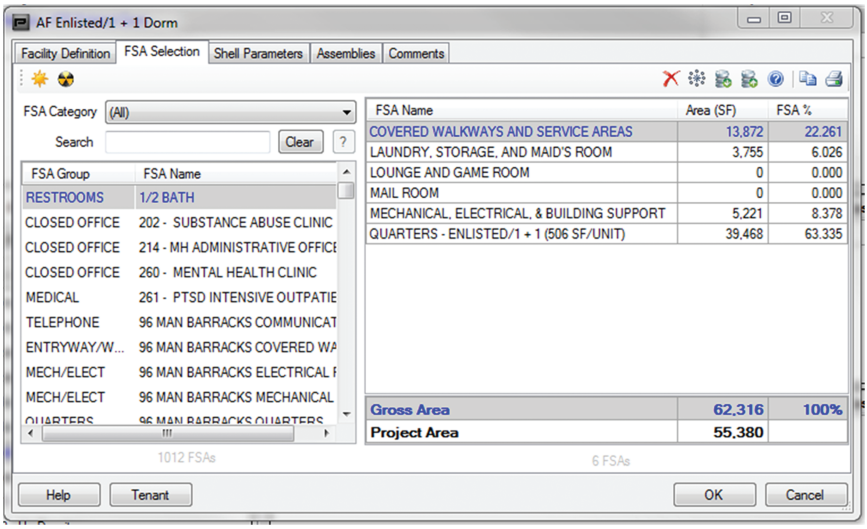


Figure 4-13. Customizing the facility shell with additional functional use areas.

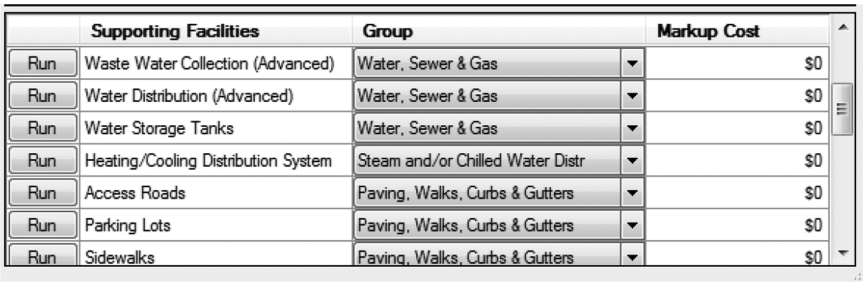


Figure 4-14. Supporting facility possibilities within PACES™.

MILCON TRANSFORMATION

The DoD is constantly seeking to improve its MILCON processes. Applications like PACES™ were implemented in the 1990s to help ensure greater certainty in the **programming and estimating phase** of the facility lifecycle. In the first decade of the 21st century, the DoD employed BIM as a way to help improve **design certainty**. BIM use in the architecture, engineering, construction, and operations (AECO) industry increased from 17% in 2007 to 49% in 2009 to 71% in 2012 according to McGraw Hill's Smart Market industry-wide surveys (Berstein 2012). One of the contributing factors attributed to this increase was requirements from large owners like the U.S. Army Corps of Engineers and U.S. Air Force that BIM-based designs serve as the basis for MILCON projects. The Army began suggesting that BIM was desired in 2006 (Brucker 2006) and made it a requirement in 2009.

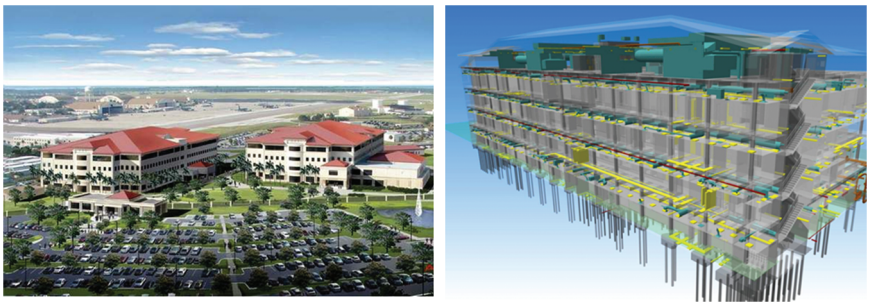


Figure 4-15. Burns & McDonnell (A-E firm) rendering of the HQ joint intelligence center and central command facilities at MacDill air force base, florida alongside a navisworks™ view of the first ever mandated air force BIM-based project.

The Air Force started requiring BIM on October 1, 2009 for projects designed in fiscal year (FY) 2010 and beyond (Sinkfield 2010). The first project that the Air Force ever required to be designed with a BIM-based approach was actually in FY09, the Central Command Headquarters facility at MacDill Air Force Base (See Figure 4-15).

Stated either directly or indirectly, the intent of the Army and Air Force for new BIM design requirements was to save money, decrease project delivery time, and improve project design and construction quality (Temple 2006). However, little research has been accomplished to evaluate if this new variable (BIM-based designs) has improved the facility delivery cycle in accordance with DoD intent. This research sought to fill that void.

BIM IN THE US ARMY

For FY 2013, the MILCON budget declined to $9.6 billion, $1.8 billion less than the 2012 budget. Of the three departments, the Army experienced the biggest drop in funding; declining $995 million to $3.2 billion in 2013. Air Force MILCON fell $893 million to $566 million, while the Navy's account decreased $339 million to $1.9 billion (ADC360 2012). Clearly, military funding for construction is increasingly competitive today. Conversely, in 2005 under the last Base Realignment and Closure (BRAC) commission, the DoD had a windfall of large MILCON budgets. In order to accommodate record MILCON budgets at that time, the Army sought to transform its MILCON procedures to adapt to the large amount of construction projects. The Army's MILCON Transformation primary initiatives were standardized projects that were "adapt-built" across the country as well as implementing a BIM Based approach to support their designs. In order to have a clear way forward, the Army promulgated their BIM strategy in the "BIM Road Map" (Temple 2006). Despite being less than 100 pages long, the Army BIM Road Map

of 2006 was a landmark document for owners seeking to document their BIM strategy and has been used by many other owners since as a basis for rolling out BIM-based design requirements.

Since 2006, USACE has partnered with BIM-aggressive, private-sector individuals, firms, and academia in conducting discussions and workshops on mutually beneficial BIM issues, such as best practices, standards, and contract language. Their goal is to strengthen public and private sector BIM initiatives. Part of the original MILCON Transformation Strategy was rapidly creating project requests for proposals. The Army created an "RFP-wizard" that contained boilerplate language that could be easily adapted for the large volume of projects. As a subset to this RFP-wizard, Attachment F (Whole Building Design Guide 2013) outlined BIM-based deliverables for A/E firms competing to win the projects. Attachment F dictated minimally acceptable requirements in BIM-based designs (Hutsell 2011). Moving forward to 2012, USACE BIM contract requirements/mandates from Attachment F were replaced by the more collaborative BIM Project Execution Plan (PxP) template and the Minimum Modeling Matrix (M3). There are several differences and improvements in the M3 approach versus the old Attachment F contract language (Foster and Hutsell 2012). When the Army initially created the Army BIM Road Map in 2006, BIM was viewed as a way to save time and labor associated with producing architectural drawings sets. In 2012, with the new release of the second iteration of the BIM Road Map, the Army focused on using BIM as a vehicle for business process transformation throughout the facility lifecycle from design through construction and into the facility management phase (See Figure 4-16).

As described in Attachment F (Whole Building Design Guide 2013), designers or Architecture and Engineering (A/E) firms were required to submit a BIM execution plan. The intent of the BIM plan was to establish the organizations' general means and methods of meeting the Scope and Deliverable requirements of USACE BIM Contract Language, and USACE was permitted to withhold payment for design or construction until the plans were acceptable to the Government. The plan was important because the government could withhold payment for contractors who did not accomplish acceptable performance in executing their BIM plans (Brucker 2006).

In reality, when most firms submitted their plan, plans were approximately one page of writing saying, "we will do BIM" and 50 pages of marketing material on the history and benefits of BIM (Foster and Hutsell 2012). The Army knew that a new approach was necessary. The solution and new approach for USACE BIM plans is to use the USACE Performance Execution Plan (PxP). The PxP was devised with assistance from Pennsylvania State University and the buildingSMART alliance™. The primary benefit of this new approach is that it establishes specific BIM project goals and objectives with clear accountability on which party will accomplish or support accomplishment of the design goals. Moreover, process maps help demonstrate the chronological progression of BIM

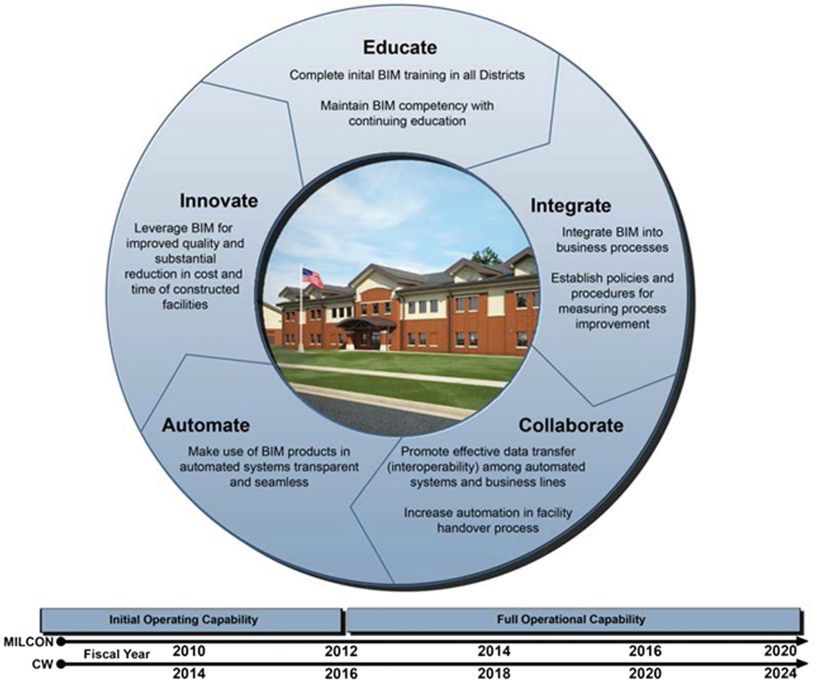


Figure 4-16. Army BIM road map plan for business process transformation across the facility lifecycle.

deliverables as the individual project matures. In this way, project partners can "map out" where they will model specific portions of the project's design, as well as how the model will mature throughout the life of the project. This foresight also aids in model accountability, so that all project partners know who should be modeling what.

Diving deeper, the Army's Minimum Modeling Matrix (M3) is a Microsoft Excel based interface that helps determine modeling requirements in conjunction with scope, Level of Detail (LOD), and grade of model for execution by project participants. The M3 uses the Construction Specification Institute OmniClass ID system and its accompanying parent items like "substructure" and then child items like "foundations" to delineate what will be modeled at what phase of the project's BIM execution plan (See Figure 4-17).

The Army's approach, outlined in their updated 2012 BIM Road Map, represents the leading strategy in the federal government with respect to clarity and specificity regarding BIM guidance. Because of the Army's collaboration with the private-sector and academia, their work benefits all A/E firms who wish to win contract awards for the DoD's billions of annual MILCON—and should eventually result in better designs and facilities.

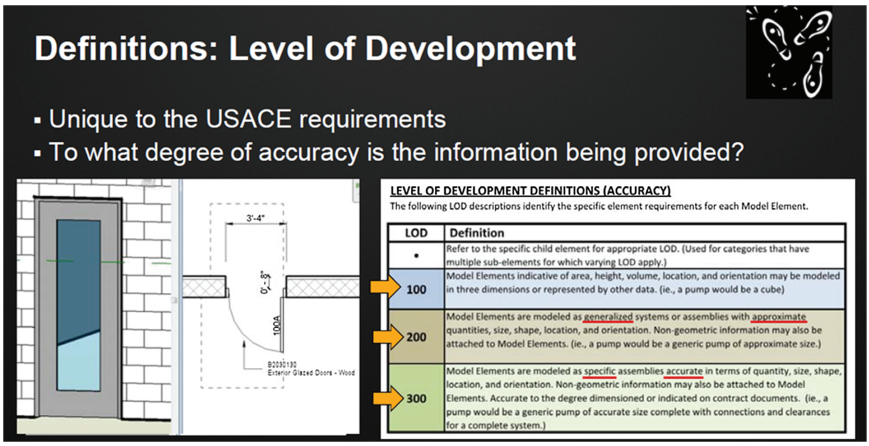


Figure 4-17. Visual component tied to omniclass element tied to level of detail (LOD) (Courtesy of Foster and Hutsell 2012).

BIM IN THE US AIR FORCE

The United States Air Force began requiring BIM-based designs on their MILCON projects on October 1, 2009 for their FY2010 MILCON program. Mr. Rick Sinkfield, Air Force Chief Architect, worked in conjunction with Colonel Michael Hutchison and others from the Air Force Civil Engineer Center's office of Air Force Capital Investments to include language in all new Design Instructions (DIs) that year requiring A/E firms to accomplish their designs with a BIM-Based approach. The Air Force modified the Army Corps of Engineers Attachment F and adapted it as their primary document governing BIM deliverables for Air Force MILCON. Later for FY2011, the Air Force created an Air Force-specific version of Attachment F for use in both Design-Bid-Build and Design-Build projects. Most notably, the Air Force also drafted a 157-page "Air Force BIM Flight Plan" document that was meant to guide BIM Champions at the strategic, operational, and tactical level on BIM use throughout the facility lifecycle.

The BIM Flight Plan is complete and used by some today as a reference providing analysis of BIM software, capabilities, and forward thinking; however it was never formally adopted. Therefore, the Air Force accomplishes most of its BIM program *ad hoc* and BIM-use is still relegated to the design phase of MILCON projects. However, BIM data is not used downstream as it is still gaining traction in the Air Force Operations and Maintenance (O&M) community. Work with Air Force Next Generation Information Technology (NexGen IT) leaders is ongoing to integrate BIM data from MILCON projects being completed today into the Air Force's winning future asset management platform, TriRiga™.

For this reason, and until BIM can show some downstream benefits as described in the National BIM Standard, it is even more critical to evaluate BIM's use in the design phase and if there is a correlation with construction project cost to determine if it is yielding any savings in the capital investment phases of design and construction. This was the driving force for the research accomplished and described in the rest of this chapter.

RESEARCH METHODOLOGY

This research attempted to demonstrate the impact of mandating a BIM-based design approach and evaluated completed Air Force MILCON projects from FY2007 to FY2012. Research compared BIM-based projects with non-BIM-based projects of similar types to determine whether or not there were statistically significant differences in the results. The null hypothesis is that BIM-based projects would not demonstrate a statistically significant difference for cost per square meter compared to non-BIM-based projects of similar facility type or category code. Additionally, Deke Smith and the National BIM Standard (NBIMS) committee called BIM a "disruptive technology" (Smith 2007). Subsequently, the DoD wanted to disrupt the existing project design process and attempted to reduce construction time and cost growth through better, BIM-based designs. However, there is no conclusive research that shows that the DoD's BIM requirements resulted in statistically lower cost or time growth.

There are thousands of projects tracked by the Army and Air Force with a myriad of funding types at locations all over the world. The first step for beginning the quantitative portion of the research was to determine the "filters" for distilling all of the projects into a control population of typical construction performance for a few types of frequently recurring projects. In other words, it was important to determine which projects would and would not be evaluated.

If all of the projects in the Air Force from 2007 to 2012 were the initial dataset, the research team set out to filter that dataset down to a manageable amount of projects. The first filter used to create the dataset was the year in which the projects were funded.

Next, projects were filtered to evaluate only those that were "construction complete." This included projects that were physically complete, substantially complete, financially complete, and/or those that were fully complete and resided in construction history after transitioning into real property operations and maintenance.

The third filter applied eliminated projects of facility types (or category codes) that were not primarily vertical construction. For example, airfield pavements and utility projects were eliminated from analysis.

The fourth filter applied eliminated facility types that did not have at least 30 projects in their datasets. The remaining facility types had a mean of 62 projects per facility type. After the initial dataset of control projects was filtered according to the four steps discussed, the Air Force Civil Engineer Center helped identify

which projects in the dataset were accomplished using a BIM-based approach. AFCEC is the central agency for all staff functions in Air Force civil engineering and serves as the centralized office charged with managing all traditional Air Force MILCON projects worldwide (Wolff 2012).

After receiving BIM information from AFCEC, one final step was taken to filter the data. Project category codes that had no BIM-based projects in their complete dataset were removed. (e.g. the military family housing project dataset met all the other filterable criteria, but had no BIM-based projects, so it was removed).

DATA ANALYSIS

The initial data collection and reduction of Air Force MILCON projects resulted in projects in seven categories. Table 4-1 shows a breakdown of the facility type, number of projects, and number of BIM-based projects. Of the total number of projects, 434, 29 projects were accomplished with a BIM-based approach. This represents less than 7 percent of the total number of projects in the design phase of execution from FY07-12.

Upon inspection, data was further filtered and research focused on the category with the most BIM-based projects for some initial, simple descriptive statistics. Fitness/youth centers had 14% of the project dataset being accomplished via a BIM-based approach; representing a percentage that is twice as high as the average number of project categories. Specifically for fitness/youth centers (category code 740), there were 57 projects total and of those, eight were accomplished with a BIM-based approach. With an average size of 3,510 square meters and average cost of $9.15M, it is notable that this facility type had an average cost per square meter of $2,607 for non-BIM-based data.

Focusing solely on the eight BIM-based projects, they had an average size of 3,506 square meters and $8.69M for an average cost per square meter of $2,478.

Table 4-1. Initial filtered data description

Cat Code	*Description*	*# of projects*	*# of BIM based projects*
141	Operations/Admin	79	2
171	Technical/Training	72	3
211	Hangars	77	6
721	Dorms	48	1
730	Support	54	4
740	Fitness/Youth Centers	57	8
610	HQs	47	5
Mean		*62*	*4.1*

Table 4-2. BIM-based project cost comparison for fitness/youth centers

# of projects in 740 Cat Code	*Average Size (SM)*	*Average Cost ($USD)*	*$/SM*
57 (non-BIM based)	3,510	$9.15M	$2,607
8 (BIM-based)	3,506	$8.69M	$2,478
Variance			−5%

This represents a favorable 5% difference in average cost per square foot for BIM-based projects (See Table 4-2). [Author's Note: MILCON projects are switching over to using metric measurements for facility area and some projects in the dataset were already represented in metric. Therefore, metric area measurements were used for standardization purposes.]

HYPOTHESIS TESTING

Further research was conducted to evaluate all category codes and compare the BIM-based projects with their control dataset of projects that were not accomplished with a BIM-based approach. First, the average cost per square meter (final construction cost) for all category codes was used in conjunction with the standard deviation and sample size to determine if the sample size provided a normal distribution (See Figure 18). According to Devore, hypothesis testing a dataset in a two tailed t-test requires a normally distributed population (Devore 2008). To determine if the sample sizes were large enough to be considered normally distributed with the amount of variance the dataset demonstrated, a statistical "rule of thumb" was applied. The equation for this test is:

$$\text{Target Sample size} = \frac{tvalue^2 * deviation^2}{.15^2 * mean^2} \qquad \text{Eq. 4-1}$$

Five of the six category codes evaluated had a sample size that exceeded the statistical rule of thumb sample size for normal distribution. Except for category code 730 (support facilities) which had too much variance, the control datasets were large enough and demonstrated acceptable variance to be considered normal distributions. Therefore, the data was appropriate for comparison with the BIM-based variable datasets of similar category code. It is important to note that Category Code 721(dorms) had to be eliminated from the initial dataset because its sole BIM-based project did not have sufficient area data and therefore was impossible to compare to the control dataset. Upon further investigation, half of the six facility types had an average cost per square meter lower than their control dataset's average. However, half of them had average costs per square

CAT CODE	141	211	171	730	740	610
Metric	COST/SM	COST/SM	COST/SM	COST/SM	COST/SM	COST/SM
avg	$3,139	$3,444	$3,325	$3,877	$2,628	$3,207
dev	$1,716	$1,876	$1,704	$3,828	$1,375	$1,221
std dev of the mean	204	234	205	591	196	184
Actual Sample Size	71	64	69	42	49	44
95% t value	1.994	1.998	1.995	2.018	2.010	2.015
90% t value	1.667	1.669	1.667	1.682	1.677	1.680
95% interval value	406.08	468.45	409.33	1192.15	394.62	370.89
90% interval value	339.42	391.37	342.09	993.59	329.22	309.22
95% CV	0.13	0.14	0.12	0.31	0.15	0.12
90% CV	0.11	0.11	0.10	0.26	0.13	0.10
95% Low	$2,733	$2,976	$2,915	$2,685	$2,234	$2,836
95% High	$3,545	$3,913	$3,734	$5,070	$3,023	$3,578
90% Low	$2,800	$3,053	$2,983	$2,884	$2,299	$2,898
90% High	$3,479	$3,836	$3,667	$4,871	$2,957	$3,516
Sample Size (.15 CV)	52.81	52.62	46.48	176.46	49.10	26.16
Sample Size (.15 CV)	36.89	36.73	32.47	122.57	34.17	18.18
BIM-BASED	COST/SM	COST/SM	COST/SM	COST/SM	COST/SM	COST/SM
BIM Sample Size	2	5	2	4	8	5
BIM 740	$3,746	$3,095	$3,304	$4,769	$2,478	$3,654
Comparison (95%)	OUTSIDE	INSIDE	INSIDE	INSIDE	INSIDE	OUTSIDE
Comparison (90%)	OUTSIDE	INSIDE	INSIDE	INSIDE	INSIDE	OUTSIDE
+/- AVERAGE?	UNFAVORABLE	FAVORABLE	FAVORABLE	UNFAVORABLE	FAVORABLE	UNFAVORABLE

Figure 4-18. Normality testing and comparison for BIM-based projects.

meter that were higher than their control dataset's average. Additionally, two of the six facility types were unfavorably outside the 90% and 95% confidence intervals for cost per square meter. In other words, according to the data, you could predict with 95% certainty that a future project in the 141 or 610 (operations/administration or headquarters) facility types accomplished with a BIM-based approach would cost more per square meter than a project that was not accomplished with a BIM-based approach. For these category codes, the data provides evidence contrary to the null hypothesis that BIM-based projects would not demonstrate cost per square meter differences.

DISCUSSION

With the stochastic nature of construction project execution (Ellirtgwood 1987), it is important to note that the correlations for this data subset do not suggest causation. For the category codes that were less expensive on the average (training facilities, hangars, and fitness/youth centers), researchers could speculate or infer that there was possibly less rework and greater design certainty, leading to less overall cost per square meter. Unfortunately, there were also administration or headquarters projects that cost more per square meter for BIM-based projects. Possible explanations include geographical

variables or market forces. (e.g. a BIM-based project in one area of the world may have a great design but be less successful in the construction phase due to poor management or labor shortages particular to that contractor or area).

As the results are inconclusive, more research is required to determine further correlation or trends associated with comparing traditionally non-BIM-based with BIM-based projects. Moreover, it would be beneficial to apply a new statistical approach that uses sensitivity analysis to find which key performance indicator could be the most predictive, rather than explanatory, for future construction success.

Furthermore, there needs to be an easier way for MILCON project managers to enter their project data so that the data can be more reliably evaluated for changes in productivity when variables such as BIM, LEED, or others are introduced into the system. There were many projects that had to be eliminated from analysis after learning that their data was incorrectly entered in some of the fields, rendering them useless for analysis with respect to the approach accomplished here. For Air Force leaders to make informed decisions, future MILCON databases need to be populated with reliable data and should be saved or indexed in a way that makes them easy to query. Perhaps NexGen IT initiatives will incorporate easier graphical user interfaces or other initiatives to accomplish this for the Air Force.

The initial research also set out to analyze Army construction metrics, as well, but the datasets were even more unwieldy than the Air Force's, resulting in an inability to run the normality or confidence interval approach on the voluminous data. Despite support from Army contacts at the Seattle District and their central Resident Management System (RMS) helpdesk, applying this research methodology was like trying to fit the "proverbial square peg in a round hole." Unfortunately, Army data will have to be analyzed differently for future research efforts.

Lastly, it was informative that despite the BIM-based requirement, the Air Force had a very low (less than 7%) proportion of projects that are completed that have been accomplished with BIM. Further research will aim to include many more projects that were accomplished with BIM, as well as projects that were accomplished by firms with more BIM experience, further lowering the initial capital cost of "going BIM." It is reasonable to infer that future trends may indicate that BIM-based projects will demonstrate lower cost per square meter than the data analyzed here from the projects from FY07-12.

DYNAMIC PROTOTYPES

In 2008, the Air Force partnered with Jacobs Global designers to create BIM-based designs that would optimize and standardize repetitive facilities like enlisted dormitories, security forces facilities, fitness centers, and fire stations. The

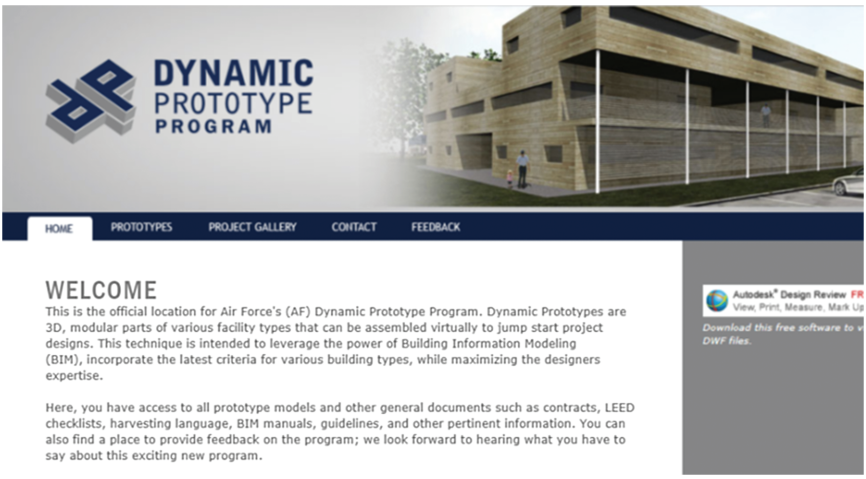


Figure 4-19. Dynamic prototypes site screen capture.

philosophy was that by creating optimized layouts on a small scale with individual spaces like dorm rooms and bathrooms, these smaller, optimized layouts could be repeated and combined to make optimized facilities. In other words, the BIM provided a "kit of parts" or "Legos™" for building better facilities. This was the genesis of the dynamic prototypes.

In 2009, Jacobs completed the Air Force's first dynamic prototype, enlisted dorms. By going to the Dynamic Prototype Program and using an AFCEC provided login, any designer creating a new facility can use the dynamic prototypes to quickly create approved Air Force designs that optimize useable area (See Figure 4-19).

Design teams used the dynamic prototypes for design charrettes or Rapid Design Development (RD2) sessions to help plan future projects. In one particular case, Jacobs designers used the dynamic prototypes to create entire campuses of dorms for Lackland Air Force Base in only two days (see Figure 4-20). The designers noted that previously, they would have spent most of their time trying to determine room layouts, but because of the dynamic prototypes, they were able to maximize design on a much larger scale, in much less time.

The dynamic prototype program started with enlisted dormitories and is working on creating more dynamic prototypes for the facility types the Air Force builds the most. Additional benefits of the dynamic prototypes exceed the geometric benefit, and emphasize the "I" in BIM. Dynamic prototypes are pre-loaded with, and allow for additional specifications tied directly to the building data within the design. In this way, assembly codes and their appropriate spec sections are embedded in the kit of parts. The software used to accomplish this is called "eSpecs™ for Revit" (see Figure 4-20). AFCEC is excited about the possibility of requiring this even on designs that do not use dynamic prototypes.

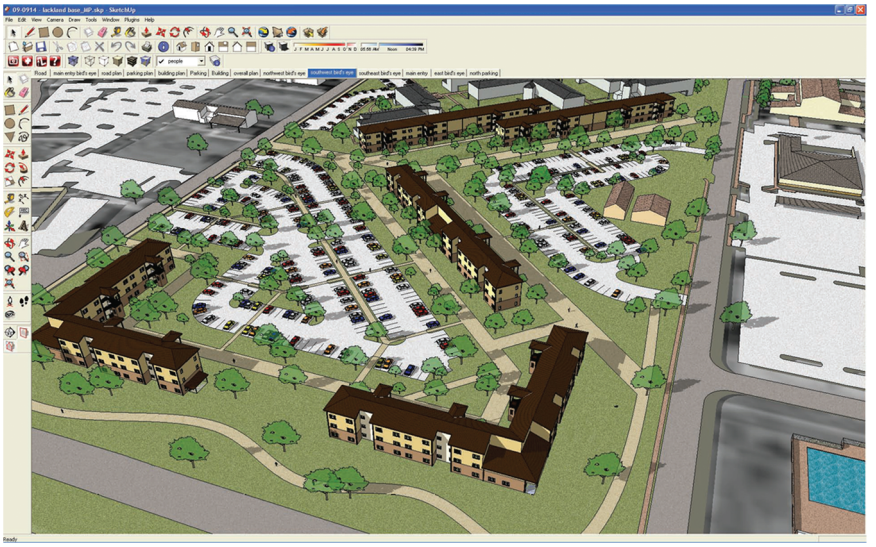


Figure 4-20. Screen capture of RD2 end product using dynamic prototype dorm layouts.

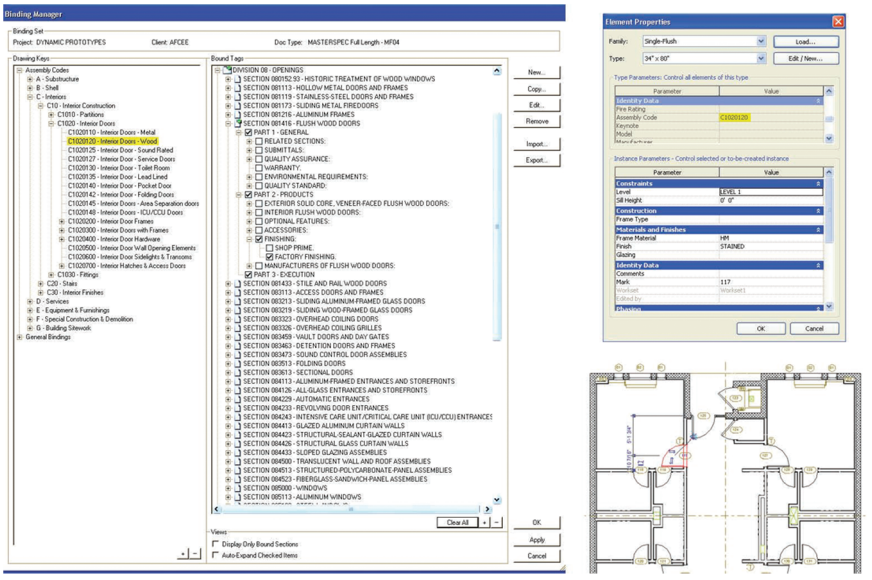


Figure 4-21. Screen capture of embedded specifications tied to geometry in the BIM.

CONCLUSIONS AND RECOMMENDATIONS

It is imperative that the federal government improve its "culture of cost consciousness." Because MILCON budgets are typically in the billions of dollars, even a slight percentage process improvement would yield millions of dollars in return on investment. Therefore, this research's impact should be two-fold. BIM-based mandates should continue in line with industry trends of noted improvements and best business practices should be documented and benchmarked to drive down MILCON costs. As an owner, the Department of Defense needs to strive towards continuous improvement. For future A/E firms to be successful, they will need to align their processes and organizational behavior with DoD BIM-based project design and acquisition requirements.

Lastly, the military needs to reflect more on the impact of their strategic mandates. In other words, military leaders should apply the scientific method when implementing process improvements to evaluate whether their changes yield the desired results in the long term. In this way, the best process improvements will become part of the standard operating procedure, while other changes may be discarded in favor of more successful process improvements.

Conclusions and recommendations for the primary items/initiatives discussed here will be provided in the same order as listed in the chapter. First, one way to apply the scientific method to the "traditional" process of estimating as described at the beginning of the chapter and published in Air Force Manual 32-1084 and the Unified Facility Code is for the government to accomplish metric collection and test for sensitivity analysis to determine those variables that have the greatest impact on construction cost and time growth. Applied further, estimators could apply ranges of sensitivity and provide cost estimates with confidence intervals to commanders and Congress for a more accurate picture of MILCON estimates. Applied even further, contracting officers could incentivize contracts for contractors who are able to meet quicker schedules and lower overall cost targets. In this way, MILCON contractors would be motivated to complete their projects more quickly and for less overall cost, if they knew there was an incentive (in the form of increased pure profit) for finishing within specified targets.

Second, estimating like PACES or the Army's TRACES tool, which also helps estimators predict cost by providing historical cost databases need to be error checked and cross-checked with traditional estimating processes like 32-1084. Some MILCON estimators have called for tools like Beck's D-Profiler that combine models with cost data so that early design can present not only massing models, but also a model-driven cost component. Currently there is no military tool or software that is widely used that provides this type of functionality. This is an area ripe for further research by computer programmers or the software industry.

Third, the paper addressed the Army's BIM PxP approach that better helps contractors and owners assimilate BIM requirements into contract language.

In follow-up, anecdotal research, leading VDC contractors like Mortenson, Inc. of Minneapolis, Minnesota are also using the PxP on projects that are not required by the owner. The BIM PxP warrants further research for how it has helped implement BIM on projects in the public and private sectors. At first glance, it appears that is as achieved the often sought, but rarely achieved goal of a research endeavor that brought together the National Institute of Building Sciences, Universities, Contractors, Architects, and large federal owners and truly provided a tool that is so useful all the parties specify its use. In fact, since this chapter's first draft, the U.S. Air Force followed suit and also mandated a slightly Air Force-specific version of the BIM PxP for use on all FY14 (and later) MILCON projects.

Fourth, owners need to evaluate the impact of their mandates. Every year, there are scores of mandates, Executive Orders, Engineering Technical Letters, and laws levied on MILCON projects. However, other than the occasional Government Accounting Office (GAO) audit, there are rarely ever efforts accomplished to determine the impact of the new requirements. The Department of Defense needs to do a better job of using their supervision, inspection, and overhead employees to become an "army of sensors" who are able to document and provide data for knowledge management and data mining to determine trends regarding new initiatives. Only initiatives that can demonstrate successful goal accomplishment should be retained and pursued. Others should be abandoned. This research demonstrated one relatively simplistic way to include metrics in response to mandates.

Fifth, the dynamic prototypes and e-specs initiative should progress for all facilities which are commonly found on Air Force installations. They serve as optimized facility layout tools and their updates will help increase design innovation. Contrary to the Army's facility standardization initiative of the mid 2000s, the Air Force's dynamic prototypes initiative better accommodates base architectural standards, flexibility, and model-based simulations while still retaining optimized facility functionality. As demonstrated in the Lackland charrette, dynamic prototypes allow designers the ability to provide more design options more quickly, which should be the ultimate goal of every design charrette.

ACKNOWLEDGMENTS

The views expressed in this research are those of the authors and not necessarily those of the U.S. Air Force Academy, the U.S. Air Force, the Department of Defense, or the U.S. Government.

The authors would like to thank the Air Force Civil Engineer Center Facilities Excellence branch, specifically, Mr. Jim Winslow in the "World's Best Integration Cell" for his tireless support and access to Air Force MILCON data. Additionally, thanks go to Mr. Steve Hutsell, Chief, Geospatial Section, USACE BIM Contract Language Lead, US Army Corps of Engineers and Mr. Van Woods, BIM Program Manager, Northwest Division Regional BIM Coordinator, Center

of Standardization BIM Technical Coordinator, US Army Corps of Engineers Seattle District. This research would not have been possible without their support regarding all items related to Army MILCON policy, procedures, and data. From the Air Force Academy's Department of Civil and Environmental Engineering, thanks go to Lt Col John Christ, PhD, P.E. for his advice on statistical testing as well as Ms. Carolyn Robinson for her thoughtful editing.

References

Bernstein, H. (2012). "The Business Value of BIM in North America: Multi-Year Trend Analysis and User Ratings (2007-2012)." *McGraw-Hill Smart Market Report*.

Brucker, B., Case, M. P., East, E. W., and Huston, B. K. (2006). "Building information modeling: A road map for implementation to support MILCON transformation and civil works projects within the US Army Corps of Engineers," Champaign, IL, p. 6–9.

Carter, A. (2012). "Energy Security and Innovation" *Deputy Secretary of Defense Remarks given at Georgia Institute of Technology on April* 16, 2012 Sam Nunn Policy Forum. <http://www.defense.gov/pubs/pdfs/Energy_Security_and_Innovation_based_on_remarks_given_at_Georgia_Tech_04DB.pdf>

DC360 (2012). "MILCON delay contributes to budget savings," *Association of Defense Communities* <http://www.defensecommunities.org/headlines/milcon-delay-contributes-to-budget-savings/#>

Devore, J. (2008). *Probability and Statistics for Engineering and the Sciences*. Thomson Brooks/Cole, California, 314–315.

Ellirtgwood, B. (1987). "Design and construction error effects on structural reliability," *J. of Structural Engineering* vol. 113(2), Feb. 1987, 409–422.

Foster, S. and Hutsell, S. (2012). "A dissection of the U.S. Army Corps of Engineers BIM requirements," *Autodesk University*, Dec 2012.

Hutsell, S. (2011). "Opportunities and Challenges of BIM at the Army Installation—USACE District Perspective," *USACE Infrastructure Conference*, Jun 2011.

Shen, Z. and Issa, R. R. A. (2010). Quantitative evaluation of the BIM-assisted construction detailed cost estimates, *Journal of Information Technology in Construction (ITcon)*, Vol. 15, pg. 234–257.

Sinkfield, R. (2010). "Air Force BIM for MILCON transformation - Guidelines," Whole Building Design Guide.

Smith, D., et al. (2007). "National Building Information Modeling Standard" National Institute of Building Sciences.

Suermann, P. (2009). "Evaluating the impact of BIM on construction," University of Florida PhD dissertation.

Temple, M. (2006). "MILCON Transformation: Delivering quality sustainable facilities in less time at lower cost," *Public Works Digest*, vol XVIII (5) Sept/Oct.

Whole Building Design Guide (2013). "The Gateway to Up-To-Date Information on Integrated 'Whole Building' Design Techniques and Technologies" for AFMAN 32-1084, Attachment F, UFC 3-730-01, and UFC 3-701-01 <http://www.wbdg.org>

Wolff, R. (2012). "Leader Profile: Joe Sciabica, SES," *The Military Engineer*.

CHAPTER 5

BIM Inertia: Contracts and Behaviours

M. Hooper*
K. Widén†

Abstract: *Whilst Building Information Modelling (BIM) promises significant improvements in construction quality and efficiency, current contractual models do not encourage its use; indeed actively inhibit the collaboration at its core. To help bring BIM into the mainstream, it is claimed we need to re-craft existing contractual relationships to facilitate collaborative decision making and to equitably allocate responsibility among construction participants. This chapter looks at the case of Sweden and aims to identify and appraise observed hindrances to BIM collaboration and digital information stewardship. It presents an understanding of the connections between the commercial environment and contractual provisions that regulate the party's business relationships and the resultant procedural and behavioural phenomena that can be viewed to thwart BIM collaboration and degrade the value or integrity of digital deliverables. The study then, in a more general context, asks what we can learn here that may have wider application through consideration of suitable BIM collaboration support mechanisms that may reduce or remove collaboration barriers, induce open, sharing behaviours and support the creators and users of digital information. Methods employed include a critical review of existing contract forms, synthesized with focus group interviews (FGIs) with representatives from diverse AEC disciplines. Results indicate that a number of systemic difficulties exist that can create an inertia which can be traced through behaviours and circumstances to contractual provisions. An understanding of such difficulties is presented and a consensus emerges on a number of key supporting mechanisms that may better facilitate meaningful early BIM collaboration and oil the wheels of communication without recourse to re-writing the rule-book.*

*Department of Construction Sciences, Lund University, Faculty of Engineering, Box 118, 22100 Lund, Sweden; PH +46 (0)732-604271; email: martin.hooper@construction.lth.se

†Department of Construction Sciences, Lund University, Faculty of Engineering, Box 118, 22100 Lund, Sweden; PH +46 (0)46-2227845; email: kristian.widen@construction.lth.se

INTRODUCTION

BIM implies an increased collaborative effort in the early stages of construction projects (Jongeling, 2008; Eastman et al. 2011). But in what ways is this prerequisite manifesting itself in contractual provisions and procurement? In the US, Ashcraft (2008) has highlighted the need to re-craft existing contractual relationships to facilitate collaborative decision making and to equitably allocate responsibility among all construction participants. Consequently the American Institute of Architects (AIA) has developed through its partners a series of new contractual arrangements compatible with an Integrated Project Delivery (IPD) philosophy. Reports are emerging on the successful and advantageous application of IPD to support BIM (Cohen 2010), whilst elsewhere the industry is toiling with half-hearted collaborative processes, thwarted by contractual inertia imposed though traditional procurement routes.

In Europe, progress towards contractual support for BIM and delivery of integrated processes has been markedly slower. Pfitzner et al. (2010) reminds us that changes are required at national and project level, including commitment among project team members to collaboration. Owen et al. (2010), in connection with collaborative processes and BIM, explains current conditions exhibit underlying cultures of distrust and litigation that impede experimentation, iterative approaches to design solutions, and progress with BIM integration. Furthermore, that silo mentalities prevail and document-based information exchange across professions and throughout supply chains ensure digital information and particularly any associated intelligence, coordination and agility is either corrupted or lost and it passes downstream.

Owen et al. (2010) further argue that successful implementation of integrated processes requires changes including: a team approach, support for innovation and tolerance of failure in a team; strong lateral linkages and decentralized decision making; networks of commitment; and new forms of contracting, transparency and risk management. Finally, Race (2012) claims BIM as a means of cooperating through information management in the project team is currently at odds with the legal and commercial environment in which it has been invented, and that contracts and procurement documentation tend to insulate and isolate rather than actively support collaboration. They set boundaries and barriers which are not conducive to working in a BIM mode.

These studies and reports present a broad range of difficulties associated with BIM collaboration and information sharing within the contractual arena but lack insight and practitioner feedback on perceived connections between contractual provisions and behaviours and secondly on the suitability of emerging measures to mitigate barriers to BIM collaboration and the delivery of integrated digital construction project information. Accordingly, research conducted so far on contract related hindrances to BIM collaboration is limited and requires further investigation. There are areas in need of further investigation which bring together behavioural and procedural aspects of contract execution with the need for

improved early collaboration on BIM projects. This may provide a method in which one can consider if and how the traditional mindset can be overcome.

From the above we can identify the following research question: *What is the connection between traditional contracting and BIM inertia and what are the necessary components that may facilitate more effective early BIM collaboration?*

More specifically, the research here aims to examine the connections between the legal and commercial environment of construction contracts and the resulting procedures and behaviours that may be seen to hinder BIM collaboration. An understanding of the issues involved may shed light on the suitability or otherwise of BIM collaboration support mechanisms emerging elsewhere.

Collaboration is at the core of the use of BIM technology across sector disciplines and through facility life cycles. Ashcraft (2008); Knight (2008); Pfitzner et al. (2010); Eastman et al. (2011); Race (2012) all suggest that change in contractual arrangements, whether addendums to existing contracts or entirely new contracts are evitable but there is still little knowledge on what to add or subtract to facilitate a more effective early collaboration centred on the smart use of BIM resources, technology, and applications. This study aims to shed new light on the barriers and challenges to earlier and meaningful collaboration around BIM implementation, presents an understanding of the key issues and considers the suitability of plausible collaboration support mechanisms based on the AIA's E202 Model (AIA 2008).

This research builds on that in the field and contributes with insights into real world collaboration difficulties in connection with the creation, use and exploitation of digital project information in the commercial and legal context regulated by the construction contract.

The enquiry focuses on phenomena experienced in the Swedish construction industry which can be considered typical (vis-à-vis contracts and behaviours) within the European arena and considers what aspects from the results may have wider relevance or application. The literature review supports the study. The empirical data collected has been limited to interviews with a number of national organisations and covers a broad and representative range of disciplines.

The context of BIM inertia, contracts and behaviours, focuses on those: 1) In connection with the design – construct – operate process generally; 2) In connection with generating and implementing a project-specific BIM-Plan; 3) In connection with planned BIM-Uses and down-stream utilisation of digital information.

The investigations enable an articulation of discrete relationships between construction contracts, the legal and commercial environment, and the circumstances and behaviours that create barriers to collaboration in connection with BIM and the exploitation of digital information. The findings reveal a number of distinct behaviours, remnant from traditional contracting, are present in BIM projects that significantly hinder full utilization of digital data and compromise project outcomes. Finally, broad support for some form of BIM-Addendum to contract exists however a resistance to new contract forms prevails. The question

that remains is whether BIM-Addenda will themselves reduce or eliminate barriers to BIM collaboration. Nevertheless, BIM-Addenda are seen as a means to support an improved and meaningful BIM collaboration and represent a first step towards a more integrated approach to project delivery.

The chapter begins with a description of the methods used in the study. The outcomes from document review and industry interviews are then presented which emerge as a set of key issues against which BIM collaboration support mechanisms can be arranged. This is followed by a discussion of the results and their implications.

METHOD OF INVESTIGATION

A qualitative approach was adopted from a critical realism perspective where acknowledgement is made to contextual factors (associated with case) whilst also arguing the phenomena under study can occur in similar settings (Saunders et al. 2009). Adoption of this approach supports the investigation in so far that it allows for the study of a complex and contemporary phenomena over which the investigator had little or no control (Yin 2009). Data gathered has been deductively analysed to expose and interrogate the key components that influence the particular phenomena under study and enable a clearer understanding of both contractual and behavioural challenges to BIM collaboration in context and provide insight into emerging issues that can be deemed as relevant generally.

The main findings on BIM inertia, contracts and behaviours builds upon a critical analysis of the key documents outlined below and applies Focus Group Interviews (FGI's) as secondary research method of data collection to identify where industry perceive hindrances exist and assess the level of concern. FGI's differ from surveys and questionnaires as they not only enable the collection of more in-depth data, but they also provide a forum for the different disciplines to share and clarify their views on various discussion issues (Denscombe 2008).

The presented literature enabled development of the research proposition that *if adequate contractual provision is present to support an integrated BIM approach, behavioural and circumstantial barriers to collaboration may be reduced or eliminated* - which is tested qualitatively. Support for this fundamental proposition is based upon the analysis of the collected data extrapolated from document review and interview responses. Together this aims to provide a new understanding of inertia-making factors and what mechanisms impact on digital information stewardship.

Literature review suggests that existing research tends to focus on outcomes from isolated experiences or obstacles to full adoption of BIM at a more general level. However, it does reveal sufficient evidence to suggest real compatibility difficulties exist between traditional contracting and working in a BIM mode. With this knowledge our proposition is formulated which enables the study to stay within feasible limits (Yin 2009).

The data collection process started with an interview protocol, which was developed to increase consistency of the research (Yin, 2009). Accordingly, all interviews followed similar case questions and collection procedures. The protocol focused on a narrow set of questions designed to unravel known and perceived contractual and behavioural difficulties on BIM projects.

A deductive approach is chosen for maximizing reliability and credibility in the results. The main unit of analysis is evidence of barriers to BIM collaboration with embedded units being the responses from the interview sessions. Analysis began with transcribing interviews into summary statements thereby abstracting and transforming the data into emerging patterns and then into a set of key issues where evidence was convergent and corroborated. This enabled the establishment of patterns and connections between contractual provisions and behaviours on BIM projects and furthermore, their effects. To provide a structure to aid data analysis and presentation of results, the emerging key issues are interpreted into categories and themes (Denscombe 2008). From here a selection of generalised conclusions are drawn.

A Review of Key Documents

As part of the empirical data collection in connection with this study a number of key contextual documents were collected and reviewed including existing local contract documents and BIM supporting documents such as the AIA Document E202-2008 (AIA 2008), Integrated Project Delivery: A Guide (AIA 2007), and the buildingSMART alliance™ BIM Project Execution Planning Guide (Anumba 2010).

Focus Group Interviews

Six interview sessions were carried out with industry participants including architects, engineers and contractors. The selection was based on a prior knowledge of their advanced BIM adoption and targeted to enable collection of empirical data from those who create or author digital information and might be the chief *users* of such tools as the BIM-Docs mentioned above and illustrated in Figure 5-1.

Whilst owners or clients are important in connection with BIM and setting minimum requirements etc, here, owners were not included in the interviewed groups. Instead, focus is placed primarily on the AEC team, their contracts and behaviours. Typically owners expect or demand data drops or digital deliveries corresponding to phases and are seldom concerned with the *how* aspects of delivery. Whereas, there is usually a myriad of exchanges within the AEC group demanding planning and standardized procedures if the digital data is to maintain its integrity downstream.

Those interviewed are active in all industry sectors (inc. commercial, residential, industrial, civil) and represent the leaders of those BIM adopters in Sweden. The interviews were semi-structured and focused on discussions centring around the identification (from a user perspective) of known process barriers to the use of BIM in connection with the functioning of Traditional and

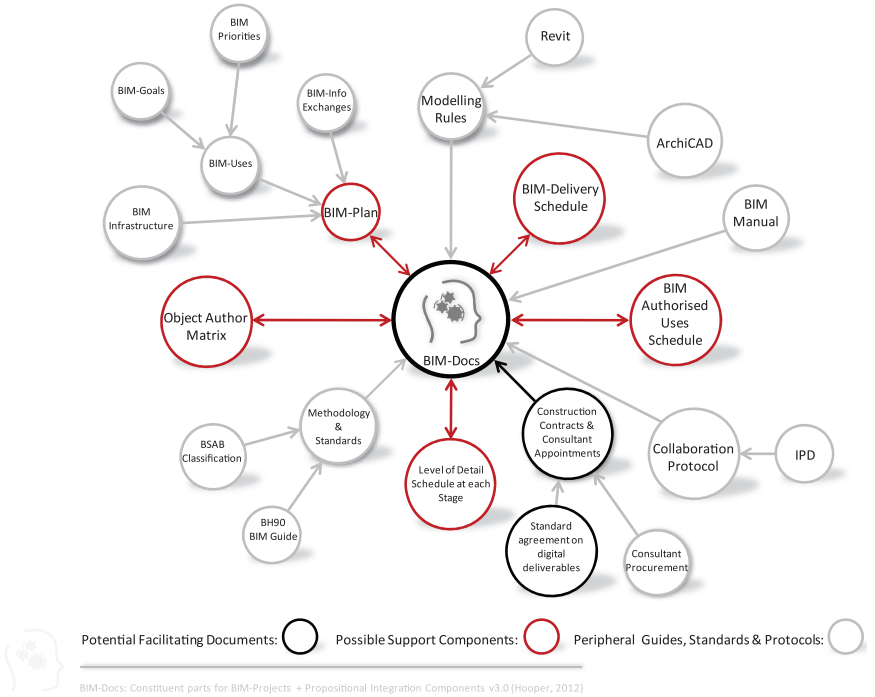


Figure 5-1. BIM-docs: constituent parts for BIM-projects + propositional integration components.

Design & Build construction contracts, and the standard form of consultant appointment. Consideration was afforded to the impact of a standard agreement on digital deliverables (OpenBIM 2010) and relevant aspects of the AIA's Document E202-2008 Building Information Modeling Protocol Exhibit (AIA, 2008). Respondents were asked to suggest where they thought obstacles to collaboration exist, in particular in relation to:

- Existing contractual provisions and BIM.
- Downstream transmission of digital information (information exchange).
- The ability to create and implement common, project-specific strategic BIM plans.
- Successful project coordination with regards to level and commitment to collaboration.

Conducted through a consistent interview protocol, the interviews with industry consultants focused on collecting responses to a concise set of questions and points of view in relation to the diagram in Figure 5-1 (BIM-Docs: Constituent parts for BIM-Projects + Propositional Integration Components) which derives from and builds upon the principle research proposition. The diagram presents the existing contract documents to be found in Sweden today, together

with a number of ancillary documents that are emerging within the industry here and elsewhere that are purported to support BIM processes and facilitate enhanced cooperation. Respondents were asked to consider the relevance, application and suitability of all interconnected documents (existing and propositional) and their influence on project team capacity and propensity to collaborate on BIM projects.

Interviews were carried out at various levels within six large AEC organisations, with consideration to both building construction and infrastructure construction case projects. In all organisations BIM is already an area of strategic interest and well established amongst organisation leaders.

Figure 5-1 pulls together a number of key concepts that collectively may help to shed new light on the question of what are the necessary components that may facilitate more effective early BIM collaboration and safeguard the downstream use of digital data. The diagram attempts to map out the key existing BIM documents and protocols that have a bearing on the use and implementation of BIM on construction projects today, and combines a selection of plausible collaboration supporting mechanisms based on the AIA's model.

UNDERSTANDING CONTRACTUAL AND BEHAVIOURAL OBSTACLES TO BIM COLLABORATION

This section presents the main results of the study and is divided into findings from the document review and those from the industry participant interviews. These are pulled together with a summarising section reflecting on procedural circumstances and behavioural fallout from contractual inertia.

Outcome from Document Review

Standard Form of Consultants form of Appointment (ABK 09)

In Sweden, there is only one standard form of design Consultant Appointment (ABK 09) that is recognised nationally. It is neutrally written with regards to the details of how Consultants exchange and deliver design information for construction. Often separate project specific appendixes are added to this form of agreement to deal with matters of information management on ad hoc basis. ABK 09 (BKK 2009) has been developed from previous versions in an attempt to meet today's requirements; however the form makes no reference or accommodation for provisions to support collaboration in connection with the use of digital information and BIM. Edgar (2011) notes that it merely regulates copyright and responsibility for design information presented as paper drawings and as such, is not tailored for digital information or BIM.

Furthermore, ABK 09 lacks any form of specific support for integration. It has no provisions for either strategic collaboration or projects centred around BIM technology and processes and as Blom (2010) states: "*There is nothing in ABK09 that*

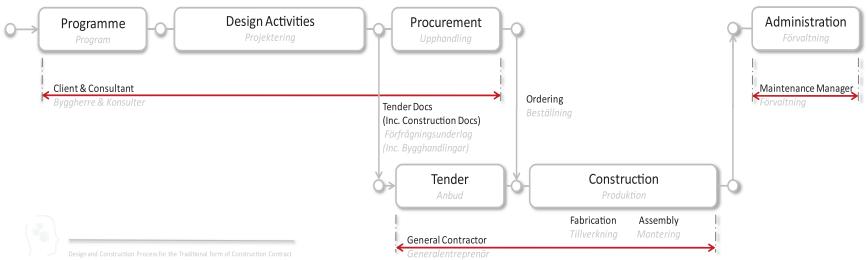


Figure 5-2. Design and construction process for the AB04 traditional form of construction.

regulates who owns the digital information, what the copyright is worth and what access rights are valid, or even responsibility for the accuracy and correctness of the digital information." These deficiencies have attempted to be addressed through the option to append a new standard form dealing with digital deliveries (OpenBIM 2010). Its deployment so far has been limited but has brought behavioural issues into discussion and reinforces the need for better contractual support.

Traditional Form of Construction Contract (AB 04)

The Traditional form of Construction Contract (AB 04) (BKK, 2004), approaching 10 years old, offers little support to BIM concepts and the implied need for early project team collaboration. The AB family of contract forms are set out with similar chapters covering responsibility, fees, etc. What is not regulated in AB is: collaboration means or methods, compensation or strategic incentives, how subcontractors are procured and managed. It can be said that the design and construction process associated with the Traditional Form (Figure 5-2) compromises opportunity for cross discipline collaboration centred around the BIM. The limited overlap between the design phases and construction phases thwarts collaborative efforts from the start. In a BIM mode, however, the effect of misaligned scopes and absent or ad-hoc buy-in to BIM-Project goals can be seen to present a new set of challenges.

Here the traditional procurement system, shares some of its main characteristics with the British traditional method (except for, the role of the architect). The client typically initially appoints a Project Manager as representative who advises the client on further appointments. Contractors tender on the work based on completed design documentation and the client's only contractual relationship with the contractors is that with the main or general contractor. The main contractor procures subcontractors to carry out work sections but is responsible for coordination of the construction and the performance of subcontractors. Subcontractors may have design portions, but are often on board after the main design effort is complete.

From the organisation of the traditional model (Figure 5-3), one can observe that the inherent separation of the client and consultants on one side and contractor team on the other, immediately creates barriers, contrary to the ideas

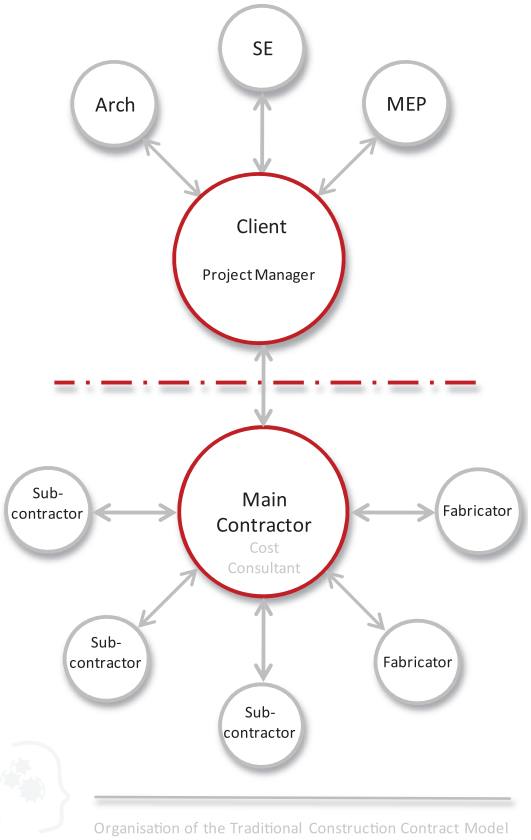


Figure 5-3. Organisational structure of the traditional procurement system.

of team-building, collaboration, and working together towards common goals for the good of the project. Separation of not only design and construction activities but contractual relations can be seen to inhibit the necessary free communication, cooperation and feedback between teams. This has been shown to lead to knowledge islands and defensive behaviour (Pfitzner et al 2010).

Design & Build/Performance Form of Construction Contract (ABT 06)

Intended for use in connection with so-called turnkey projects, the Design & Build/Performance Contract (ABT 06) presents conditions of Contract for works where the contractor undertakes total execution of the construction and also undertakes to produce all or a substantial part of the design. Here the main contractor's presence through a substantial part of the design and construction phases (Figure 5-4) enables a high degree of consistency of purpose and team optimisation to occur. However, such contracts can lead to a restriction of competition since only a few contractor organisations have sufficient

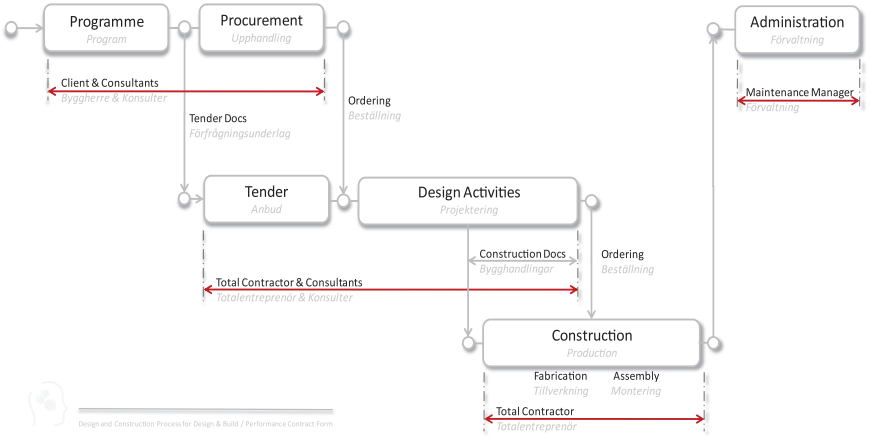


Figure 5-4. Design and construction process for design & build/performance contract form.

economic resources to manage the design, meaning only a few can compete for the work.

As with the Traditional contract, D&B/Performance (ABT 06) offers little specific support to BIM or BIM processes per se, but equally no specific hindrance. Often client or contractor organisations will append or insist on the adoption of in-house IT/BIM Manuals setting out strategic and administrative decisions on a project bases. One hindrance here is that there is a lack of National BIM Standards in Sweden and BIM 'demands' are generated by the most powerful actor in the team almost on an ad-hoc basis.

This form of contract corresponds in principle to the British Design and Build procurement in which the client provides a skeleton brief detailing functional requirements upon which the main contractor develops the building design. Clients may employ an Architect to develop a programme and concept design who may later be novated to the Contractor. The number of projects under this form of contract in Sweden varies from year to year, but the system has been known to account for more than 50% of the market (Nordstrand 2009).

This contact procurement system is an example of a response to the increasing need for a more integrated design and construction process. The main contractor is responsible for the whole process of leading and coordinating the integrated design and construction phases and takes total control over the building project. The contractor has a single contract (Figure 5-5) covering both planning and execution of the building project and is responsible for construction in accordance with the current standards and with the functional requirements laid out by the client.

Significant characteristics of the Design & Build / Performance contract in the context of BIM planning, information flow and early collaboration include:

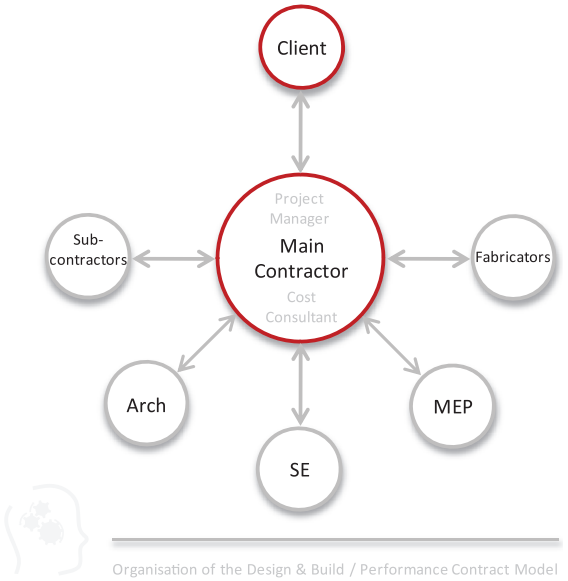


Figure 5-5. Organisation of the design & build/performance contract model.

- The Design & Build/Performance Contract offers the greatest potential for meaningful collaboration since a fuller team is assembled from the beginning.
- It provides a suitable platform for partnering agreements – a move toward IPD.
- The contractor has the opportunity to demand project team compliance with project goals as opposed to only internal organisational goals.
- Client has a single point of contact. Less control over detailed aspects of the design.
- Contractor is responsible for design *and* construction which more readily enables a more robust digital information stewardship through the presence of a downstream continuum from the start.
- Construction work can be started earlier as design work can proceed in parallel, however, the time required to prepare work packages depends on the complexity of the project.
- Statutory Consent is a concern since building permits are often not applied for until the contractor is appointed and can take an uncertain amount of time to be granted. Delays in this respect can have serious consequences.
- To be successful, tender documentation must be explicit regarding requirements and expected operation and maintenance costs.
- Such contracts can lead to a restriction of competition since only a few contractor organisations have sufficient economic resources to manage the design, meaning only a few can compete for the work.

Notwithstanding, a number of major contractors are developing various forms of transparent construction contract with clients - partnering solutions – which demonstrate a desire for greater collaboration and can be seen to represent a move toward IPD.

Agreement on Digital Deliveries (ADL 2010)

Supported and available through OpenBIM, the Agreement on Digital Deliveries (OpenBIM 2010) is intended to address the contractual deficiencies of the standard Consultant Appointment (ABK 09) with regards to the adoption of BIM and the use of digital information. It contains formal clauses to facilitate agreement concerning delivery and use of digital information for building construction projects (a similar form is expected to emerge for infrastructure projects). The form can be used to regulate and agree the details regarding delivery of digital information, specifically:

- The rights to the output from the commission.
- Delivery specification of digital information.
- Control of receipt of that digital information.
- The client's use and access rights to the digital information.
- The suppliers/consultants responsibility for the digital information.
- Archiving of design material.

The motivations behind such an appended form are clear, however a number of opportunities have been missed. Examples of parts that continue to be problematic and need to be further investigated include:

- The scope of the model including which systems and disciplines to be included for which uses.
- The level of development in models for different stages.
- The accuracy and status of BIM content (eg, as scanned, as measured, as designed, etc).
- Whether the model shall constitute the contract documents or should the extracted 'dumb 2D drawings' be the only valid document.
- Review and approval processes of design proposals/digital information content.
- If the model contains too much information how one must sort out what applies for the purpose.
- Ownership, copyright, etc. need to be reviewed in relation to AB and ABK.

AIA Document E202-2008 & Integrated Project Delivery

The AIA Document E202-2008 Building Information Modeling Protocol Exhibit (AIA 2008) in the US has been developed specifically to support BIM

collaboration and enable project organisations to leverage the benefits of BIM in a systematic way. It presents a formal means of agreeing BIM project priorities and deliverables in a standardised form, enabling teams to proceed with foresight, setting out what models are to be produced and how the models can be used. The document includes provisions to agree: *BIM Delivery Schedule, BIM Uses Schedule, Level of development at project stages, Model Authorship* and *Model Use Authorisation*.

The E202 establishes protocols on expected level of development (LOD) and authorised uses of the BIM data on a project basis. It assigns specific responsibility for the development of each model element to a defined LOD at each project stage. By contrast, in Sweden there is a lack of standard documentation to enable the expected scope and objectives for BIM to be agreed, detailed and suitably documented. It is conjectured that an adapted version of these five concepts may be of practical application in Sweden to support cross boundary BIM collaboration. By formalising these five concepts through a standard set of contractual provisions, project participants can nurture a greater clarity of purpose and remove confusion around matters of authorship, liability and intellectual property.

Integrated project delivery (IPD) is already in use in some form on many projects around the world. It yet has to make its debut in Sweden although it is the source of intense discussion for key stakeholders in the Design-Construct-Operate (DCO) industry. Whilst BIM offers the possibility of dramatic advances in project information coordination and collaboration, the full potential of BIM will not be achieved without adopting structural changes to project delivery methods (Autodesk, 2008). IPD offers an opportunity to redress traditional difficulties where key issues regarding compensation, contractual relationships, risk allocation, and so forth can be overcome. Greater awareness, owner mandates, and industry initiatives are critical to the widespread adoption such of new delivery methods.

The AIA defines IPD as: "*a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction*." (AIA 2007)

Accordingly, the definitive characteristics of IPD include:

- Highly collaborative processes that span building design, construction, and project handover.
- Leveraging the early contributions of individual expertise.
- Open information sharing amongst project stakeholders.
- Team success tied to project success, with shared risk and reward.
- Value-based decision making.
- Full utilization of enabling technological capabilities and support.

With IPD the relationships of project participants are fundamentally altered, which gives rise to the demand for new forms of standard contract documents

(such as the ConsensusDocs and AIA E202-2008) that address important new BIM collaboration issues. Already changes in business models, scopes of services and deliverables are redefining the relationships of interested parties around measured outcomes. The IPD philosophy offers impetus towards improved project coherence through combating fragmentation.

The buildingSMART alliance™ BIM Project Execution Planning Guide (BIM PEPG)

The buildingSMART alliance™ BIM Project Execution Planning Guide (BIM PEPG) (Anumba et al, 2010) is a new supporting guide with the primary aim to help construction professionals clarify roles and responsibilities, determine scope and level of detail, cut costs and optimise return on investment (ROI). The plan claims that to successfully implement BIM, a project team must perform detailed and comprehensive planning. A well-documented BIM Project Execution Plan will ensure that all parties are clearly aware of the opportunities and responsibilities associated with the incorporation of BIM into the project workflow. A completed BIM Project Execution Plan should define the appropriate uses for BIM on a project (e.g., *design authoring, cost estimating*, and *design coordination*), along with a detailed design and documentation of the process for executing BIM throughout a project's lifecycle. Once the plan is created, the team can follow and monitor their progress against the plan to gain the maximum benefits from BIM implementation.

The plan suggests that project participants from the earliest stages generate a strategic BIM-Plan that enables agreement on common goals through 4 key steps:

- Identify high value BIM uses during project planning, design, construction and operational phases.
- Design the BIM execution process by creating process maps.
- Define the BIM deliverables in the form of information exchanges.
- Develop the infrastructure in the form of contracts, communication procedures, technology and quality control to support the implementation.

BIM PEPG provides a useful resource for teams to set out project goals as part of an integrated effort to collaborate meaningfully and deliver a BIM project. However, pilot studies on digital information exchange (Hooper and Ekholm, 2010) that sought amongst other things to assess the suitability and practicality of implementing such a project-orientated strategic BIM-Plan, identified that although players thought it was a good idea to have a strategic BIM-Plan in place, a number of execution difficulties emerge:

- The BIM-Plan required to be implemented at the early design phases meaning owner, design team and contractor buy-in. Many key project participants were not and could not be present – such as the main contractor and key subcontractors – since they had not been appointed yet and where simply not on the scene.

- Absence of key players during the implementation of a so-called project-wide BIM Implementation Plan compromised its purpose and diluted its credibility.
- A tendency for individual consultant disciplines to focus on their own contribution rather than the down-stream use and value of their design effort prevailed.
- Participants agreed that some sort of common strategic BIM plan was of benefit and helped to address the deficiencies of existing guides.

Yet a shift in project organisation from Design & Build/Performance contract model toward IPD indicates it may be possible that the fundamental difficulty associated with the timing of appointments and formation of the core team can be overcome. It is further conjectured that as part of a move to incorporate collaboration supporting mechanisms and protocols, a project specific, common strategic BIM-Plan is a necessary component to enable delivery of a collaboration-rich project.

BIM Inertia – Contracts

Table 5-1 presents a summarized and categorized overview of contracts and their respective characteristics pertaining to BIM projects.

In seeking to collect empirical data from industry participants, interview discussions centred around responses to probing questions connected with the practical use and application of the documents cited in Figure 5-1 on BIM projects were conducted. Identification of perceived barriers or inadequacies was sought. Specifically, respondents were asked to *suggest (from a user perspective) known and suspected contractual barriers to the use of BIM in connection with the functioning of said documents.* We then turned to ask where *participants thought obstacles to collaboration exist, in particular in relation to downstream transmission of digital information (information exchange); the ability to create and implement common, project-specific strategic BIM plans; and successful project coordination*. Finally, responses were sought in connection to the propositional diagram (Figure 5-1: BIM-Docs: Constituent parts for BIM-Projects + Propositional Integration Components) which suggests a number of key concepts purported to support an integrated delivery process. Here respondents were asked whether *there is appetite in the industry to use some or all of these concepts in practice today. And to suggest where they thought obstacles exist in adapting these as national branch standard to support BIM collaboration.*

Outcome from Focus Group Interviews

Variance of points of view across sector disciplines was observed as minimal and considered insignificant for this study. For this study, focus is placed on reporting on matters where consensuses of opinions were revealed. Responses are summarised and are later reflected upon as procedural circumstances and behavioural fallout from contractual inertia. Table 5-2 presents a categorization of the key issues that emerged from discussions which can be distilled meaningfully into 3 themes: *Procedure, Circumstance* and *Behaviour*.

Table 5-1. BIM Inertia – Contracts

Contract	*Risk*	*Fees/Reward*	*Responsibility*	*Intellectual Property*	*Legal Liability*	*Insurance*	*Incentives (for project success)*	*Industry Tendencies*
ABK 09	Individually managed, transferred to the greatest possible extent.	Individually pursued; minimum effort for maximum return.	Responsible for professional execution of defined scope of work. Duty of care to discover and resolve any failures in timely fashion.	Consultants often pressurised to 'sign-away' Intellectual Property Rights. Clients insist on being allowed to use the data as they wish.	10 year joint defect liability in connection with consultants design contributions.	Consultants responsibilities insurance required based on contract value. Traditional liability.	Credibility. Bonuses available.	Individuals and companies protect their contribution to the project and project self-importance. Information issued on a need-to-know basis.
AB 04	Individually managed, transferred to the greatest possible extent.	Individually pursued; shortcuts and economies sought at every opportunity; minimum effort for maximum return.	Execution of clients requirements through implementation of consultants designs and documentation.	N/A	10 year defect liability for construction works.	Insurance cover for 1st and 3rd person claims.	Greater profits.	Re-work; installation difficulties, blame culture; construction budget and programme overruns.

ABT 06	Individually managed, transferred to the greatest possible extent.	Individually pursued; shortcuts and economies sought at every opportunity; minimum effort for maximum return.	Execution of clients requirements through implementation of consultants designs and documentation.	N/A	10 year defect liability for construction works.	Insurance cover for 1st and 3rd person claims.	Greater profits.	Re-work; installation difficulties, blame culture; construction budget and programme overruns.
Partnering	Collectively managed, agreed & monitored through steering group.	Partial sharing project profits; value-based.	Collective competencies optimised, project targets articulated.	N/A or as AB family of contracts.	ABK 09, AB 04 or ABT 06 are used as legal basis below the partnering letter of intent.	ABK 09, AB 04 or ABT 06 are used as legal basis below the partnering letter of intent.	Part share in project profits.	Use of Partnering is increasing but only within contracting organisations.
IPD	Collectively managed, appropriately shared.	A portion of remuneration is tied to project success; value-based.	All project team members responsible for the success of the project. Responsibility for data accuracy defined in the **Object Author Matrix**.	Use of digital information defined in the **BIM Authorised Uses Schedule**. Copyright protection for model authors.	Project participants remain responsible for individual scopes of work, IPD approach should not alter traditional approach.	Insurance cover for 1st and 3rd person claims requires tailored to align with scope of IPD duties.	Share in project profits.	Individuals care more about the results than their own ego.

Table 5-2. BIM Inertia: Obstacles to BIM Collaboration

Procedure	*Circumstance*	*Behaviour*
Current standard forms of agreements **are neutrally written** with respect to information management. **Low levels of support for BIM processes** exist within these contractual forms of agreement, however appended documents can be included to clarify how information management should be performed. As models and the data within them are **not considered contract documents**, they are essentially shared with a precautionary '**for information only**' status, compromising their potential downstream value. The larger individual sector organisations have developed their **own in-house IT/ BIM manuals** in attempt to address a lack of national standards. However, it is observed that the in-house IT/BIM manual contributes to **fragmentation of approaches** since there is **no common standard** for their content and scope.	A **lack of standardised documents** prevails. Areas in need of further investigation include: A method of describing scope of model(s), LOD, Level of Accuracy, A standard information approval scheme, Model ownership & copyright, and whether the model itself should constitute a contract document or 2D drawings extracted from the model. **Responsibility for the accuracy** of a data rich model is exponentially greater than the information on a 2D drawing. There are a number of particularly acute areas where the responsibility (for authoring and maintaining correctness) of digital information remains problematic including **holes, doors, geotechnical data and quantities**. Where **multi-party input is required, confusion about overall responsibility is exists**. Issues of responsibility are often resolved on an **ad hoc** basis. Precarious and negotiated consensus has to be achieved	A tendency exists for organisations to develop **isolated internal standards** for the benefit of their own organisation resulting in **compromised cross sector co-ordination**. **A fear exists** of data being wrong. An associated resistance exists to share that information till the author can define its status under current standards. The submission of drawings (the use of which can be more easily controlled) as part of the contract is preferred. It is considered a more **comfortable means** of formal information exchange. Whilst construction contracts themselves present **little direct hindrance** to BIM collaboration, many administrative and **behavioural obstacles** to collaboration and BIM processes exist which are interlinked.

BH90, the industry's digital information handbook could be said to represent something of a hinder due to it is **abstract concepts** and that it **lacks concrete examples** for users.

The matter of **copyright and intellectual property rights** (IPR) is a concern. Often designers are forced by client or contractor to waive the copyright over their designs without any compensation.

The traditional contract (AB 04) is the most **problematic** with regards to the value adding potential of BIM and project outcomes as **contractor claims** are more frequent.

The AB family of **contracts collectively fail to adequately support BIM planning**, decision making and early collaboration that is critical on BIM projects. Such matters are usually dealt with in a more **fragmented way through appended documents**.

by **unstructured and sub-optimal means**, exposing teams to **unnecessary risk**.

There is a feeling in the industry that **risk and reward is not amicably distributed** amongst project team members – design consultants in particular feel they are getting a bad deal for their effort.

Still much **repetition in data** entry due to lack of information stewardship, reliability, chain of information responsibility.

Imbalanced investment v. economic benefit across sector.

Limited scope to realize **win-win initiatives**.

Difficulties is distinguishing and **defining the boundaries** between company BIM business strategy, project based BIM-Strategy and national BIM-Strategy.

For those who are not BIM-ready a **traditional mindset prevails**.

Resistance to change and the preservation of the **traditional mindset** in which project participants consciously or otherwise **raise barriers around their contribution** or design deliverables making it **difficult to implement new collaborative procedures**.

High dependence on informal **trust** and **management prioritisation of *internal* optimisation over *project* optimisation**.

Contractors **re-model** the entire projects to enable 4D (Programming) and 5D (Cost Analysis) capabilities of BIM. To address this **re-work** issue contractors have developed BIM-Manuals which are issued to consultants on BIM projects.

(Continued)

Table 5-2. BIM Inertia: Obstacles to BIM Collaboration (Continued)

Procedure	*Circumstance*	*Behaviour*
The Public Procurement Act requires **separate budgets** are established for consultant contributions, project management, construction work etc. Affecting a fragmented approach to procuring sector players. • Design consultants are commissioned on time-cost basis and thereby compelled to watch closely their **allotted budget of time and money** so as not to make a loss out of the commission. • Furthermore, **no incentive for adding value** to the project exists, quite the opposite, consultants are under pressure to produce the necessary documentation for the minimum cost.	**Time & money catch 22** - when there is good economic conditions and pressure in the industry there is not the time to spend in developing BIM expertise, when there is a depressed economy there is n't the money to invest in BIM. Fragmented industry **compartments efficiency initiatives**.	**Lack of adherence to** existing process improvement internal and external **standards**. **Disintrest in following through** common objectives following initial enthusiam. **Ambivalence** towards each others BIM-Information requirements. Lack of knowledge of interoperability standard IFC – **tendency to reject** utilisation/only use if forced. **Lack of trust in IFC**.

Regarding the proposition presented through Figure 5-1: BIM-Docs: Constituent parts for BIM-Projects + Integration Components, the following observations are noted:

- ***Level of Development Schedule at each Stage*** – was something that all respondents thought would be useful to aid and support collaboration. Currently this is missing and no comprehensive standard method of presenting this information as part of contract documents exists in Sweden.
- Many questions remain over the responsibility for the correctness of digital information. For this reason amongst others, a standard form of ***Object Author Matrix*** was considered of value in conjunction with an information approval system.
- Whilst a number of internal *BIM-Plans* exist (taking various forms) a standard project specific ***BIM-Plan*** with an objective to align to whole-team BIM-Goals was recognised to be of benefit.
- Scepticism prevailed regarding the relevance of an ***Authorised Uses Schedule*** (documenting how the recipient of a model may use the data) – since today models are generally only issued for information only, and for this reason authors see no reason to regulate the recipient's use of it. But a model can potentially be used for a raft of different uses (costing, scheduling, performance simulation, code checking, and visualization, to name just a few), it seems obvious that the author of the model should define the suitability of the model for a particular use.
- It is acknowledged to be of **national interest** to have such concepts accepted as sector standards. Obstacles **include lack of client interest** and **absence of state intervention**.

A general consensus emerged agreeing that if these supporting components were lifted from being ad-hoc to being formulated into readily available sector standards, the industry may benefit from a more integrated approach through an enhanced scope for meaningful collaboration. The augmented diagram presented as Figure 5-6 summarises the substance of the respondents' reactions to the proposed chart, extracted from field notes. It furthermore suggests that a core of interconnected supporting mechanisms are desirable amongst AEC players which may, at least in part, address the observed inertia in BIM collaboration that can be seen to be generated by behaviours and circumstances stemming from, inter alia, the traditional construction project mindset.

Reflections on Procedural, Circumstantial and Behavioural Fallout from Contractual Inertia

Key phenomena or patterns are observed. Here, the raw qualitative data summarised in the previous section is examined through an emerging set of procedural, circumstantial and behavioural issues, stemming to a greater or lesser extent from contractual provisions or the lack of them. These are reflected upon through attaching effect and outcome parameters and cognisance is considered to the impact of plausible BIM collaboration supporting mechanisms. Table 5-3 presents

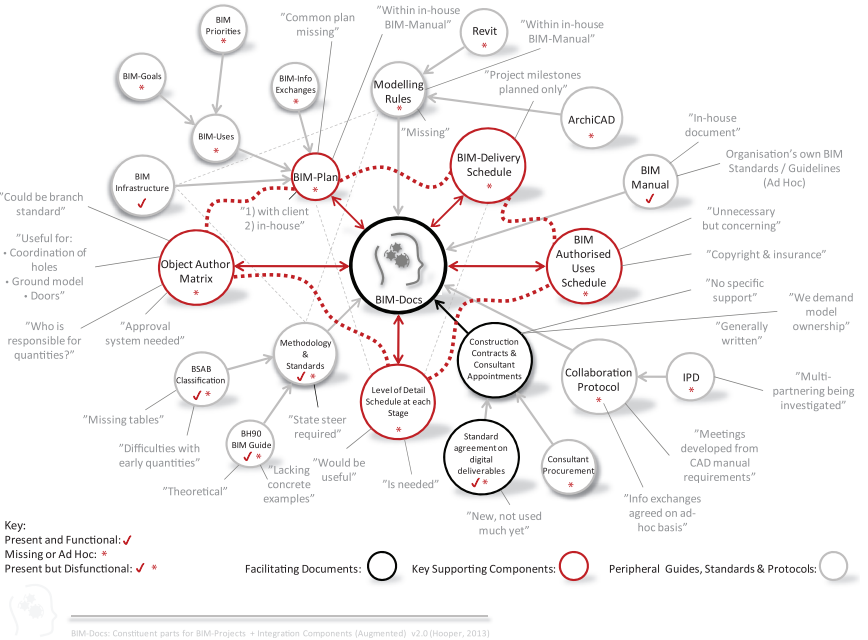


Figure 5-6. BIM-Docs: constituent parts for BIM-projects + integration components (augmented).

a simple breakdown of patterns observed interpreted as fallout from contractual indifference to BIM processes and integrated approaches. The results can be seen to shed new light on the connections between contractual provisions and procedural circumstances and behaviours on BIM projects that may have wider application.

In Table 5-3, 26 discrete issues surfaced as being significant in the context of BIM projects resulting in, amongst other things, setbacks and frustration. Understanding traditional behaviours and their impact on BIM project outcomes brings the need for decision-making and collaboration supporting mechanism into focus. Whilst not all obstacles can be removed through the application of BIM-Addenda championing BIM collaboration supporting mechanisms, a number of the most important issues can be suitably addressed, enabling teams to affect a greater level of integration.

DISCUSSION AND IMPLICATIONS

This chapter examines the connections between the commercial environment and contractual provisions that regulate party's business relationships and the resultant procedural and behavioural phenomena that can be viewed to thwart BIM collaboration and project outcomes. Whilst this research focuses on the case of

Sweden, the patterns observed can be deemed typical and therefore can be seen to strengthen and broaden the application of the emerging results.

The findings indicate that most industry representatives perceive similar patterns of existing barriers to BIM collaboration, however are hesitant to place the fault directly on contracts themselves, rather on a combination of circumstances and behaviours associated with traditional mindsets and the commercial environment. The emerging issues cited in the results point towards a more tacit set of phenomena that can be seen to relate to contractual provisions (or the lack of them). A certain consensus emerged on ways to tackle said difficulties however procedures remain ad hoc and a lack of standard approach prevails.

Having rationalised the attributes of certain BIM inertia into a set of re-occurring procedural, circumstantial and/or behavioural issues one can more readily draw an understanding of the connections to contractual provisions and in the case of Sweden the lack of standard BIM collaboration supporting clauses or addenda. Furthermore, the repeat occurrence of particular behaviours and associated effects provides strong evidence to show that teams require support on BIM projects to better manage decision making and deliver a more integrated approach to project execution.

The balance between enabling and disruptive tensions that traditional contractual arrangements can generate offers us insights into what collaborative processes are important. Project outcomes purporting attributes of misaligned goals or divergence over methodology can readily be traced back to poor or non-existent provisions leading to protective behaviours. Accordingly, it is recommendable that branch standard supporting mechanisms are adopted to avert setbacks. This is consistent with past research. The novelty of this research is that it provides a more comprehensive view of those behaviours that hinder collaboration and can lead to inertia on BIM projects. This extends previous studies, for example, Gu and London, (2010) which highlights the need for decision-making frameworks to integrate solutions to both technical and non-technical challenges or Rekola et al. (2010) which simply classifies problems into technology, people and process categories.

The contribution of the research is an improved understanding of BIM inertia, extended insight into the connections between specific behaviours, traceable circumstances and BIM project outcomes, and a knowledge of a local consensus behind the need for, and focus of, a number of BIM collaboration support mechanisms.

CONCLUSIONS

This chapter investigated contractual and behavioural challenges to BIM collaboration and digital information stewardship. It highlights a number of discrete phenomena viewed as detrimental on BIM projects and validates the need for tailored BIM collaboration supporting mechanisms to underpin the value and

Table 5-3. BIM inertia: contracts & behaviours – effects & outcomes on BIM projects

Procedural/Circumstantial/ Behavioural Issues	*Effect on BUM Projects*	*Outcome on BIM Projects*	*Impact of Plausible Supporting Mechanisms*
#1: Lack of Standard BIM-Orientated Contracts	Compromises & ad hoc negotiations	Confusion, resistance to change	Reduce
#2: Lack of Standard Documents (inc. BIM-Addenda)	Fragmented approaches, confusion	Lack of confidence, expense, setbacks	Reduce
#3: Isolated Initiatives	No integration, limited gains	Compromised cross-sector coordination	Reduce
#4: The Fear of Sharing	Late decision making, poor coordination	Loss of value, missed opportunities, waste	Eliminate
#5: Responsibility for Accuracy & Multi-Party Input	Confusion, missing info, error	Blame-game	Eliminate
#6: Comfort Zone	Missed opportunities	No positive outcome	Reduced
#7: 2D = Contract Documents, 3D ≠ Contract Documents	Limited value creation, lack of confidence	Loss of value, missed opportunities, waste	Eliminate
#8: Issuing data with 'For Information Only' status	Information used at own risk	Loss of value, missed opportunities, waste	Eliminate
#9: Traditional Mindset	Resistance, lack of commitment	Frustration, disappointment	Reduce
#10: Ad Hoc Negotiations	No control	increased risk	Reduce
#11: Imbalanced Risk & Reward	No incentives to add valve	Focus on own contribution	N/A
#12: In-House BIM-Manuals & Fragmented Approaches	Short term order, longterm chaos	Most powerful actor benefits the most	Reduce

#13: Abstract Concepts & Lack of Concrete Examples	Confusion, no sense of direction	Creation of own concepts & examples	N/A
#14: Copyright & Intellectual Property Rights	Frustration & marginalisation	Compromised protection of original ideas	Eliminate
#15: Claims Culture	False budgets, ro positive outcome	Overspend & delay	N/A
#16: Inadequate & Non-Standard BIM-Supporting Mechanisms	Confusion, chaos	Lack of confidence, missed opportunities	Eliminate
#17: Dependency on Trust & Co-operation	Setbacks, frustration, time wasted	Surprises, overspend & delay	Reduce
#18: Whim of Individuals & Anti-Teamwork Attitudes	Risk, frustration, lack of commitment	No positive outcome	Reduce
#19: Public Procurement, Compartmented Budgets & Teamwork	No connection, or incentives to add value	Loss of value, missed opportunities, waste	N/A
#20: Re-work: Re-Modelling & Repeat Date Entry	Risk of error & waste	Duplication of effort, 'wins' negated	Reduce
#21: Confidence Existing Standard Solutions	Traditional thinking, stagnation	Compromise, limited value added	Reduce
#22: A Collaborative Culture	Cooperative dispositions	Low no. of lawsuits	N/A
#23: If no clarity on Status of Deliverables & Model Status	Data Misuse, confusion, error	Poor coordination	Eliminate
#24: If no clarity on BIM-Uses	Data Misuse, confusion, error	Re-work & waste	Eliminate
#25: Lack of definition of Cross-Party Interface	Communication fiasco	Frustration, disappointment	Eliminate
#26: Timing & Scope of Appointments	Compromised cross-party strategic buy-in	Loss of value, missed opportunities, waste	N/A

downstream utility of authored digital information about facilities. To the original research questions of *what the connection is between traditional contracting and BIM inertia and what the necessary components are that may facilitate more effective early BIM collaboration,* we can now say, first that traditional project structures and contracts can create discrete and often competing agendas and associated behaviours. Lack of contractual provisions that support technology, people and processes, can be said to be particularly problematic when working in a BIM mode. Here a whole new set of procedural, circumstantial or behaviour issues can emerge if left unchecked. Difficulties can be traced through commercial and legal pressures to protective behaviours which can compromise collaborative efforts and ultimately project outcomes.

Respondents highlighted the need for five key supporting mechanisms, which if standardised, may offer a means to avoid communicative setbacks and frustration on BIM projects. Whilst ensuring collaboration and making BIM work on a project wide basis may come down to the individual behaviours of the parties' involved, certain contractual provisions can provide the framework to encourage and support collaboration and guide team players to realising project BIM objectives with minimum friction.

To the question of *what we learned here that may have wider application through consideration of suitable BIM collaboration support mechanisms that may reduce or remove collaboration barriers*, we can conjecture that the five collaboration support mechanisms cited deployed as a project wide or even national standard BIM-Addendum may, in theory, offer the active collaboration support necessary to reduce or remove BIM inertia. Further work is required to test and tune this hypothesis and assess the real impact of BIM addenda on project outcomes, however results support Kuiper and Holzer (2013) conviction that 'bolt-on' addenda to existing contract arrangements appear to be a necessary stepping stone towards delivering integrated projects and this work contributes toward unravelling the uncertainty over what such addenda should contain and what should be standardised for the benefit of the industry and project outcomes. It will take time to establish proven best practices and further time for de facto standards to emerge. But what this study shows is that if one wishes to remove or reduce BIM inertia one must first understand the behaviours and outcomes one wishes to change.

ACKNOWLEDGMENTS

Particular thanks to those interviewed and who provided feedback on the results. This research project is funded by SBUF, Formas-BIC, Interreg VI and members of OpenBIM.

References

Anumba, C., Dubler, C., Goodman, S., Kasprzak, C., Kreider, R., Messner, J., Saluja, C., and Zikic, N. (2010). *Building Information Modelling Project Execution Planning Guide*,

Version 2.0, The Computer Integrated Construction Research Group, The Pennsylvania State University, Pennsylvania, USA.
AIA (2007). *Integrated Project Delivery: A Guide*, Version 1, AIA and AIA California Council, California, USA.
AIA (2008). *AIA Document E202-2008: Building Information Modeling Protocol Exhibit*, AIA and AIA California Council, California, USA.
Ashcraft, H. (2008). "Building Information Modeling: A Framework for Collaboration," *Construction Lawyer*, Vol. 28, No. 3, Summer 2008, American Bar Association.
Autodesk (2008). *Improving Building Industry Results through Integrated Project Delivery and Building Information Modeling*, Autodesk Whitepaper, Autodesk: California.
Autodesk (2010). *Autodesk BIM Deployment Plan: A Practical Framework for Implementing BIM*, Autodesk: California.
BIS (2011). *BIM Management for value, cost and carbon improvement: A report for the Government Construction Client Group— Building Information Modelling (BIM) Working Party Strategy Paper*, London.
BKK (2009). *Allmänna Bestämmelser ABK 09: För Konsultuppdrag inom Arkitekt- och Ingenjörsverksamhet*, Svenskbyggtjänst, Stockholm. [Terms and Conditions ABK 09: For consultant commissions in Architectural and Engineering Practice]
BKK (2004). *Allmänna Bestämmelser AB 04: För Byggnads-, Anläggnings- och Installationsentreprenader*, Svenskbyggtjänst, Stockholm. [Terms and Conditions AB 04: For Traditional Contracts]
BKK (2006). *Allmänna Bestämmelser ABT 06: För Totalentreprenader Avseende Byggnads-, Anläggnings- och Installationsarbeten*, Svenskbyggtjänst, Stockholm. [Terms and Conditions ABT 06: For Design & Build / Performance Contracts]
Blom, H. (2008). *ByggIndustrin - Brist på samordning hotar BIM*— Jan 2008. http://www.byggindustrin.com – visited October 2011. [Lack of coordnination threatens BIM]
Blom, H. (2010). *OpenBIM - Viktigt att skriva avtal om digitala leveranser*. <http://www.openbim.se> (Nov. 2011).
Cohen, J. (2010). *Integrated Project Delivery: Case Studies*, AIA California Council 2010, Sacramento, USA.
Denscombe, M. (2008). *The Good Research Guide for Small-Scale Social Research* Projects, 3rd Edition, Maidenhead: Open University Press.
Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, 2nd Edition, John Wiley & Sons.
Edgar, J-O. (2011). *ByggIndustrin– Entreprenörer bygger på egen risk*— Nov 2011. http://www.byggindustrin.com – visited October 2011. [Contractors build at their own risk]
Gu, N. and London, K. (2010). "Understanding and facilitating BIM adoption in the AEC industry." *Automation in Construction*, 19(8), 988–999. doi: 10.1016/j.autcon.2010.09.002
Hilson, M. (2008). *The Nordic Model - Scandinavia since 1945*, Reaktion Books: London.
Hooper, M. and Ekholm, A., (2010). "A Pilot Project - Toward BIM Integration - An Analysis of Design Information Exchange & Coordination," *Proceedings of the 27th Annual CIB W78 International Conference - Applications of IT in the AEC Industry*, Cairo, Egypt. 15-17 November 2010.
Jongeling, R. (2008). *Forskningsrapport: BIM istället för 2D-CAD i byggprojekt - En jämförelse mellan dagens byggprocesser baserade på 2D-CAD och tillämpningar av BIM*, Luleå tekniska universitet, Sweden. [Research Report: BIM instead of 2D CAD in

construction projects - a comparison between today's construction processes based on 2D CAD and Applications of BIM]

Knight, D. (2008). *Teams, Contracts & BIM*, ASHRAE Journal, September 2008.

Kuiper, I and Holzer, D. (2013). "Rethinking the contractual context for Building Information Modelling (BIM) in the Australian built environment industry," *Australasian J. Construction Economics and Building*, 13(4), 1–17.

Nordstrand, U. (2009). *Byggprocessen*, Liber, Stockholm. [The Construction Process]

Manning, R. and Messner, J. I. (2008). "Case studies in BIM implementation for programming of healthcare facilities," *Electronic Journal of Information Technology in Construction*, Vol. 13.

OpenBIM (2010). *Avtal för Digitala Leveranser*, OpenBIM, Stockholm. [Contractual agreement for digital deliveries]

OpenBIM (2012). *Avtal behövs även för de digitala leveranserna*, OpenBIM, Stockholm. [A contractual agreement is needed for digital deliveries]

Owen, R., Amor, R., Palmer, M., Dickinson, J., Tatum, C. B., Kazi, A. S., Prins, M., Kiviniemi, A., and East, B. (2010). "Challenges for integrated design and delivery solutions" *Architectural Eng. and Design Mgmt.*, 6(Special Issue), 232–240. doi: 10.3763/aedm.2010.IDDS1

Pfitzner, M., Benning, P., Tulke, J., Outter, N., Nummelin, O., and Fies, B. (2010). *InPro – D29— Barriers and Opportunities – Future ICT and Organisational Requirements*, The InPro Consortium.

Race, S. (2012). *BIM Demystified*. London: RIBA Publishing.

Rekola, M., Kojima, J., and Mäkeläinen, T. (2010). "Towards Integrated Design and Delivery Solutions: Pinpointed Challenges of Process Change." *Architectural Engineering and Design Management*, 6(4), 264–278. doi: 10.3763/aedm.2010.IDDS4

Saunders, M., Lewis, P., and Thornhill, A. (2009). *Research methods for business students*, 5th ed., Harlow: Pearson Education Ltd.

Swedish Standards Institute (2008). *Bygghandlingar 90: byggsektorns rekommendationer för redovisning av byggprojekt. D. 8, Digitala leveranser för bygg och förvaltning*, Stockholm: SIS Förlag AB. [Construction Documents 90: construction sector recommendations for accounting for construction projects. Part 8, Digital deliveries for construction and facilities management.]

Yin, R. K. (2009). *Case Study Research: Design and Method*, London: Sage Publications.

CHAPTER 6

An Integrated Green BIM Process Model (IGBPM) for BIM Execution Planning in Green Building Projects

Wei Wu, A.M.ASCE*
Raja R. A. Issa, F.ASCE†

Abstract: *The symbiotic convergence of green building and building information modeling (BIM) is represented by an emerging trend – green BIM. Project teams find that synergies between green and BIM can improve project outcomes and they are in a better position to accomplish established sustainability goals. Nevertheless, the full potential of green BIM is yet to be explored, as indicated by recent market research. The hypothesis is that for companies to successfully deliver green BIM project, a holistic approach that strategically plans for BIM execution to achieve sustainability goals is needed. The BIM Project Execution Planning Guidelines (PEPG) is currently being adopted by project teams as a standard workflow of strategic BIM implementation. PEPG, however, was not configured to address green building projects specifically. This research sees an opportunity to inherit PEPG's framework and develop an integrated green BIM process model for BIM execution in green building projects. Considering the prevalence of Leadership in Energy and Environmental Design (LEED) green building rating system in the North American building industry, this research focuses on LEED projects as an exemplary use case. Two major activities conducted include: 1) a comprehensive literature review of existing green BIM strategies and best practices, and 2) the proposition of an Integrated Green BIM Process Map (IGBPM), which is essentially adapting PEPG and initiatives such as the Architecture, Engineering, Construction, Owner & Operator, Phase 1 (AECOO-1) Joint Testbed to address unique business processes*

*Construction Management Program, Lyles College of Engineering, California State University, Fresno, 2320 E San Ramon Ave, MS/EE 94, Fresno, CA 93740-8030; PH (559) 278-6011; FAX (559) 278-4475; email: weiwu@csufresno.edu

†Rinker School of Construction Management, University of Florida, P.O. Box 115703, Gainesville, FL 32611-5703; PH (352) 273-1152; FAX (352) 392-9606; email: raymond-issa@ufl.edu

of implementing BIM in LEED projects. The deliverables of this research include the overall framework of IGBPM, the Level 1 IGBPM and exemplary Level 2 IGBPM process maps, discussed along with case studies for verification and validation.

INTRODUCTION

Companies who are at the leading edge of building information modeling (BIM) and green building have found remarkable synergies between the two major industry trends. The term "green BIM" is coined as the representation of their symbiotic relationship. Project teams are increasingly discovering how BIM implementation might have facilitated accomplishing sustainability goals in project delivery. Not only because BIM provides immediate insight into how design decisions impact building performance, but the adoption of BIM also necessitates integrated design process (IDP) and collaborative project delivery (McGraw-Hill Construction 2010). Technical strengths of BIM in assisting sustainability analyses and performance simulation in building design and construction were relatively well understood. Studies conducted by Azhar et al. (2009, 2011), Barnes and Castro-Lacouture (2009) and Bynum et al. (2013) have demonstrated the capacity of BIM in facilitating decision-making and multidisciplinary collaboration at early design and preconstruction phase to accomplish sustainability goals. Krygiel and Nies (2008), Hardin (2009) and McGraw-Hill Construction (2010) delineated the technical strength and best practices of utilizing BIM to plan, design and construct buildings in compliance with sophisticated performance criteria and regulatory requirements.

Nevertheless, there is little research on how the process of BIM execution in green building projects will influence the project outcome. An exemplary use case in the North American building market is how to leverage BIM to accomplish the Leadership in Energy and Environmental Design (LEED) green building certification (Wu and Issa 2012). Current investigation of future green BIM development has been technological-centric and focuses heavily on tool/functionality enhancement (McGraw-Hill Construction 2010) to streamline certification compliance with rating systems (e.g. LEED, Green Globes) and/or green codes (e.g. International Green Construction Code (IGCC)). Providing that existing BIM software applications may fall short of industry expectation, a handful of leading companies have been very successful in green BIM, utilizing just about the same collection of off-the-shelf BIM applications. Therefore, a legitimate guess is that technological factors are only partially contributing to successful BIM implementation in green building projects. This speculation concurs with the research findings from Häkkinen and Belloni (2011) in investigating barriers and drivers for sustainable building. They suggest that "sustainable building is not hindered by a lack of technologies and assessment methods, but is instead beset with organizational and procedural difficulties entailed by the adoption of new methods".

Research Objectives and Scope

The hypothesis of this research is that the business process of BIM execution has a significant impact on accomplishing project sustainability goals such as the LEED certification. The hypothesis is made based upon the observation of broad acceptance and utilization of the BIM Project Execution Planning Guide (PEPG). PEPG is the first systematic effort in standardizing the planning of BIM implementation at project level. However, PEPG is generic for all building projects, which inevitably lacks the emphasis or simply is not meant to address the specificity of using BIM in green building projects.

This research intends to adapt general PEPG tenets and guidelines to address specificities of green building projects, especially LEED projects; and to promote and facilitate green BIM practices. The objectives of this research include:

- Conduct a comprehensive literature review of current research efforts and industry best practices of green BIM;
- Propose and develop an integrated green BIM process map (IGBPM) using Business Process Model and Notation (BPMN) as a special case of PEPG;
- Verify the proposed IGBPM and its possible implementation with LEED as a use case via case studies.

The scope of this research is limited to identify the general execution planning of BIM use in green building projects especially LEED projects, and the development of IGBPM Level 1 & exemplary Level 2 process maps with LEED as a use case. Preliminary validation is also conducted to verify the applicability of the proposed IGBPM concept through case studies. The longer term goal of this research is to adapt PEPG to green/LEED projects and create a practical process model that is going to be utilized by companies who have been looking for assistance on achieving better outcomes of green BIM projects.

BACKGROUND

Proposition of a dedicated BIM execution planning for green building projects is premised on the convergence of two distinct but synergistic industry trends. Lessons can be learned through the review of current literature on process modeling of green building project delivery and generic BIM project execution principles. It is also beneficial to examine industry best practices and current research efforts on green BIM, which is anticipated to provide a desirable balance of empirical and theoretical literature references that this research is grounded in.

Modeling Green Building Process

Process plays a key role in successfully delivering a high performance green facility within budget and on time, according to Horman et al. (2004). Modeling is the critical first step to better understand the green building delivery processes. For modeling to be effective, it must consider the unique attributes of the process it is

representing (Klotz et al. 2007). As a result, it is important to understand that the unique sustainability goals pose additional requirements on the delivery process to accomplish the project's green certification, and necessitate early involvement of key project stakeholders, owner commitment to sustainability and rigorous use of performance modeling/simulation tools (Riley et al. 2004, Riley and Horman 2005, Beheiry et al. 2006, Horman et al. 2006). The theory underpinning high performance project delivery is that reduced process waste is able to enhance both sustainable outcomes and the business case for sustainability (Horman et al. 2006). Emerging concepts such as integrative design (Reed and Gordon 2000), the integrated design process (IDP) (WBDG 2012) and integrated project delivery (IPD) (AIA 2007) in the AEC industry also confirm the importance of understanding the project delivery attributes which require multidisciplinary teamwork. Molenaar et al. (2009) confirmed that collaborative project delivery methods such as CM At-Risk, Design-Build and IPD were statistically more successful in delivering LEED projects.

Building process models (BPMs) are products of implementing general process modeling tenets, which were originated in the manufacturing industry, in the AEC industry. BPMs define the essential functions required to provide a facility to the end user (Wallace et al. 1987) and emphasize important information, relationships and/or elements concerning the provision of the facility. Conceivably, the essence of building process models are the steps of "how" the facility is constructed and "who" provides the necessary competencies to do so, contained within the legal framework provided by the particular project delivery method. In return, a BPM forms the basis for developing important understanding about the characteristics of high performance building delivery (Horman et al. 2006). For example, the Integrated Building Process Model (IBPM) developed by Sanvido (1990) using the IDEF0 modeling language has been the foundation for extensive research into how to map a facility delivery process from inception to turnover. IBPM does not explicitly contain information about value added and waste activity, and it is difficult to follow the overall process flow (Lapinski et al. 2005), but it could be adapted or further developed with the additional elements to understand high performance building project processes (Horman et al. 2006). Both IBPM for High Performance Buildings ($IBPM^{HP}$) and the Integrated Design Process Model for High Performance Buildings ($IDPM^{HP}$) are able to articulate project value and process waste, integrating environmental objectives and requirements for project team competencies (Korkmaz et al. 2010). Another example, the Integrated Building Lifecycle Process Map (IBLPM), is based on the third level of IBPM to enable energy efficient design at the building system level with lifecycle visualization (Lee et al. 2012).

Recent development of BPMs starts to acknowledge enhanced implementation of information and communication technology (ICT) technology in green building project and attempts to integrate "Lean" principles (e.g. Lapinski et al. 2005 and 2006, Klotz et al. 2007) and "System Engineering" criteria (e.g. Bersson 2012). It is intriguing however, none of the existing BPMs have touched upon the impacts and implications of BIM implementation on LEED project delivery,

providing that most literature reviewed above referred to LEED certified building projects that were relying on BIM for sustainability analyses and critical performance modeling.

Modeling BIM Project Execution Process

Similar to green building, BIM implementation prefers more collaborative project delivery methods and is urging a paradigm shift in current construction business processes (Derrick and Mei Kuen 2008, Mihindu and Arayici 2008). Smith and Tardiff (2009) labeled BIM as a "disruptive technology" that posed a fundamental challenge to the AEC industry considering the inherent fragmentation in the overall supply chain (NIBS 2007). Discrepancies in the BIM sophistication of project team members (Wix 2007) and interoperability difficulties associated with use of heterogeneous BIM software applications (Gallaher et al. 2004) add extra dimensions of complexity to BIM project execution. Laiserin (2007) shed some lights on potential areas of improving BIM implementation to look at the accuracy, consistency, integration, coordination and synchronization of the execution process.

Process modeling efforts to address challenges in BIM adoption and implementation at project level were rare before the introduction of PEPG (Saluja 2009, Coates et al 2010). The IPBM and the Generic Design and Construction Process Model (GDCPM) (Kagioglou et al 2000) as foundational BPMs were also examined to help better understand BIM execution. However, neither IPBM nor GDCPM specifically focused on the tasks that a project team must perform to effectively implement BIM at the project level. They were insufficient for supporting the strategic decisions to be made by a construction team since an information handover is required encompassing many specific BIM tasks, company information and other external information (Saluja 2009).

PEPG provided the first well-formatted process model for BIM implementation at the project level. It defined the appropriate uses for BIM on a project (e.g., design authoring, cost estimating, and design coordination), along with a detailed design and documentation of the process for executing BIM throughout a project's lifecycle. Major contributions of PEPG to facilitate better integrated BIM process in project execution include: a method to identify BIM Uses; a procedure for designing the BIM Process for the project; a method for defining the information exchange (IE) requirements; a method to define the infrastructure necessary to support the BIM Process; a structured method for team implementation of the procedure through a series of meetings and intermediate tasks; and a structured method for individual organizational development of typical methods for BIM implementation (CIC 2010). PEPG is now widely adopted and utilized as an industry standard for BM project execution, including in LEED green building projects.

However, PEPG is not crafted to target green building projects but more about providing a generic process model for any projects that implement BIM. The authors have interviewed several BIM or Virtual Design and Construction (VDC) managers and coordinators who have substantial projects experience with

both BIM and LEED. A few most frequently mentioned barriers to conscientiously explore BIM integration in LEED certification to full extent reside in:

- Owner's willingness and/or project requirements: Seldom there are owners ambitious enough to mandate use of BIM to accomplish LEED certification. Project teams see no motivation to take unnecessary liability and risks to use BIM in LEED calculation;
- Costs: LEED is expensive, so is BIM. Project teams often target the low-hanging fruits of LEED credits to reduce LEED certification costs, which is often achievable effortless without BIM;
- Technology: Providing the competency of current BIM tools, project teams are still challenged or feel impractical to use BIM to qualify certain LEED credits, and produce desired metadata to prepare LEED documentation and submittals. It is however possible for some leading firms to invest in internal research and development (R&D) for expanded BIM capacity to gain competitive edges;
- Interoperability: Not only members on a project team might use distinct BIM applications, but also the sophistication level of BIM literacy and skills of team members vary significantly. Information exchange and project information flow may potentially suffer from incompatible exchange formats, or even encounter interruption due to inability for non-BIM users on the project team to produce, receive and process model data.

As a process model, PEPG did not address the above issues to clear off the path for more ambitious BIM utilization in LEED projects.

Interoperability and Level of Development in Information Exchange

To elaborate on the interoperability challenge faced by a project team, the multidisciplinary nature of a LEED project team determines that the overarching solution to interoperability should consider: *What information needs to be exchanged*? *What format*? *What business rules*? *When and between whom*? Initiatives in the industry take both proprietary and open-source approaches. Partnerships between software vendors to articulate each other's data formats are mostly done in a proprietary manner, while the development of Extensible Markup Language (XML) based exchange formats (e.g. green building XML or gbXML) and the Industry Foundation Classes (IFC) are primarily open-source.

IFC holds the promise to be the interoperable standard for the exchange of building product information and intends to cover all vital information about the building in its life cycle (Eastman 1999). Major BIM software vendors are IFC-certified to produce models and exchange model information in IFC format. However, there are known issues in vendors' compliance with IFC schema, which result in geometric misrepresentation, loss of object information, confusion in interdisciplinary revisions, large file size, and specific application requirements. Fallacies like such can undermine the reliability of data exchange using IFC (Pazlar

and Turk 2008). Meanwhile, IFC alone is not able to capture the business process and its various developments which a user may later need, nor does it account for the ways in which information is created and shared by the practitioners. Development of the Information Delivery Manuals (IDM) and Model View Definitions (MVD) are key enhancements to the IFC framework. IDM aims to provide the integrated reference for process and data required by BIM by identifying the discrete processes undertaken within building construction; the information required for their execution; and the results of that activity (Grobler 2010). The main components of an IDM include Process Map (PM), Exchange Requirements (ER) and Functional Parts (FP). MVD defines a legal subset of the IFC Schema (being complete) and provides implementation guidance (or implementation agreements) for all IFC concepts (classes, attributes, relationships, property sets, quantity definitions, etc.) used within this subset. It thereby represents the software requirement specification for the implementation of an IFC interface to satisfy the ER as defined in the IDM (Wix 2007).

There are some successes in IFC-based BIM execution process modeling. Eastman et al. (2009, 2010a and 2010b) and Panushev et al. (2010) provided case studies of IE standardization in process modeling for precast/pre-stressed concrete using the IFC/MVD/IDM framework. IFC-based information exchange is also broadly adopted in energy simulation workflow. Energy efficiency is an essential step that leads to green building certification and long term cost savings in facility operation. Maile (2007) and Bazjanac (2008) mapped out information flow in IFC format between major energy simulation engines (i.e. DOE2.2 and EnergyPlus) and commercial graphical user interfaces (GUIs). The Architecture, Engineering, Construction, Owner Operator Phase 1 (AECOO-1) Joint Testbed is another epic effort in developing and implementing IFC/IDM/MVD based methods to streamline communications between parties in the conceptual design phase to get an early understanding of the tradeoffs between construction cost and energy efficiency (OGC 2010). A dilemma of relying on IFC as the primary IE standard throughout BIM execution in building projects resides in the fact that even IFC-certified software vendors would not enforce its use, nor do they encourage their customers to do so because there are extra efforts needed in validation using model checking tools (e.g. Solibri IFC Optimizer) to ensure the data integrity when model information is exchanged between software applications using IFC (Malleson 2012).

In addition to interoperability, effective IE in project delivery is also content-driven. The specific model components that are exchanged for a defined sub-process within a discipline/domain often only represent a small ratio of information captured in the model. Therefore, the project team has to arrive at a certain Level of Development (LOD) to feed the information needed for the specific business process to take place. In AIA (2008), a Model Element Table (MET) was used to pair Model Element Authors (MEA) with LOD to guide the appropriate project model development. PEPG also provides an IE worksheet that uses Model Element Breakdown (MEB) to explicitly spell out the relationship between the model elements and corresponding responsible parties for each BIM

uses at a specific project delivery stage. In BIM execution planning, LODs are critical in that it has a direct impact on model information allocated to domain-specific sub-processes, which constitute the most practical aspects in implementing a BIM project execution plan (CIC 2010, BIMForum 2013).

Best Practice and State-of-the-Art Research in Green BIM

PEPG is an innovation based upon the creative synthesis of industry best practices of BIM implementation and knowledge gains from the research frontier. Therefore, it is hoped that a similar approach of reviewing the following best practices and research efforts can shed lights on developing the proposed IGBPM.

National/International Green BIM Initiative

Building sustainability is an applied concept of sustainable development. It bears considerations not only related to building performance, but also attempts to address the triple bottom line, specifically, the environmental, economic and social impacts of the building industry. Because of the abundance of needed information, efficient information-technological solutions are desirable. BIM arose as a solution to support the supply, integration and management of information throughout the building life cycle (Häkkinen and Kiviniemi 2008). In the US, the General Service Administration (GSA) is leading the efforts to leverage BIM for high performance buildings, by establishing the National 3D-4D BIM program and publishing the BIM Guide Series (GSA 2012). The US Department of Energy (DOE) and the office of Energy Efficiency and Renewable Energy (EERE) have also instituted efforts to utilize advanced modeling and simulation technology via broad stakeholder involvement for significant energy savings in capital projects. The Building Technologies Program, the Commercial Building Initiative (CBI) and the Commercial Reference Building Models for National Building Stock are highlights among these efforts (DOE 2011).

Internationally, in the European Union (EU), the STAND-INN project commissioned by the Europe INNOVA initiative was directed to facilitate the integration of open standards into the business process to reduce cost and increase the productivity and promoting sustainable development in the construction sector. The STAND-INN project investigated BIM as a practical approach to achieve life cycle sustainability of construction projects. The project proposed interoperability based sustainability via the "Open BIM", which was built upon the information exchange framework using open standards such as the IFC, the International Framework for Dictionaries (IFD) and IDM. It suggested that IFC-based BIM should vastly improve its usefulness in facilitating sustainable construction (Europe INNOVA 2008). A more comprehensive initiative, the Energy Efficient Buildings, under the Information and Communication Technology (ICT) for Sustainable Growth policy framework, was funded by the European Commission (EC) through instruments like the 7th Framework Program (FP7) for Research and Technological Development (RTD) and the Competitiveness and Innovation Program (CIP). An open and extensible energy-enhanced BIM

framework (eeBIM) was proposed to support the data flows for energy efficient design and lifecycle management. The eeBIM framework, with clearly defined ontology and information delivery manual, when bounded with a SOA-based Integrated Virtual Energy Laboratory, IVEL (as developed in the HESMOS project), would enhance the "energy interoperation" between energy simulation model(s), Building Automation Systems (BAS) and Building Energy Management Systems (BEMS) hosted in a semantic web environment (Katranuschkov et al. 2011, Scherer et al. 2011).

Green BIM Research and BIM/LEED Synergies

There is a good diversity of scholarly research on BIM and green building design and construction. The following focus areas are categorized by particular BIM uses:

- BIM for building performance modeling, including energy and thermal simulation (e.g. Yoon et al. 2009, Schlueter and Thesseling 2008, Bazjanac 2008, Laine and Karola 2007, O'Sullivan and Keane 2005), lighting simulation (e.g. Huang et al. 2008), daylighting simulation (e.g. Welle et al. 2012).
- BIM for integrated design process (IDP) optimization, e.g. Wong and Fan (2013), Oh et al. (2011) and Wang et al. (2010).
- BIM-based building evaluation, e.g. Motawa and Carter (2013) and Nguyen et al. (2010).
- BIM software green design capacity evaluation, e.g. Reeves et al. (2012) and Azhar et al. (2009).

Findings from the above listed studies may not immediately relate to objectives of this research, but they provide insights into various contexts of BIM uses in green building projects, which is valuable to devise the sub-processes of IGBMP that are domain-specific and task-driven.

With LEED being a globally-recognized green building rating system, BIM implementation in LEED design, credit analysis and documentation have caught a lot of attention in the research community. In a simplistic manner, challenges to accomplish LEED certification boil down to performance and documentation. LEED is a prescriptive (versus performance based) rating system, using a set of prescribed criteria with allocated scores to evaluate the "greenness" of a building. Not only does the project team have to design accordingly, but also they have to document the process in an exhaustive manner for certification review purposes. The most recent update of LEED confirms its resolution to transform to performance-based criteria and requires performance auditing for energy efficiency, which makes facility management and the life-cycle perspective an essential part of project certification endeavors. Most researchers have addressed BIM/LEED synergies. For instance, Biswas et al. (2008) and Wu and Issa (2010a) proposed system level integration of BIM and LEED; Barnes and Castro-Lacouture (2009) and Bank et al. (2010) demonstrated the possibilities of using BIM as a sustainable design decision-making tool, and relying on BIM-based information for certain LEED points calculation. In addition, O'Keeffe et al. (2009), Azhar et al. (2010),

and Wu and Issa (2010b) looked at how BIM could facilitate the LEED certification process with design analysis optimization, information management, documentation generation and certification review. Wu and Issa (2011, 2012) also proposed a cloud-BIM based framework to automate LEED certification process in response to the *LEED Automation* program that encourages seamless information flow across heterogeneous software platforms (USGBC 2010). Although none of abovementioned research has explicitly examined the project level BIM/LEED execution process, they collectively made a convincing case that a holistic approach for BIM execution planning in LEED projects bears significance from the research and business perspectives.

Literature Review Summary

The literature review clearly revealed the underlying synergies between BIM and green building. More importantly, it helped confirm the following assumptions:

- There is a strong interest among industry players and research scholars in how BIM interacts with green building to facilitate more sustainable project outcomes.
- Spontaneous efforts have been made by companies in exploring the best practices of implementing BIM to achieve a wide range of sustainability goals, such as energy efficiency, renewable energy potential, water conservation, materials and resources optimization and indoor environmental quality.
- Functionality of current BIM tools is not perfect, but sufficient in performing green building design and analysis to meet compliance requirements of codes, standards and rating systems with relatively affordable costs.
- Current green BIM practices are heavily technology-driven instead of process-driven. The business goals of BIM uses in green projects such as LEED projects are not well defined. The roles and responsibilities are not explicitly identified, allocated and enforced. The mechanism and standards for information exchange are not established or not to the right LOD.

Sound process modeling and process mapping can significantly increase the productivity and add value to green building and BIM projects. A better, integrated process will promote green BIM practices to a different level. Existing process models such as PEPG have been well developed to provide the skeleton of a new, unique green BIM process.

METHODOLOGY

Process Mapping Methods and Development Procedures

Business Process Model and Notation (BPMN) is a popular process modeling standard and graphical representation specifying business processes (White and Miers 2008). It offers simple but standardized visual communication for users to

understand the external and internal business procedures through a business process diagram. BPMN is adopted by the National BIM Standards (NBIMS) in the IDM for better integration with the detailed information exchange mapping initiatives (Saluja 2009). The process maps in PEPG are also created using BPMN in Microsoft Visio. A typical BPMN process has clearly defined business goal(s), the process input/output, the responsible parties, tasks or sub-processes and the information exchange. Processes may occur sequentially or concurrently, or sometimes will reiterate.

The proposed IGBPM is developed using BPMN, following similar procedures of PEPG but oriented to LEED projects in particular. Step 1 of the procedures identifies the primary (LEED certification) and secondary (LEED credits) business goals and potential BIM uses. Project delivery methods (PDMs) are also analyzed, considering that project team building and information exchange timeline are both affected by PDMs. Step 2 lays out the overall sequence and interaction of identified processes according to the BIM uses at a specific PDM phase. Step 3 presents the process-specific BIM uses driven by certain LEED credit requirements, designates responsible parties, and spells out information exchange strategy and the expected process outcomes.

Use Cases and Validation Plan

The IGBPM Level 1 process map acts like a placeholder to pinpoint Level 2 processes to project phases. In contrast, a Level 2 process map looks at a BIM use and its intended LEED credit criteria with much closer scrutiny. Considering the various LEED rating systems and the overwhelming amount of LEED credits, this research is not intended to create all Level 2 process maps for each individual credits. Rather, a selected exemplary use case was discussed in detail, which examined *BIM Use: Energy Analysis* implemented to accomplish *LEED Credit: Optimize Energy Performance* (applicable to several LEED rating systems) and demonstrated the development of this process into a Level 2 process map. It is believed that such discussion will offer adequate detail of guidance on developing similar process maps for any other BIM Use – LEED Credit use cases.

The proposed IGBPM needs to verify the concept and practicality of implementing standardized business processes such as the ones developed in the IGBPM to facilitate BIM execution in LEED projects. The authors conducted a comprehensive literature review of case studies with key words of IPD, BIM and LEED. The criteria and procedures used to screen and select the suitable case studies in this research are illustrated in Figure 6-1. The rationale behind this approach is to address the reality of integration of IPD, BIM and LEED in the industry, where sophistication levels of knowledge and experience among companies are very diverse. Organizational level of IPD/BIM/LEED integration is identified as the highest and represents the new paradigm that the industry pioneers have established in terms of implementing IPD, BIM and LEED in their business operations. Project level integration and process level best practices are corresponding to the IGBPM Level 1 and Level 2 processes proposed in this research.

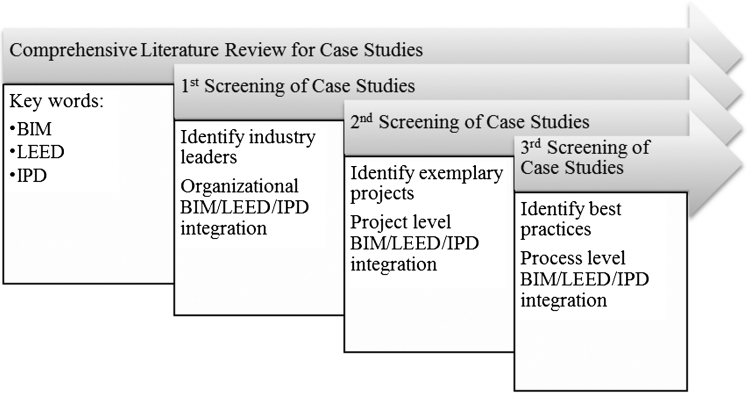


Figure 6-1. Case study screening and selection criteria and procedures.

DEVELOP THE IGBPM

Step 1: LEED Strategy – BIM Use Mapping and Team Building

A LEED strategy is a recipe formulated by the project team at the inception of a LEED project (often through a process called *Design Charrette*) to determine the feasibility of achieving a certain certification level (primary business goal) based on the accumulated LEED credit scores (secondary business goals). Depending on the project delivery method, the LEED strategy also assigns individual LEED credits with responsible parties on the project team. The completed LEED strategy is a checklist that represents the project compliance path to LEED certification. The mapping of BIM uses is then conducted on the basis of analyzing each attainable LEED credit against its compliance requirements and anticipated project activities. Figure 6-2 presents the *LEED Category: Energy & Atmosphere* excerption of the developed *LEED Strategy - BIM Use Analysis Worksheet* based upon PEPG's Goal-Use Analysis Worksheet. The contents filled in Figure 6-2 came from a real LEED project that used minimum BIM execution in the LEED *Design Charrette*. As is shown, all LEED credits (including prerequisites) are firstly summarized into corresponding LEED activities, which are essentially tasks that need to be accomplished in order to score the LEED points assigned to this credit. A green BIM use is then mapped with the LEED activity, which implies the responsible party will rely on a particular functionality of BIM to conduct the desired performance analysis and simulation to confirm the design will meet the LEED credit requirements. The responsible party is usually the domain expert that specializes in performing such tasks using BIM. Once the worksheet is completed, it is like to become a great communication tool for everyone on the project team to clearly understand the roles and responsibilities early on.

Concurrent with the mapping process is the team building. Collaborative PDMs such as IPD encourage BIM used by multiple parties. One of the major

LEED Points				LEED Category: Energy & Atmosphere	Project Activity	BIM Use	Value to Project	Responsible Party*	Value to Resp Party	Capability Rating			Resources and Competencies	Notes	Proceed with Use
Total Possible Points = 35				LEED Credits	LEED Activity	Green BIM Use	High / Med / Low		High / Med / Low	Scale 1-3 (1 = Low)					YES / NO / MAYBE
Possible	Yes	Maybe	No							Resources	Competency	Experience			
0	Y			P1 Fundamental Commissioning of Building Energy Systems	Building Commissioning	Building System Analysis	High	EMC	High	3	3	3	Recorded Model, Building System Analysis Software	CxA to fill LEED Online templates	Yes
0	Y			P2 Minimum Energy Performance	Whole Building Energy Analysis	Energy Analysis	High	RBGB	High	3	2	2	Energy Model, Energy Simulation Software	Pending Review Response Request	Yes
0	Y			P3 Fundamental Refrigerant Management	Refrigerant Management	Mechanical Analysis	High	NBP	Low	3	1	1		Anticipated	No
19	10		9	1 Optimize Energy Performances	Whole Building Energy Analysis	Energy Analysis	High	RBGB	High	3	2	2	Energy Model, Energy Simulation Software	Pending Review Response Request for P1 (Energy Model)	Yes
7	1		6	2 On-Site Renewable Energy	On-Site Renewable Energy Potential Analysis	Energy Analysis	Med	Southface	Med	3	2	2	Energy Model, Energy Simulation Software	Pending Review Response Request for P1 (Energy Model)	Yes
2	2			3 Enhanced Comissioning	Building Commissioning	Building System Analysis	High	EMC	High	3	3	3	Recorded Model, Building System Analysis Software	CxA to fill LEED Online templates	Yes
2	2			4 Enhanced Refrigerant Management	Refrigerant Management	Mechanical Analysis	Med	NBP	Low	3	1	1		Anticipated	No
3	3			5 Measurement and Verification	Building Automation and Control	Building System Analysis	High	Southface	High	3	2	2	Recorded Model, Building System Analysis Software	RBGB provide documentation at construction submittal	Yes
								RBGB	High	3	2	2			Yes
						Asset Management	High	EMC	High	3	3	3	Recorded Model, Asset Management System		Yes
2			2	6 Green Power	Green Power Purchasing	–	Low	–		–	–	–			–
35	18	0	17												

Figure 6-2. LEED Strategy—BIM Use Worksheet: Energy & Atmosphere Excerption.

features of IPD is that it encourages early involvement of stakeholders and encourages concurrent activities and enhanced collaboration among project participants. Recent industry research of IPD best practices (AIA 2010, 2012) summarized case studies delivered with integration of BIM and found that IPD tended to encourage "just-in-time" information exchange and eliminating redundant work in decision-making, which are exactly the characteristics of BIM-based project information workflow. According to these case studies, there is a tendency of increased use of IPD in BIM projects. In this research, identified IPD project phases include: *Conceptualization, Criteria Design, Detailed Design, Implementation Documents, Agency Coordination/Buyout, Construction* and *Post-Construction*. Accordingly, the project team consists of the following major stakeholders: Owner, Architects (expandable to include Landscape Architect) Engineers (expandable to specify Civil, Mechanical, Electrical, Structural, etc.), Contractors, Commissioning Agent (CxA), Consultants (including LEED Administrator), Trade Contractors (expandable to M/E/P, etc.), and Suppliers. These assumptions are obviously subject to great flexibility in real IPD project settings.

Step 2: Develop the IGBMP Level 1 Process Map

The Level 1 process map was developed based upon PEPG and the LEED of New Construction (LEED-NC) 2009 rating system, and could be easily adapted to other LEED rating systems, considering that the general environmental categories are mostly equivalent in the whole family of LEED rating systems. A "process" is the fundamental unit of a BPMN process map. Microsoft Visio provides built-in BPMN templates and notations to streamline the mapping efforts. Figure 6-3 presents a typical Level 1 green BIM process with components breakdown. A "LEED activity" (e.g. Perform Energy Analysis – Conceptual) for a specific LEED sustainability goal (e.g. Minimum Energy Performance) was defined first, the potential "BIM use" (e.g. Energy Analysis) as a sub-process (Level 2 process)

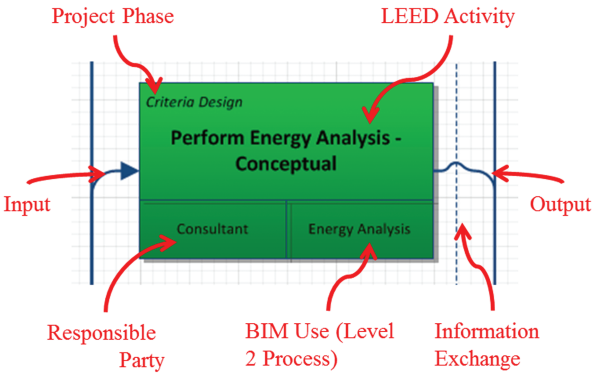


Figure 6-3. A typical Level 1 process with components breakdown.

was then looked up from the LEED Strategy – BIM Use Worksheet developed at ***Step 1*** (Figure 6-2) with the primary designated "responsible party" (e.g. Consultant). The process has an "input" and "output". IE incidences are expected to take place between responsible parties involved in this process. The process also has a designated "Project Phase" (e.g. Criteria Design) of its occurrence.

The next step is to create similar processes at the same phase (Figure 6-4). Notice there are also non-green BIM processes (marked with lighter color), which do not address LEED activities but are part of the original PEPG process map. These activities are generic and essential to any projects that implement BIM. By repeating the same workflow through the entire project delivery, the overall IGBPM Process Mapping – Level 1 is completed and illustrated in Figure 6-5 (with limited resolution due to the size of the diagram).

As shown in Figure 6-5, there are two "blocks" of BPMN notations, defined as "swimlanes". Swimlanes are used to partition and organize activities. The upper swimlane contains the bulk of all developed green BIM and non-green BIM processes at each project phase, while the lower swimlane captures all IE incidences and various inputs/outputs generated along with the process progression. Notice some of the IE incidences are marked in darker color. These IE incidences are dedicated to LEED activities and represents LEED-relevant deliverables. These deliverables contain the raw data that will be further manipulated to prepare LEED documentation for certification review purposes. The processes, BIM uses and IE incidences at Level 1 are general and brief in nature, and act as placeholders to present the team with a big picture of the BIM execution as project elapses. It is living document that needs revisiting for update to reflect the actual progress of BIM execution through the project delivery.

Step 3: Develop the IGBPM Level 2 Process Maps

The IGBPM Level 2 processes are essentially the elaborated discussions of BIM uses (e.g. Energy Analysis) identified in Level 1 green BIM processes. A Level 2 process is task-driven, tied with specific LEED sustainability goals (e.g. Optimize

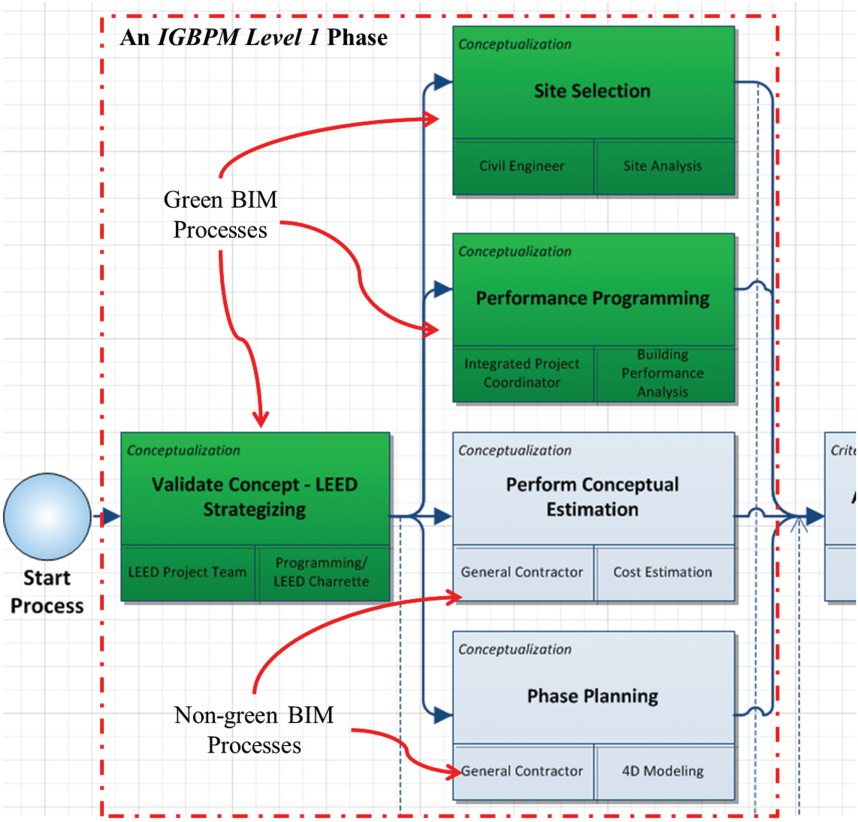


Figure 6-4. A typical IGBPM Level 1 phase, e.g. "Conceptualization".

Energy Performance) and often entails a domain-specific business workflow (e.g. Whole Building Energy Simulation) but interfaces with a multidisciplinary team. Responsibilities and IE requirements are clearly defined between responsible parties. Exchange formats/data schemas and business rules of information delivery are also stipulated and agreed upon. Figure 6-6 illustrates the IGBBP Level 2 – Energy Analysis use case and its components breakdown.

In comparison with Level 2 processes in PEPG, Figure 6-6 exemplifies some of the "LEED" flavor of an IGBPM Level 2 process. For instance, the "LEED Gateway" is a process control of business decision-making, and is driven by the LEED strategy, or applicable LEED reference standards. For the Energy Analysis use case, the first business decision to make is about which compliance path option the project team should take to meet the credit requirements of optimizing energy performance. Only Option 1: Whole Building Energy Simulation is applicable to this use case. The second business decision is to determine if the BIM model has been appropriately developed and configured for energy simulation.

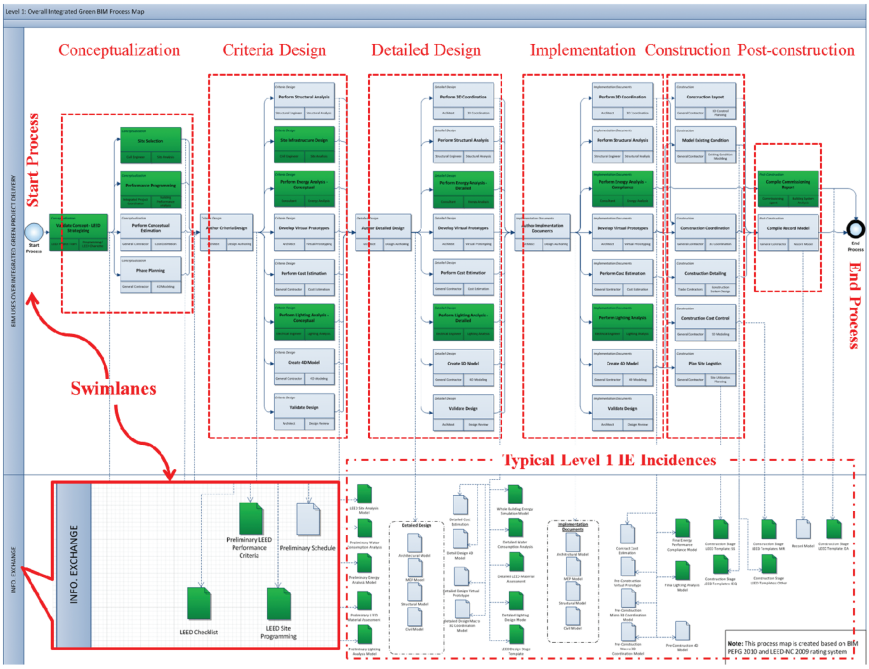


Figure 6-5. Overview and major components of IGBPM Level 1.

LEED modeling requirements for energy simulation are regulated by the ASHRAE 90.1-2007 standard, and refer to the following specificities (USGBC 2011, GSA 2012):

- Physical elements: building elements such as walls (including openings and curtain walls), slabs/floors, roofs/ceilings, columns and shading devices need to be modeled with the designated tools in BIM;
- Spaces/Rooms/Zones: prepare spaces with defined heights and boundary conditions, and assign spaces to appropriate thermal zones and HVAC zones; and
- Space boundaries: develop 2nd level space boundaries that account for adjacent spaces.

In addition to "accuracy", a BIM model should also be developed to the sufficient LOD to satisfy energy analysis needs at different project phases, as shown in Table 6-1. Current workflow of leveraging BIM data to develop the Building Energy Model (BEM) for energy analysis in the industry is illustrated in Figure 6-7. A major challenge in this process is the mapping between the BIM data and BEM input file, which is largely determined by the data schema files. The industry is using a matrix of both proprietary and open source data schemas to streamline this process, depending on the energy simulation tools adopted by the

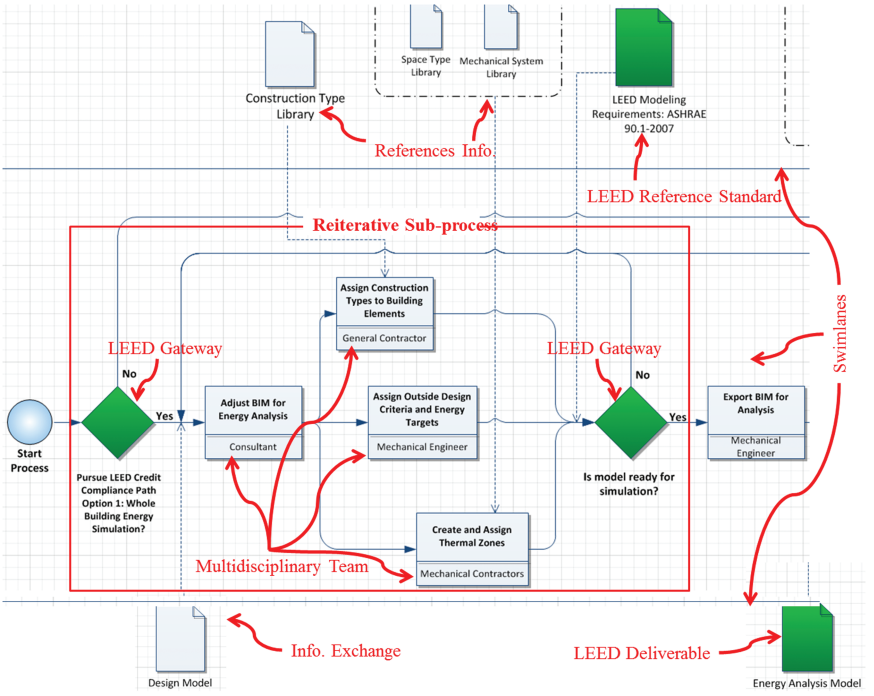


Figure 6-6. IGBPM Level 2 Process—Energy Analysis components breakdown.

project team. Figure 6-8 provides a summary of IE in BIM-based energy simulation, which is able to address contemporary industry practices using state-of-the-art software packages. In summary, the Energy Analysis use case is one of the more challenging IGBPM Level 2 processes. By adopting a similar method, other LEED use cases can also be developed.

IGBPM Development – Summary

The model development is still a working process, but the results so far are sufficient as a proof of concept for a unique process model that addresses BIM implementation in efforts to meet green criteria such as the LEED rating systems requirements. The Level 1 and Level 2 process maps are only examples of adapting PEPG to green BIM project needs through innovation. It is recommended by the authors that project teams should evaluate the IGBPM as a possibility instead of a finished product. The value of the IGBPM resides in the fact that it identified the limitations of PEPG in accommodating the highly diverse and complex technological and managerial needs experienced in LEED project delivery, and demonstrated the feasibility and necessity of critical thinking in inventing better business processes.

Table 6-1. Implement LODs in BIM-based energy modeling (adapted from GSA 2012)

LOD	*Equivalent Project Phase*	*Modeling Detail*	*Depth of Energy Analysis*
LOD 100	Conceptualization	Site location, building orientation, massing, and default assumptions	Quickly assess large-scale impacts of design alternatives
LOD 200	Criteria Design/Detailed Design	Building geometry, preliminary layout, construction, mechanical equipment, and intermediate assumptions	Evaluate and compare proposed design schemes, intermediate analysis, preliminary code compliance
LOD 300	Implementation Documents	Building geometry, detailed layout, detailed construction and envelope design, mechanical equipment, building controls, and detailed assumptions	Estimate final design energy performance, detailed analysis, preliminary code compliance
LOD 350	Buyout	Detailed model	Finalize estimated energy performance and code compliance
LOD 400	Fabrication/Construction	Detailed model	Assess impact of change orders and construction detailing
LOD 500	Post Construction	As-built/field validated model	Evaluate actual building energy performance, including HVAC control systems

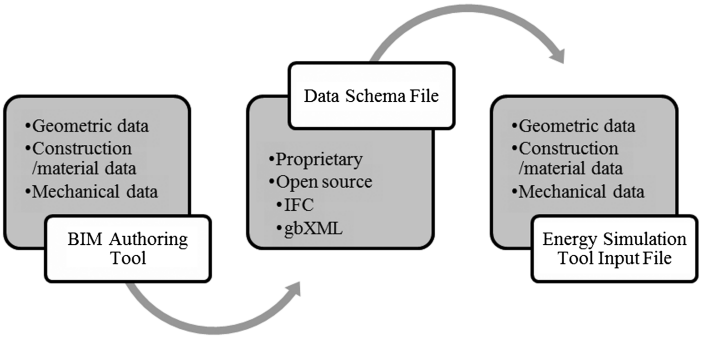


Figure 6-7. Sequence of information transfer in BIM-based energy modeling (adapted from GSA 2012).

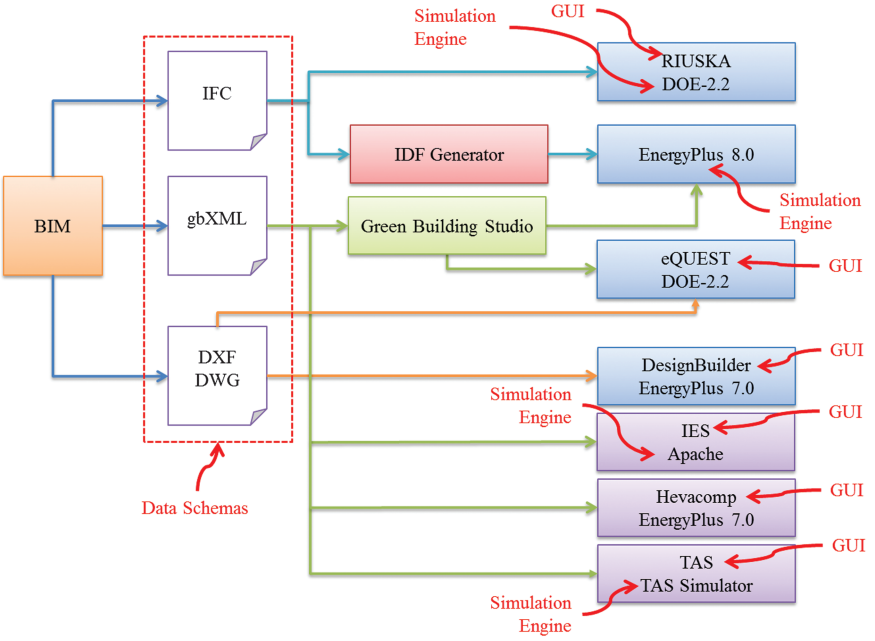


Figure 6-8. Summary of IE in BIM-based energy simulation (adapted from Maile 2007).

CASE STUDIES

The following case study exhibits the holistic approach that Turner Construction had adopted to cultivate a culture of BIM, Lean and Green in their business operations. The findings through the interview provided clear evidence that industry leaders such as Turner had been practicing green BIM proficiently and

created standardized business processes to plan and manage the life cycle of green BIM projects.

Organizational Level of Integration

The following paragraphs briefly introduced the corporate vision and business strategies of The Turner Corporation in BIM and Green/LEED via collaborative project delivery.

Corporate Vision – Commitment to BIM and Green

The Building Design + Construction (BDC) *2013 Giants 300 Reports* ranked The Turner Corporation as number one in both Top BIM Construction Firms (2012 BIM Revenue more than $5.92 billion) and Top Green Building Construction Firms (2012 Green Revenue more than $5.32 billion) (BDC 2013).

Business Strategies – Integrated Building Solutions

Turner relies on the Integrated Building Solutions (IBS) as the core of business strategies to meet client project requirements and deliver better project outcomes. The keywords of IBS are BIM, Lean and Green. The essentials elements of IBS can be briefly represented in Figure 6-9:

- **IPD:** Turner advocates IPD to encourage early collaboration and streamline use of BIM through a Lean production process. Two major formats of IPD Turner uses include 1) Traditional Contract tied with Partnering Agreement with Incentives and 2) Integrated Form of Agreement.
- **Lean:** Turner counts on Lean process to maximize client value and minimize waste.
- **BIM:** Turner adopts BIM at organizational level to ensure performance design and effective collaboration.

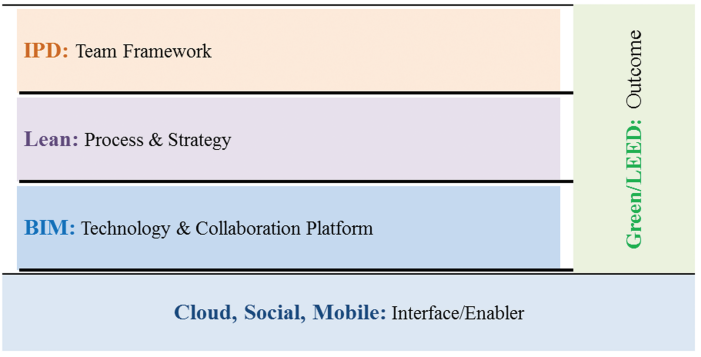


Figure 6-9. Representation of the Integrated Building Solutions (adapted from Bullain 2012).

- **Cloud, Social and Mobile:** Turner innovates the use of new social media and cloud & mobile computing to enable more robust and reliable design communication.
- **Green/LEED:** Turner gains improved productivity and integrated sustainability as project outcomes via synergies of IBS elements.

BIM Execution for Green/LEED: Key Innovations

A quick exploration of Turner's project portfolio yielded 122 green BIM projects whereas 87 are LEED-BIM projects. The telephone interviews uncovered some of the key innovations made by Turner in BIM execution to address unique requirements of green/LEED projects:

- **BIM Execution Plan (BEP):** A BEP becomes a standard document in all green BIM projects, and is typically established early in the Planning and Design Charrette phase and stays as a living document throughout the project delivery. PEPG and its templates are often used as baselines but finalized BEPs are usually customized by project teams. However, only a few BEPs so far have been established with reference to LEED credit requirements and LEED points targeted in the projects. But when this happens, BIM uses are mapped out in BEP with Level 2 processes typically established by LEED consultants, key specialty contractors and dedicated "Green Team" on the project.
- **Content Plan:** A Content Plan is developed internally by Turner. It is a map that guides the development of the 3D model according to specific standards designed to support the organized input of information so that reliable information can be extracted. The Content Plan organizes the project according to the ASTM UniFormat II Classification of Building Elements. Estimators can use the Content Plan to record project individual building elements to be quantified from the 3D Model for model based estimating. The Content Plan is also a tool for Turner to verify the quality of the 3D model for various purpose including performance modeling, LEED material selection and tracking. Figure 6-10 presents a snapshot of the Content Plan.
- **Model Progression Specification (MPS):** A MPS is a tool that Turner uses to define every element and task in the building construction process. It serves as a coordination point for information about the building, what is being modeled, and to what LOD it is being modeled, estimated, and scheduled. It provides the efficient framework for the project stakeholders – a written checklist that matures from a very schematic LOD to a high LOD in terms of 3D geometry, cost, and time. The MPS assumes the premise that as the LOD increases during the design process, the estimated cost and schedule becomes more accurate. Figure 6-11 presents a snapshot of the MPS.
- **iRoom and Virtual Coordination:** Multidisciplinary model coordination is empowered by iRoom (an immersive environment enabled by SMART Boards and 3D projectors) and use of cloud and mobile computing technology. Team members are usually co-located in the iRoom for constructability

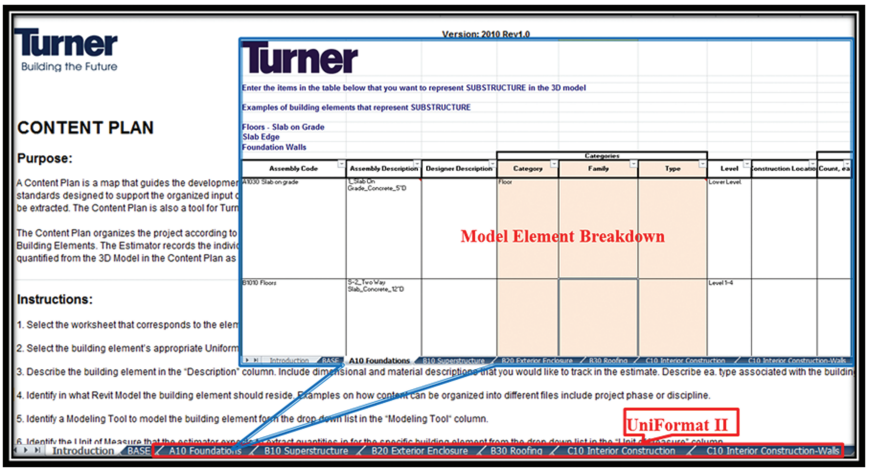


Figure 6-10. Content Plan—a snapshot (image courtesy: Turner Construction).

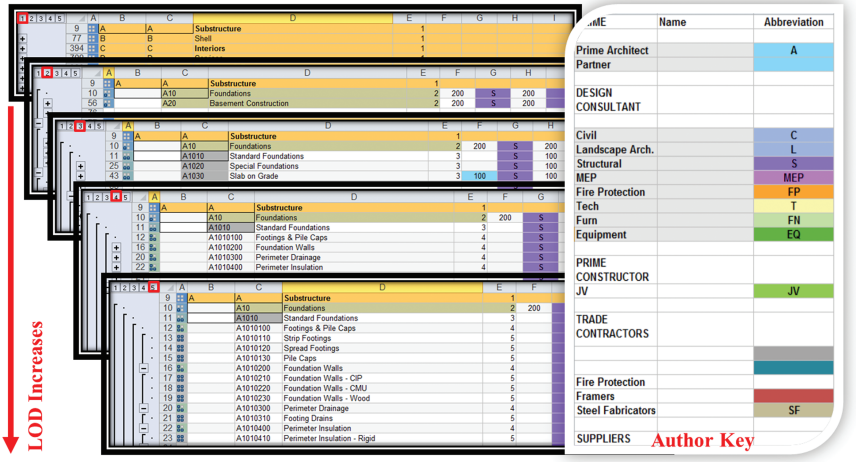


Figure 6-11. MPS—a snapshot (image courtesy: Turner Construction).

reviews. Model based layout and field verification are communicated with the office through iPads, smartphones and cloud solutions including SMART Meeting Pro™ and SMART Bridgit. Paperless trailers are also being advocated to phase out reliance on conventional 2D documents for jobsite coordination but transfers to digital document management.

- **VOXEL iSTUDIO (Vi)**: Vi is a toolkit that extends the value of BIM through design and construction into the facility management (FM) phase. It leverages information of the as-built BIM (or recorded BIM) and creates dynamic association between models and projects documents that are essential to the

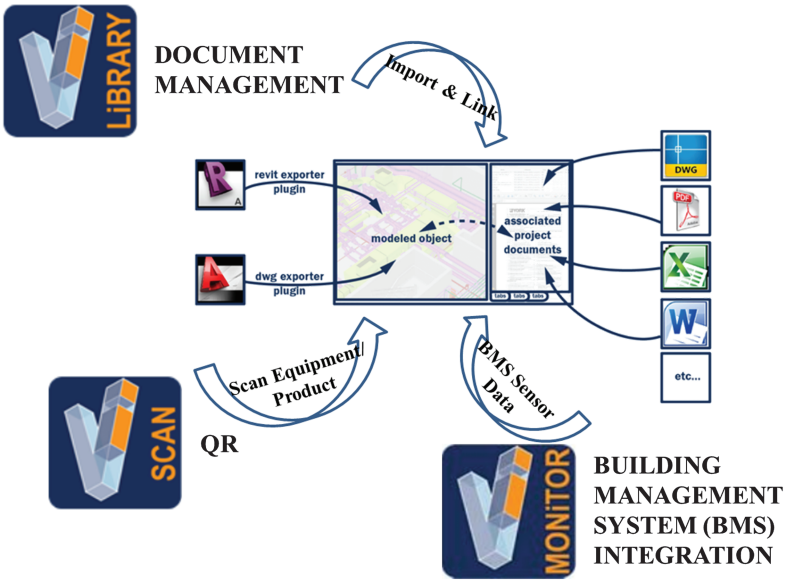


Figure 6-12. Voxel iStudio—a snapshot (image courtesy: Turner Construction).

operation and maintenance of the facility. Figure 12 illustrates the working mechanism of Vi. The *Vi LiBRARY* imports and links as-built model and model objects with facility project documents. The *Vi Scan* creates the association between model information and installed equipment and products through Quick Response (QR) codes. The *Vi Monitor* links BMS sensor points, and creates alarm simulation in model by importing BMS sensor data via Building Automation and Control Network (BACnet) protocols. BIM-based FM offers LEED projects unprecedented advantages in performance auditing. It ensures the integrity of building performance over the longer term will meet the design expectations, and also provides insights to facility owners of the building's real time operational status.

Project/Process Level Integration

The San Francisco office is currently working on a mega commercial project that is demanding true integration of BIM, LEED and IPD. The project is currently at the pre-construction stage. Due to confidentiality agreements, the owner's information and identities of project team members are not disclosed. The following paragraphs will discuss about the project's overall approach in planning BIM execution for streamlining LEED certification oriented design management. One of the project's focuses is to achieve LEED material points in compliance with criteria such as regional materials, recycled contents, rapidly renewable materials as well as FSC certified wood. A Level 2 process labeled as LEED Material Selection Workflow (notice this is not a typical BIM use or Level 2 process in PEPG) will be examined in detail.

Overall Green BIM Execution Approach

The project used the Design-Build delivery method led by a joint-venture (JV) team. The owner proactively engaged in the project programming and design process and formed a "Green Team" to supervise the LEED efforts of the project. Key trade contractors, major manufacturers and suppliers were involved in the project kick-off meeting, which was a co-located Design Charrette. A BEP was developed immediately with target LEED points in mind, using PEPG as the template. Critical Level 2 Processes were identified and mapped out. Responsible parties were urged to further develop these sub-processes to make sure the efforts to achieve the target LEED points were managed throughout the project design, construction and handover.

Exemplary Green BIM Execution – Level 2 Process: LEED Material Selection

The project team created a robust strategy of authoring, screening, specifying, verifying and tracking the LEED materials according to the applicable LEED criteria. Figure 6-13 delineates the overall workflow of the Level 2 Process: LEED Material Selection and Figure 6-14 is an expansion of Figure 6-13 with elaboration on the special screening process adopted by the project team as a Quality Control (QC) measure. As shown Figure 13, major characteristics of this workflow include:

- Broad engagement of project team members at early stage of project design, and clear roles and responsibilities in the execution process.
- Reiterative process (the Weekly Process Cycle) to address the features of criteria design and target-value design that are typical in DB projects.

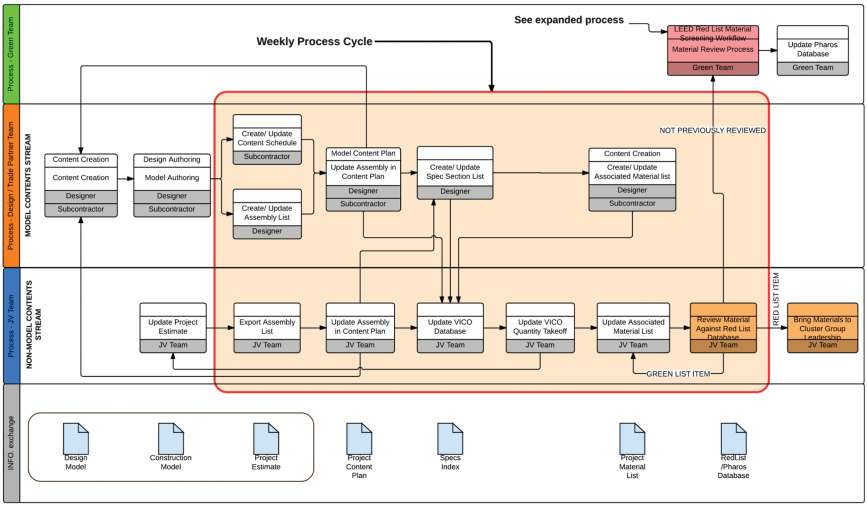


Figure 6-13. Level 2 Process Map: LEED material selection (adapted according to interview).

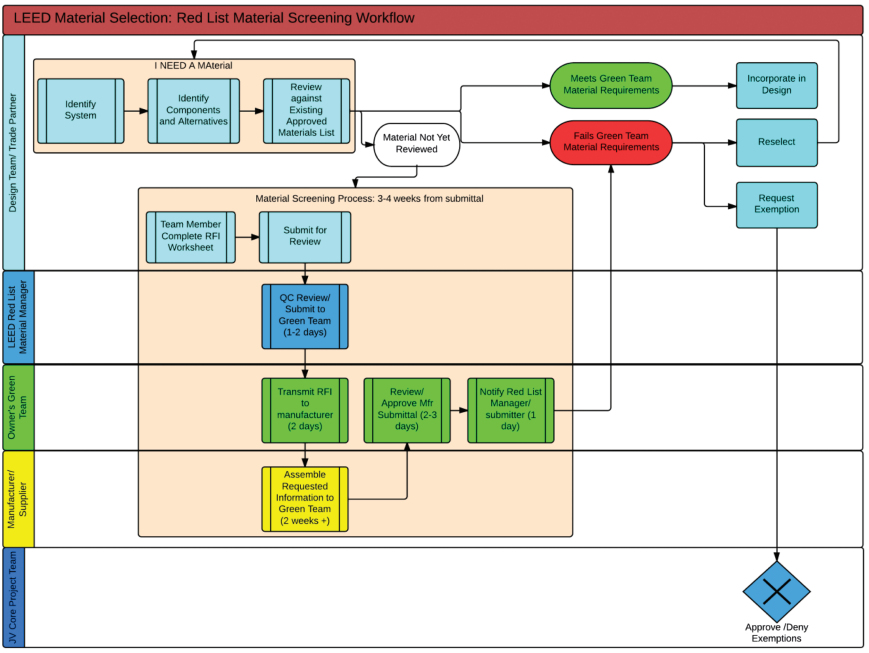


Figure 6-14. Level 2 Process Map: Red List material screening workflow (adapted according to interview).

Use of Content Plan and MPS to maintain the consistency of content authoring, material specification and tracking. Enforcement of the material review process and establishment of a customized material database to standardize the selection process and implement Knowledge Management (KM) for future projects (notice the material database is constantly updated to accommodate materials not previously reviewed). Figure 6-14 is the highlight of the case study. The LEED material screen workflow was innovative because it addressed the impacts of BIM execution on the overall project progress with clearly identified turn-around time for each individual task. This is significant because it provides owner and the project team with a possible means of quantitatively measuring the efficiency of BIM execution, which has not been well understood yet in the industry.

Case Study Summary

The case study helped verify that green BIM projects have unique characteristics and project requirements, which urges companies like Turner to initiate innovative business processes to address the specificities and synergies in delivering these projects. As an industry leader, Turner has been very successful in both green and BIM, not only because the company's vision of embracing both industry trends, but more attributed to its commitment to the integration of BIM, Lean and Green at the organizational, project and process levels. The case study confirmed that PEPG as a generic guidance on BIM execution can be further developed via

creative thinking by project teams when implemented in green BIM projects, and the innovative strategies uncovered in this case study offered some good examples. However, due to fact that the project is still on-going, it is difficult to quantitatively measure the impacts of integrated green BIM execution on the project outcomes.

CONCLUSIONS

In conclusion, this research recognized green BIM as an emerging trend in the AEC industry, and identified the lack of a standard business process to address BIM execution in green, especially LEED projects in particular. Given the prevalence of PEPG, it does not address the specificity of green building projects. Thus, the research proposed to develop a unique BIM execution process model to promote green BIM practices and improve LEED project outcomes. The new process model, IGBPM, was developed as a special case of PEPG. The major contributions of this research include:

- It conducted a comprehensive literature review on efforts in process modeling for green building and BIM projects, as well as the body of knowledge in understanding the synergies between BIM and green/LEED.
- It proposed a new process model, based upon PEPG and best practices, to address the unique business process of green BIM projects, and attempted to preliminarily develop Level 1 and Level 2 process maps of the new model.
- It reviewed and discussed relevant case studies to verify the concept of the new process model, and examined the real needs and state-of-art solutions to the emerging business opportunities in BIM, Lean and Green.

Nevertheless, the research is limited in several aspects. The first and biggest limitation is the lack of industry participation in developing the proposed IGBPM. Secondly, most Level 2 process maps have not been completely developed yet, and the IE incidences for each Level 2 process need to be specified. Thirdly, the proposed IGBPM did not address the use of open standards such as IFC, which could have been a major contribution to the body of knowledge. Last but not least, the proposed IGBPM needs further validation with quantitative project information and metrics that clearly prove the impacts of the integrated green BIM execution on LEED project outcomes. Future research will focus on industry outreaching through focused panel reviews for continuing model development, and further exploration of validation strategies.

References

AIA. (2007). "Integrated Project Delivery: A Guide." *The American Institute of Architects*, <http://www.aia.org/contractdocs/AIAS077630> (Mar. 1, 2013).

AIA. (2008). "Document E202™ - 2008 BIM Protocol Exhibit." *The American Institute of Architects*, <http://www.aia.org/contractdocs/training/bim/aias078742> (Mar. 1, 2013).

AIA. (2010). *Integrated project delivery: Case studies*, AIA California Council, Sacramento, CA.

AIA. (2012). *IPD case studies*. AIA Minnesota, Minneapolis, MN.

Azhar, S., Brown, J., and Farooqui, R. (2009). "BIM-based sustainability analysis: An evaluation of building performance analysis software." *Proc., the 45th ASC Annual Conference*, April 1-4, Gainesville, Florida, 1–4.

Azhar, S., Carlton, W., Olsen, D., and Ahmad, I. (2011). "Building information modeling for sustainable design and LEED rating analysis." *Automation in Construction*, 20(2), 217–224.

Bank, L. C., McCarthy, M., Thompson, B. P., and Menassa, C. C. (2010). "Integrating BIM with System Dynamics as a Decision-Making Framework for Sustainable Building design and Operation." *Proc., 1st International Conference on Sustainability Urbanization*, December 15-17, Hong Kong, China.

Barnes, S. and Castro-Lacouture, D. (2009). "BIM-enabled Integrated Optimization Tool for LEED Decisions." *Proc., 2009 International Workshop on Computing in Civil Engineering*, ASCE, June 24-27, Austin, TX, 258–268.

Bazjanac, V. (2008). "IFC BIM-based methodology for semi-automated building energy performance simulation." *Lawrence Berkley National Laboratory*, <http://escholarship.org/uc/item/0m8238pj.pdf> (Mar. 01, 2013).

Bersson, T. F. (2012). "A Framework for Application of System Engineering Process Models to Sustainable Design of High Performance Buildings." *Dissertation*, George Washington University, Washington, D.C.

Beheiry, S. M. A., Chong, W. K., and Haas, C. T. (2006). "Examining the business impact of owner commitment to sustainability." *Journal of Construction Engineering and Management*, 132(4), 384–392.

BIMForum. (2013). "Level of Development Specification, Draft 1." <http://bimforum.org/wp-content/uploads/2013/05/DRAFT-LOD-Spec.pdf> (Sep. 01, 2013).

Biswas, T., Wang, T. H., and Krishnamurti, R. (2008). "Integrating sustainable building rating systems with building information models." *Proc., 13th International Conference on Computer Aided Architectural Design Research in Asia*, April 9-12, Chiang Mai, Thailand, 193–200.

Building Design + Construction. (2013). "2013 Giants 300 Report." *Building Design + Construction*, <http://www.bdcnetwork.com/2013-giants-300-report> (Dec. 01, 2013).

Bullain, V. (2012). "Integrated Building Solutions." *Turner Construction Company*, <http://www.turnerconstruction.com//Turner-Innovation-Series-Presentations> (Dec. 01, 2013).

Bynum, P., Issa, R., and Olbina, S. (2013). "Building information modeling in support of sustainable design and construction." *J. Constr. Eng. Manage.*, 139(1), 24–34.

CIC. (2010). *BIM Project Execution Planning Guide, Version 2.0*, CIC Research Group, Pennsylvania State University, University Park, PA.

Coates, P., Arayici, Y., Koskela, K., Kagioglou, M., Usher, C., and O'Reilly, K. (2010). "The key performance indicators of the BIM implementation process." *Proc., the International Conference on Computing in Civil and Building Engineering*, June 30–July 2, Nottingham, UK.

Derrick, R. and Mei Kuen, L. (2008). "Implementation of Building Information Modeling (BIM) on the renovation of the art gallery of Alberta in Edmonton, Alberta." *Proceedings of 18th analysis and computation specialty conference*, Vancouver, BC, Canada, 6.

DOE. (2011). "Commercial Reference Buildings." *Office of Energy Efficiency and Renewable Energy*, <http://www1.eere.energy.gov/buildings/commercial_initiative/reference_buildings.html> (Mar. 01, 2013).

Eastman, C. M. (1999). *Building product models: Computer environments supporting design and construction*, CRC Press LLC, Boca Raton, FL.

Eastman, C., Sacks, R., Panushev, I., Aram, V., and Yagmur, E. (2009). "Information Delivery Manual for Precast Concrete." *PCI-Charles Pankow Foundation*, <http://dcom.arch.gatech.edu/pcibim/documents/IDM_for_Precast.pdf> (Mar. 01, 2013).

Eastman, C., Sacks, R., Panushev, I., Venugopal, M., and Aram, V. (2010a). "Precast Concrete BIM Standard Documents: MVD for Precast Concrete." *PCI-Charles Pankow Foundation*, <http://dcom.arch.gatech.edu/pcibim/documents/Precast_MVDs_v2.1_Volume_I.pdf> (Mar. 01, 2013).

Eastman, C., Jeong, Y.-S., Sacks, R., and Kaner, I. (2010b). "Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards." *Journal of Computing In Civil Engineering*, 24(1), 25–34

Europe INNOVA. (2008). "The STAND-INN Handbook." <http://www.cstb.fr/fileadmin/documents/webzines/2009-02/Stand-Inn/handbook_standinn.pdf> (Mar. 01, 2013)

Gallaher, M. P., O'Connor, A. C., John, L., Dettbarn, J., and Gilday, L. T. (2004). "Cost analysis of inadequate interoperability in the U.S. capital facilities industry." *GCR 04-867*, August 2004, National Institute of Standards and Technology, Gaithersburg.

Grobler, F. (2010). "IDM-MVD: How do they provide solutions to user requirements?" buildingSmart, <http://www.buildingsmart.org/standards/mvd/MVD_IDM%20expl.pdf> (Mar. 15, 2013).

GSA. (2012). "3D-4D Building Information Modeling." *General Service Administration,* <http://www.gsa.gov/portal/content/105075> (Mar. 01, 2013).

Häkkinen, T. and Kiviniemi, A. (2008). "Sustainable Building and BIM." *Proc., 2008 World Sustainable Building Conference*, 21–25 September, Melbourne, Australia.

Häkkinen, T. and Belloni, K. (2011). "Barriers and drivers for sustainable building." *Building Research & Information*, 39(3), 239–255.

Hardin, B. (2009). *BIM and construction management: Proven tools, methods, and workflows*, Wiley, Indianapolis, IN.

Horman, M. J., Riley, D. R., Pulaski, M, H., and Leyenberger, C. (2004). "Lean and Green: Integrating Sustainability and Lean Construction." *Proc., CIB World Building Congress*, May 1-7, Toronto, Canada.

Horman, M. J., Riley, D. R., Lapinski, A. R., Korkmaz, S., Pulaski, M. H., Magent, C., Luo, Y., Harding, N., and Dahl, P. K. (2006). "Delivering green buildings: process improvements for sustainable construction." *Journal of Green Building*, 1(1), 123–140.

Huang, Y. C., Lam, K. P., and Dobbs, G. (2008). "A scalable lighting simulation tool for integrated building design." *Proc., third National Conference of IBPSA-USA*, July 30–August 1, Berkeley, California.

Kagioglou, M., Cooper, R., Aouad, G., and Sexton, M. (2000). "Rethinking construction: the generic design and construction process protocol." *Engineering, Construction and Architectural Management*, 7(2), 141–153.

Katranuschkov, P., Guruz, R., Liebich, T., and Bort, B. (2011). "Requirements and Gap Analysis for BIM Extension to an Energy Enhanced BIM Framework." *Proc., 2nd Workshop of eeBuilding Data Models*, October 26–28, Sophia Antipolis, France.

Klotz, L., Horman, M., and Bodenschatz, M. (2007). "A Lean Modeling Protocol for Evaluating Green Project Delivery." *Lean Construction Journal*, 3(1), 1–18.

Korkmaz, S., Riley, D. R., and Horman, M. J. (2009). "Assessing Project Delivery for Sustainable, High-Performance Buildings through Mixed Methods." *Architectural Engineering and Design Management*, 7(4), 266–274.

Korkmaz, S., Messner, J., Riley, D. R., and Magent, C. (2010). "High-Performance Green Building Design Process Modeling and Integrated Use of Visualization Tools." *Journal of Architectural Engineering*, 16(1), 37–45.

Krygiel, E. and Nies, B. (2008). *Green BIM: Successful Sustainable Design with Building Information Modeling*, Wiley Publishing, Inc., Indianapolis, Indiana.

Laine, T. and Karola, A. (2007). "Benefits of Building Information Models in Energy Analysis." *Proc., Clima 2007 WellBeing Indoors*, Helsinki, Finland.

Lapinski, A. R., Horman, M. J., and Riley, D. R. (2005). "Delivering Sustainability: Lean Principles for Green Projects," *Proc., Construction Research Congress*, April 5-7, San Diego, California, USA, 1–10.

Lapinski, A. R., Horman, M. J., and Riley, D. R. (2006). "Lean Processes for Sustainable Project Delivery." *Journal of Construction Engineering and Management*, 132(10), 1083–1091.

Laiserin, J. (2007). "To BIMFinity and Beyond! (AEC Insight Column): Building Information modeling for today and tomorrow." *Cadalyst*, <http://www.cadalyst.com/aec/to-bimfinity-and-beyond-aec-insight-column-3686> (Mar. 1, 2013).

Lee, S., Liu, Y., Chunduri, S., Solnosky, R. L., Messner, J. I., Leicht, R. M., and Anumba, C. J. (2012). "Development of a Process Model to Support Integrated Design for Energy Efficient Buildings." *Proc., 2012 International Workshop on Computing in Civil Engineering*, June 17-20, Clearwater Beach, Florida, 261–268.

Maile, T., Fischer, M., and Bazjanac, V. (2007). "Building Energy Performance Simulation Tools – a Life-Cycle and Interoperable Perspective." <http://cife.stanford.edu/sites/default/files/WP107.pdf> (Mar. 15, 2013).

Malleson, A., Mordue, S., and Hamil, S. (2012). "The IFC/COBie Report 2012." <http://www.thenbs.com/pdfs/IFC_COBie-Report-2012.pdf> (Mar. 15, 2013).

McGraw-Hill Construction. (2010). *Green BIM: How Building Information Modeling is Contributing to Green Design and Construction*, McGraw-Hill Construction, Bedford, MA.

McGraw-Hill Construction. (2013). *World Green Building Trends: Business Benefits Driving New and Retrofit Market Opportunities in Over 60 Countries*, McGraw-Hill Construction, Bedford, MA.

Mihindu, S. and Arayici, Y. (2008). "Digital construction through BIM systems will drive the reengineering of construction business practices." *Proc., the 2008 international Conference Visualization*, IEEE visualization, IEEE computer society, 29–34.

Molenaar, K., Sobin, N., Gransberg, D., McCuen, T., Korkmaz, S., and Horman, M. (2009). *Sustainable, High Performance Projects and Project Delivery Methods: A State-of-Practice Report*, Charles Pankow Foundation, Vancouver, Washington.

Motawa, I. and Carter, K. (2013). "Sustainable BIM-based Evaluation of Buildings." *Procedia – Social and Behavioral Sciences*, 74, 116–125.

Nguyen, T. H., Shehab, T., and Gao, Z. (2010). "Evaluating Sustainability of Architectural Designs Using Building Information Modeling." *Open Construction and Building Technology, 4, 1-8*.

NIBS. (2007). "United States National Building Information Modeling Standard Version 1 – Part 1: Overview, Principles and Methodologies." *Whole Building Design Guide*, <http://www.wbdg.org/pdfs/NBIMSv1_p1.pdf> (Mar. 1, 2013).

O'Keeffe, S. E., Shiratuddin, M., and Fletcher, D. (2009). "LEED Certification Review in a Virtual Environment." *Proc., 9th International Conference on Construction Application of Virtual Reality*, November 5-6, Sydney, Australia.

O'sullivan, B. and Keane, M. (2005). "Specification of an IFC based intelligent graphical user interface to support building energy simulation." *Proc., 9th International IBPSA Conference*, August 15-18, Montreal, Canada.

OGC. (2010). "AECOO-1 Joint Testbed Report."buildingSMART alliance, <http://projects.buildingsmartalliance.org/files/?artifact_id=2754> (Mar. 01, 2013).

Oh, S. M., K, Y. J., P, C. S., and Kim, I. H. (2011). "Process-Driven BIM-Based Optimal Design Using Integration of EnergyPlus, Generic Algorithm, and Pareto Optimality." *Proc., 12th Conference of International Building Performance Simulation Association*, November 14-16, Sydney, Australia.

Panushev, I, Eastman, C., Sacks, R., Venugopal, M., and Aram, V. (2010). "Development of the National BIM Standard for Precast/Prestressed Concrete." *Proc., CIB W78, 27th International Conference*, November 16-18, Cairo, Egypt.

Pazlar, T. and Turk, Z. (2008). "Interoperability in practice: Geometric data exchange using the IFC standard." *Journal of Information Technology in Construction*, 13, 362–380.

Reed, W. G. and Gordon, E. B. (2000). "Integrated design and building process: what research and methodologies are needed?" *Building Research & Information*, 28(5/6), 325–337.

Reeves, T. J., Olbina, S., and Issa, R. R. A. (2012). "Guidelines for Using Building Information Modeling (BIM) for Environmental Analysis of High-performance Buildings." *Proc., 2012 ASCE International Conference on Computing in Civil Engineering*, June 17-20, Clearwater Beach, Florida, 277–284.

Riley, D. and Horman, M. (2005). "Delivering green buildings: high performance processes for high performance projects." *Proc., Engineering Sustainability*, Pittsburg, PA, 10–12.

Riley, D., Magent, C., and Horman, M. (2004). "Sustainable metrics: a design process model for high performance buildings." *Proc., CIB World Building Congress*, May 1-7, Toronto, Canada.

Saluja, C. (2009). "A Process Mapping Procedure for Planning Building Information Modeling (BIM) Execution on a Building Construction Project." Master Thesis, Pennsylvania State University, University Park, PA.

Sanvido, V. E. (1990). An integrated building process model. Computer Integrated Construction Research Program Technical Report #1. Pennsylvania State University, University Park, PA.

Scherer, R., Grunewald, J., and Baumgärtel, K. (2011). "A Framework Approach for EEBIM and Heterogeneous EEAnalysis Data Models." *Proc., 2nd Workshop of eeBuilding Data Models*, October 26–28, Sophia Antipolis, France.

Schlueter, A. and Thesseling, F. (2009). "Building information model based energy/exergy performance assessment in early design stages." *Automation in Construction*, 18(2), 153–163.

Smith, D. K. and Tardif, M. (2009). *Building information modeling: A strategic implementation guide for architects, engineers, constructors, and real estate asset managers*. Wiley, Hoboken, NJ.

USGBC. (2010). "USGBC Announces 'LEED Automation' to Streamline and Create Capacity for LEED Green Building Projects." *The US Green Building Council*, <http://www.usgbc.org/Docs/News/LEED%20Automation.pdf> (Mar. 1, 2013).

USGBC. (2011). *Advanced Energy Modeling for LEED: Technical Manual v2.0*, U.S. Green Building Council, Washington, D.C.

Wallace, R. H., Stockenberg, J. E., and Charette, R. N. (1987). *A United Methodology for Developing Systems*, Intertext Publications, New York.

Wang, J., Li, J., and Chen, X. (2010). "Parametric Design Based on Building Information Modeling for Sustainable Buildings." *Proc., 2010 International Conference on Challenges in Environmental Science and Computer Engineering*, IEEE Computer Society, March 6-7, Wuhan, China.

WBDG. (2012). "Engage the Integrated Design Process." *Whole Building Design Guide*, <http://www.wbdg.org/design/engage_process.php> (Mar. 1, 2013).

Welle, B., Rogers, Z., and Fischer, M. (2012). "BIM-Centric Daylight Profiler for Simulation (BDP4SIM): A methodology for automated product model decomposition and recomposition for climate-based daylighting simulation." *Building and Environment*, 58, 114–134.

White, S. A. and Miers, D. (2008). *BPMN Modeling and Reference Guide*, Future Strategies Inc., Lighthouse Point, FL, USA.

Wix, J. (2007). "IDM: Guide to components and development methods." *buildingSMART*, <http://iug.buildingsmart.org/idms/development/IDMC_004_1_2.pdf/view> (Mar. 01, 2013).

Wong, K. and Fan, Q. (2013). "Building information modeling (BIM) for sustainable building design." *Facilities*, 31(3/4), 138–157.

Wu, W. and Issa, R. R. A. (2010a). "Application of VDC in LEED projects: framework and implementation strategy." *Proc. of CIB W-78 27th International Conference on IT in Construction*, November 15-19, Cairo, Egypt.

Wu, W. and Issa, R. R. A. (2010b). "Feasibility of integrating building information modeling and LEED certification process." *Proc. of the International Conference on Computing in Civil and Building Engineering*, W., TIZANI (Editor), June 30–July 2, Nottingham, UK.

Wu, W. and Issa, R. R. A. (2011). "BIM Facilitated Web Service for LEED Automation." *Proc. 2011 ASCE International Workshop of Computing in Civil Engineering*, June 19-22, Miami, Florida, ASCE, pg. 673–681.

Wu, W. and Issa, R. R. A. (2012). "Leveraging Cloud-BIM for LEED Automation." *Journal of Information Technology in Construction*, 17, 367–385.

Yoon, S., Park, N., and Choi, J. (2009). "A BIM-based Design Method for Energy-Efficient Building." *Proc., 5th International Joint Conference on INC, IMS, IDC and NCM*, IEEE Computer Society, August 25-27, Seoul, Korea, 376–381.

This page intentionally left blank

CHAPTER 7

Variations of BIM Deployment within Integrated Construction Project Management Information Systems (PMIS)

Youngsoo Jung*

Abstract: *Advances in information and communication technology (ICT) have rigorously improved productivity in all industry sectors, and the role of information systems has changed further to support organizational strategies. Thus, utilizing information systems (IS) in the construction industry has been an issue of great concern in order to achieve competitive advantages of an organization and also to enhance the effectiveness of construction projects throughout their life cycle and across different construction business functions.*

Nevertheless, despite recent outstanding advancement in building information modeling (BIM) technology, practical BIM implementation has not been widely proven to be economically feasible. It is noteworthy that economic feasibility can encompass quantified intangible benefits from BIM. Therefore, an assessment of BIM deployment from a holistic perspective is required in order to appraise the strategic and managerial advantages in a project or in an organization.

Several studies have asserted strategic benefits of BIM adoption focusing on specific application areas (e.g. scheduling or estimating) or addressing limited technologies (e.g. visualization or ontology). However, real-world implementation of information systems truly comprehends complex issues such as corporate strategy, management effectiveness, internal policy and culture, and also technical capability together at the same time. In order to explore these complex issues for effective BIM implementation; this study examines five different real-world cases of BIM implementations.

*College of Architecture, Myongji University, 116 Myongji-Ro, Yongin 449-728, Korea; PH (+8231) 330-6396; FAX (+8231) 330-6487; email: yjung97@mju.ac.kr

The five case studies from United States, Japan, and South Korea will be analyzed within two major BIM frameworks developed by the author. Project delivery methods, construction business functions, types of integration methods, and level of automation for BIM usage are the most important variables for comparing and analyzing the five cases in terms of BIM benefits. This study describes the different approaches and different benefits that BIM has to offer for practical applications.

INTRODUCTION

Advances in information and communication technology (ICT) have rigorously improved productivity in all industry sectors, and the role of information systems has changed further to support organizational strategies. Thus, utilizing information systems (IS) in the construction industry has been an issue of great concern in order to achieve competitive advantages of an organization over competitors and also in order to enhance the effectiveness of construction projects throughout their life cycle and across different construction business functions (Jung and Gibson 1999; Jung and Joo 2011).

Nevertheless, despite recent outstanding advancement in building information modeling (BIM) technology, practical BIM implementation has not been widely proven to be economically feasible (Jung and Joo 2011). It is noteworthy that economic feasibility can encompass quantified intangible benefits from BIM. Therefore, an assessment of BIM deployment from a holistic perspective is required in order to appraise the strategic and managerial advantages in a project or in an organization.

Several studies have asserted strategic benefits of BIM adoption focusing on specific application areas (e.g. design, scheduling, or estimating) or addressing limited technologies (e.g. visualization or ontology). However, real-world implementation of information systems truly comprehends complex issues such as corporate strategy, management effectiveness, internal policy and culture, and also technical capability together at the same time. In order to explore these complex issues for effective BIM implementation, this study will examine five different real-world cases of BIM implementations. The author visited and benchmarked three cases on the job sites in the US and Japan, and the author has also conducted two cases in Korea as one of principal investigators.

These five case studies from the United States, Japan, and Korea will be analyzed within a comprehensive framework for practical BIM implementation. Project delivery methods, contract type, engineering-procurement-construction (EPC) relationship, types of integration methods, and level of automation for BIM usage will be the most important variables for comparing and analyzing the five cases in terms of BIM benefits. This study will describe the different approaches and different benefits that BIM has to offer for practical applications. It will also provide implications for future direction of BIM implementation. The author

served as a BIM manager for a large construction company, and this study will balance the academic and industry aspects based on his experience in order to make it an 'action research'.

PROJECT MANAGEMENT INFORMATION SYSTEMS (PMIS) & BIM

As a fully integrated methodology encompassing planning, design, procurement, construction, and operation phases, the concept of computer integrated construction (CIC) has exerted better utilization of information technology (IT) in construction projects. Another prevalent concept of building information modelling (BIM) has also widely disseminated the utilization of multi-dimensional CAD (nD-CAD) information. Relevant concepts including business process reengineering (BPR) or process innovation (PI), enterprise resource planning (ERP), commerce at light speed (CALS), and data acquisition technology (DAT) have provided tools for boosting information systems (IS) deployment in the construction industry as well. Many different concepts and methodologies are effectively and selectively used in order to meet specific IS requirements of a construction organization.

However, even though all different enabling concepts and technologies are readily available, lack of common understanding may cause confusion in implementing IS policy, strategic IS planning, or IS development. For example, the scope, method, even definitions of BIM may be very different based on each organization's own objectives in BIM implementation. Furthermore, overall and practical effectiveness of BIM utilization is difficult to justify at this stage. Nonetheless, all different technologies and methodologies previously stated can be understood as a part of comprehensive information systems (IS) in a global sense, of which concept is very broad and subjective. Again, misunderstanding of these acronyms may result in confusion or mismanagement of costly computing resources as well as more valuable ones, such as human resources in every-day practice. For these reasons, formulating a comprehensive IS framework would effectively facilitate the strategic utilization of IS in the construction industry.

In defining a comprehensive IS in construction, the most well-known acronym is project management information systems (PMIS). Though it has a somewhat intrinsically different meaning than general IS or management information systems (MIS), the terminology of PMIS can be best used to illustrate roles of BIM within a broad set of IT in construction. Another focal point in this study is the weight of BIM applications among entire PMIS components. It premises that BIM is a component of PMIS regardless of whether BIM is physically embedded in or not.

Besides the comprehensive concept of PMIS, two most often used acronyms in construction IT are CIC and BIM. Several active CIC efforts in the 1990's have generally tried to incorporate entire graphic data (e.g. CAD) and non-graphic data

(e.g. schedule) within an organization or a project. Those CIC cases were successful in terms of technical capability and the holistic approach; however, practical effectiveness was not fully proven to be economically feasible (Jung and Gibson 1998b; Miyatake and Kangari 1993). Lessons learned from early CIC implementations (Jung and Gibson 1999) indicate that it is difficult to achieve maximum effectiveness with full-range multi-dimensional (nD) integration. On the contrary, BIM proliferation has represented a reverse approach towards achieving this integration in the construction industry. It is recognized that BIM has started to fully utilize 3D graphic data first, and then expands the usage into an nD environment (Taylor and Bernstein 2009: Jung and Joo 2011). Though utilizing 3D CAD systems solely for design practice is becoming highly beneficial, the advent of BIM concepts in recent years actively explores better utilization of 3D models.

Relative Importance of BIM within PMIS

Understanding the 'importance of design systems' among other PMIS components (or sub-functions) would facilitate exploration of BIM or CIC variations within a PMIS. In an effort to measure the degree of "informatization" at the industry level, Jung et al. (2004) proposes an informatization assessment methodology for the construction industry. In their study, one of the dimensions for assessment measures was the "IS phase" including "awareness, development and exploitation." Namely, It was assumed that an organization would "start with awareness of IS needs and then develop the systems. In the final stage, the developed systems are exploited to gain maximum advantages" (Jung et al. 2004). Table 7-1 summarizes survey results from the top 100 general contractors in Korea for intra- and inter-organizational use of IS by different construction business functions. Findings indicate that 'financing and accounting' utilizes intra-organizational IS most in terms of 'awareness' and 'exploitation,' while 'scheduling' ranked the highest in terms of the discrepancy between the need and actual effective use (Jung et al. 2004).

In Table 7-1, IS for 'design' has a relatively low 'awareness' score (69.73 where 100 is the highest); however at the same time, it has a relatively high 'discrepancy' score indicating that the IS for this 'design' function is recognized as important while it is not adequately utilized yet. This fact well represents the characteristics of general contractors' business scope. One of the reasons for their increasing interests in design systems is the fact that more projects are under design-build contracts where engineering capabilities are crucial. It is noteworthy that BIM is not a mere 'design system' by its definitions. However, from the overall PMIS perspective, BIM should utilize the design system (3D-CAD) anyhow in order to function as it is intended. In this example in Table 7-1, from the general contractors' perspective, IS for design system is quite important, while its importance compared to cost and schedule functions is relatively low. It would be quite true when considering the frequency of BIM tasks among whole daily business transactions on a job site.

Table 7-1. PMIS exploitation by general contractors (Jung et al. 2004)

	Intra-organization IS[b]			*Inter-organization IS*[b]		
Business Functions[a] *(1)*	*Awareness (2)*	*Exploitation (3)*	*Discrepancy (4) = (2) − (3)*	*Awareness (5)*	*Exploitation (6)*	*Discrepancy (7) = (5) − (6)*
Planning	72.43	54.05	18.38	59.46	38.38	21.08
Sales	78.92	63.78	15.14	70.27	44.32	25.95
Design	***69.73***	***46.11***	***23.62***	69.73	40.54	29.19
Estimating	85.41	59.46	25.95	73.51	46.49	27.03
Scheduling	84.32	54.59	29.73	70.81	41.08	29.73
Materials mgmt.	82.16	67.03	15.14	74.05	45.95	28.11
Contracting	83.78	63.24	20.54	78.92	54.05	24.86
Cost control	85.41	68.11	17.30	68.11	44.86	23.24
Quality mgmt.	78.38	54.59	23.78	70.81	43.24	27.57
Safety mgmt.	71.35	52.97	18.38	65.41	40.54	24.86
Human R. mgmt.	82.16	72.97	9.19	57.84	35.68	22.16
Accounting	88.65	82.70	5.95	61.08	42.16	18.92
General admin.	72.97	61.62	11.35	57.84	38.92	18.92
R&D	65.41	45.95	19.46	60.54	40.00	20.54
Average	78.65	60.51	18.13	67.03	42.59	24.44

[a]Business functions defined by Jung and Gibson (1999).
[b]Paired comparison t-tests were used.

Relative Weighting of BIM within PMIS

As an independent viewpoint from 'importance', it is also meaningful to examine the portion 'weighting of design systems' within a PMIS. Although the measurements were different, another survey of top 10 Korean architecture and construction management firms by Jung et al. (2011) revealed that the weighting of 'design' systems is 13.9% among their entire information systems in terms of size, which is the second largest portion following 'human resource management' system (14.6%) in Table 7-2. It is expected that architects and engineering (A/E) firms are naturally focusing on CAD systems for their primary business function. IS for 'design function' including CAD systems as such contribute differently depending on a company's value chains.

Another implication from this study (Jung et al. 2011) shows that 'design systems' for A/E firms largely utilize commercial software packages (e.g. CAD and CPM) as shown under the column titled 'specialty' in Table 7-2. This configuration requires many different proprietary interfaces in order to connect those CAD data with other applications including estimating, cost, and schedule within their organizations. In summary, in this example in Table 7-2, 'design systems' are important and also have relatively higher weightings. However, the integration between BIM and other PMIS components is not strong enough in terms of everyday practice.

Variation of BIM Deployment within PMIS

Relative 'importance' and 'weighting' of design system (including BIM) were discussed in the previous sections in order to evaluate the role of BIM under different PMIS configurations. Again, each project or each company has its own project management requirements for PMIS and BIM.

Therefore, there is no single measure for successful BIM. However, it is necessary to assess the benefits of BIM in terms of strategic fit and managerial requirements for the sake of shared understanding.

Measuring intangible benefits from any type of information systems (IS) is very difficult and subjective. In their study developing an IS planning methodology, Jung and Gibson (1999) proposed five different measures including "corporate strategy, management, computer systems, IT, and incremental investment" in order to quantify these intangible benefits for a construction organization. These five measures were evaluated over "fourteen different construction business functions throughout entire project life cycle" (Jung and Gibson 1999). In addition to the four measures, Jung and Joo (2011) proposed practical measures including 'data property', 'data relation', 'standards', 'implementation', 'maturity', and 'morphology' for BIM.

In order to analyze the variation of BIM deployment in different construction companies under different business requirements, the 'project life cycle' and 'construction business function' would be good variables. For example, the company of Case II in Figure 7-1 was using BIM extensively throughout the project life cycle under EPC contracts. The depth of each box represents relative

Table 7-2. Components and weights for PMIS of CM firms (Jung et al. 2011)

Biz Function (Jung & Gibson 1999)	*IS Configuration*					*Data*	
	Proprietary	*Packages (ERP)*	*Groupware*	*Specialty*	*Total*	*Structured*	*Unstructure*
Planning	1.9	0.2	0.5	0.9	3.5	1.1	2.5
Sales	3.4	0.5	0.9	1.1	5.9	1.4	4.5
Design	2.6	1.1	1.2	**9.0**	**13.9**	**5.9**	**7.8**
Estimating	1.5	0.7	0.4	1.3	3.9	1.8	2.1
Scheduling	0.3	3.6	0.3	3.5	**7.7**	2.7	5.0
Materials Mgmt	1.5	1.4	0.2	1.0	4.2	2.4	1.8
Contracting	4.3	1.2	0.4	0.7	**6.6**	4.0	2.6
Cost Control	3.0	2.3	0.4	1.4	**7.1**	3.6	3.6
Quality Mgmt	2.1	1.7	0.5	1.3	5.6	2.9	2.7
Safety Mgmt	1.6	1.2	0.5	1.0	4.4	1.9	2.4
HR Mgmt	7.7	2.8	2.6	1.5	**14.6**	**10.9**	3.6
Accounting	4.5	2.7	2.9	1.1	**11.2**	**7.6**	3.6
General Admin	3.7	0.8	3.1	0.8	**8.4**	5.0	3.5
R&D	1.4	0.2	0.5	1.1	3.3	1.1	2.1
Total	**39.7**	20.4	14.5	**25.6**	**100**	52	48

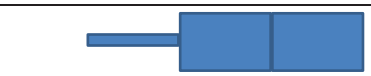
Cases	L: Life Cycle					# of Users	Remarks
	Planning	Design	Procurement	Construction	O&M		
Case I: Civil Infrastructure						130	CM: Highly Effective
Case II: Industrial Plant						2	EPC: Fully Integrated
Case III: Office Building						3	Pilot Project: With Robotics
Case IV: Highrise Complex						3	Contractor: Advanced Tech
Case V: Industrialized Housing						∞	Unspecified: Easy to Use

Figure 7-1. Different cases of BIM deployment.

weightings how actively BIM was used with other business functions (e.g. estimating, cost, and schedule). Case III in Figure 7-1 shows very opposite BIM characteristics to Case II in terms of project life cycle and business function. Nevertheless, influencing variables for BIM applications would be far more complicated. Therefore, all different possible variables should be identified first. Details of five cases will be illustrated by using the BIM variables categorized in this study.

INTEGRATED FRAMEWORK FOR IS IN CONSTRUCTION

In order to interpret different BIM deployment within PMIS, a comprehensive framework of information systems (IS) in construction is summarized in this study by combining two major frameworks by Jung and Gibson (1999) and Jung and Joo (2011) as described in Table 7-3. In addition to these two frameworks, 'business environment' and 'transaction depth (Lee et al. 2001)' are included for discussing practical issues. Finally, this higher level IS framework for the construction industry has nine major categories: environment, perspective, life cycle, business function, implementation, transaction depth, standards, data property, and data relation. It is compared with the CIC framework from a corporate level (Jung and Gibson 1999) and also with the BIM framework (Jung and Joo 2011) from an industry level to see the different perspectives.

Environment (E)

In a study reviewing 331 management information systems (MIS) doctoral dissertations, Ives et al. (1980) proposed a comprehensive framework that

Table 7-3. Comparison of IS variables in construction

Category	*IS in Construction*	*CIC Framework*	*BIM Framework*
Reference Perspective	*This Study All inclusive*	*Jung & Gibson 1999 Corporate*	*Jung & Joo 2011 Industry*
E: Environment			
	E01 Globalization		
	E02 Economy		
	E03 Project delivery methods		
	E04 Technology	*Information technology	
P: Perspective			
	P01 Industry		P01 Industry
	P02 Organization		P02 Organization
	P03 Project		P03 Project
	P04 Facility		
L: Life cycle			
	L01 Planning	L01 Planning	
	L02 Design	L02 Design	
	L03 Procurement	L03 Procurement	
	L04 Construction	L04 Construction	
	L05 Maintenance & Operation	L05 M & O	
	L06 Disposal	L06 Disposal	
F: Biz function+			
	F01 Planning	F01 Planning	F01 Planning
	F02 Sales	F02 Sales	F02 Sales
	F03 Design	F03 Design	F03 Design
	F04 Estimating	F04 Estimating	F04 Estimating
	F05 Scheduling	F05 Scheduling	F05 Scheduling
	F06 Materials mgmt.	F06 Materials mgmt.	F06 Materials mgmt.
	F07 Contracting	F07 Contracting	F07 Contracting
	F08 Cost control	F08 Cost control	F08 Cost control
	F09 Quality mgmt.	F09 Quality mgmt.	F09 Quality mgmt.
	F10 Safety mgmt.	F10 Safety mgmt.	F10 Safety mgmt.
	F11 HR mgmt.	F11 HR mgmt.	F11 HR mgmt.
	F12 Finance/ Accounting	F12 Finance/ Accounting	F12 Finance/ Accounting
	F13 General Admin.	F13 General Admin.	F13 General Admin.
	F14 R&D	F14 R&D	F14 R&D

(Continued)

Table 7-3. Comparison of IS variables in construction (Continued)

Category	*IS in Construction*	*CIC Framework*	*BIM Framework*
Reference Perspective	*This Study All inclusive*	*Jung & Gibson 1999 Corporate*	*Jung & Joo 2011 Industry*
M: Implementation			
	M01 Strategy	M01 Strategy	M01 Strategy
	M02 Management/ Policy	*Management	M02 Policy
	M03 Procedure		M03 Procedure
	M04 Manual		M04 Manual
T: Transaction depth			
	T01 Planning		
	T02 Review		
	T03 Operation		
	T04 Inspection		
	T05 Settlement		
S: Standards			
	S01 Product		S01 Product
	S02 Process		S02 Process
	S03 Classifications		
D: Data property			
	D01 Parametric		D01 Parametric
	D02 Level		D02 Level
	D03 Facet		D03 Facet
R: Data relation			
	R01 Composition		R01 Composition
	R02 Ontology		R02 Ontology
*Maturity			
			*SC Integration^{++}
			*Analysis^{++}
		*Computer systems	*Coordination^{++}
			*Visualization^{++}
*Morphology			
			*Distributed
			*Concentrated

$^{+}$Bizfunctions defined by Jung & Gibson (1999)
$^{++}$BIM Paradigm trajectory defined by Taylor & Bernstein (2009)

embraces external and internal environmental variables such as social, political, cultural considerations, organizational goals, management philosophy, etc. The environmental issue in the construction industry is a prime driver for construction IS due to the distinct built-to-order characteristic.

Among many factors, globalized (E01 in Table 7-3) competition under the ever-changing economy (E02) needs to be considered in the IS. As for the construction-specific variables, rapidly changing project delivery methods (E03) and information technologies (E04) are of great importance. With rapidly increasing number of projects under alternative project delivery methods, construction organizations should be capable of executing engineering-procurement-construction (EPC) projects. The integrated project delivery (IPD) concept is the best example of this requirement of changing project delivery methods.

Perspective (P)

Betts (1995) developed a five-level framework for strategic information systems (SIS) in construction in a study analyzing how the IT planning framework by Earl (1989) can be applied to the construction industry. The five levels include "the national construction industry, professional institution, construction enterprise, construction project, and construction product." Viewing an IS strategy on a national level is remarkable, and this particular approach was conceivable due to the distinct policy seen in Singapore, UK, Japan, South Korea, and Malaysia.

Perspective (P) represents the level of IS implementation. Four perspectives in this framework include industry level (P01), organizational level (P02), project level (P03), and facility level (P04). These four different levels of perspective (P) need to be considered in a mixed manner for a specific IS implementation. For example, a company (P02) may have its own BIM tools in-house while participating in a project (P03) with industry level (P01) standards, where many different companies work together as a team sharing common BIM data. Namely, a BIM practice of a company may need to incorporate project and industry perspective as well.

Life Cycle (L)

Any specific phase of the project life cycle characterizes information system needs. For instance, construction cost estimates can be performed in different phases of the life cycle. These involve design estimates, bid estimates, or control estimates (Hendrickson and Au 1989). According to Project Management Institute, a project is " . . . any undertaking with a defined starting point and defined objectives by which completion is identified." Therefore, a project life cycle contains four sequential phases: concept, development, execution, and termination. Each phase completes deliverables that are tangible and verifiable work products (PMBOK 1996).

For this study, the project life-cycle used in this framework is categorized into six phases: planning (L01), design (L02), procurement (L03), construction (L04), maintenance & operation (M&O) (L05), and disposal (L06). The planning phase includes all of the activities from project formulation through project scope definition.

Business Function (F)

Functional complexity exists throughout all the fragmented organizations and throughout all different phases of the life cycle. To an extent, the project life cycle itself seems to represent the required business functions for each phase. However,

a business function can be executed many times over different phases. Thus, functional representation is independent of the project life cycle. Business functions (F) represent the distinct IS requirements of the construction industry and clarify the roles shared by organizations under different project delivery methods over entire project life cycles (L).

Even though classifications of business functions may differ depending on different research purposes, this study employs 14 construction business functions defined by Jung and Gibson (1999). These functions include "planning (F01), sales (F02), design (F03), estimating (F04), scheduling (F05), materials management (F06), contracting (F07), cost control (F08), quality management (F09), safety management (F10), human resource management (F11), finance/accounting (F12), general administration (F13), and research and development (F14)."

Implementation (M)

Information systems mean much more than merely supporting tools for business functions in today's literature and practice. Information systems have become a competitive resource in this era of information. Therefore, the IS implementation (M) concerns are truly broad, and the IS concern variable in the proposed framework should cover a variety of issues.

The implementation variable strongly stresses the impact of managerial issues for successful IT utilization. As previously discussed, strategy (M01) and policy (M02) direct all activities within an organization, and hence characterize distinct requirements of information systems. Procedures (M03) can be tools for systemizing construction business functions (e.g. value chain). Details or decisions should be made before a user types in the lowest level data entry for on-site practice. Well organized manuals (M04) reflecting distinct characteristics of an organization or a project (Jung and Kang 2007) can facilitate smooth or automated operations (Jung and Joo 2011).

Transaction Depth (T)

Combining the three variables of perspective (P), life cycle (L), and construction business function (F) can effectively depict the roles and responsibilities of transactions in the construction business. However, transactions may have several different procedural activities (Jung and Woo 2004). Namely, for a specific construction management or engineering task, planning (T01), review (T02), operation (T03), inspection (T04), and settlement (T05) activities may be required (Lee et al. 2001).

These different activities are often executed by different organizations in a project. This variable is a good tool for evaluating and calculating workload and relationship among many different participants regardless of whether they are individuals or organizations.

Standards (S)

Standards (S) variables include the product (S01), process (S02), and classifications (S03). Sanvido and Medeiros (1990) also pointed out the "common

classification and coding systems," "common CAD databases," and "computer-aided process planning" as the selected tools to support CIC.

Vigorous efforts in the area of BIM standards have been developed from an industry (P01) perspective (e.g. IFC, IFD, IDM, IDEF, STEP and so on). ISO (1994), Uniclass (1997) and MasterFormat (CSI 2004) are the globalized efforts for standard classifications in the construction industry. Standards (S0) variables in this study basically stress the intensity and realm of utilizing standards, namely, the perspective (P) of standards (S) (Jung and Joo 2011). Organizational (P02) or project level (P03) standards are also of great importance for practical implementation.

Data Property (D)

Property (D0) variables represent the characteristics of BIM or CIC objects or data. The most often discussed issue in this variable is the parametric (D01) property of construction information, namely geometric (graphic, D01.1) or non-geometric (non-graphic, D01.2) properties. The level (D02) of any geometric or non-geometric data can be classified as raw data (D02.3), information (D02.2), or knowledge (D02.1) in an incremental order in terms of property intelligence and accumulation. The variable of facets (D03) for construction information is well defined by standard classifications such as ISO (1994), Uniclass (1997) and MasterFormat (CSI 2004). For the purpose of simplified and effective CIC and BIM applications in construction, this study adopts the definitions of locator (D03.2) and commodity (D03.1) by Jung and Kang (2007) as the constituents of the facet variable (Jung and Joo 2011).

Data Relation (R)

Relation (R) is defined as a physical or logical interdependency between properties (D0). This relation contains a repository for structures and semantics of properties (Jung and Joo 2011). The first variable in the relation (R) category is the composition (R01), which composes or decomposes the properties (P0). Ontology (R02) in this study focuses on logical interdependency between object properties (D). Objects (R02.3) can have physical or logical hierarchies (R02.2) with reasoning (R02.1) interpretations.

Other Variables

Maturity issues are well addressed in the qualitative and quantitative study examining BIM practice paradigms (Taylor and Bernstein 2009). Their trajectory of BIM advancement steps include "visualization, coordination, analysis, and supply chain integration". These paradigms were adopted in Jung and Joo's (2011) BIM framework, as the four phases appropriately illustrated practical maturity of BIM utilization.

The "computer systems" measure used in Jung and Gibson's (1999) CIC framework was used to evaluate "integration effectiveness" among 14 construction business functions within an organization as described in Table 7-3. In other

words, it was used to evaluate how a specific construction business function could contribute to other business functions within an IS. Thus, this variable has similar meaning with the "coordination" phase within Taylor and Bernstein's (2009) paradigm trajectory.

Another variable is the morphology which represents the types of physical and logical manipulation of BIM elements or databases (Jung and Joo 2011). The extended concept of this BIM morphology (U02) was discussed by Tobin (2008) where he tested the effectiveness of a "slice of BIM data" for "atomic BIM."

FIVE CASES OF BIM WITHIN PMIS

BIM or CIC efforts can be generally categorized into two ways; one is a passive and the other is an active use of 3D models. Passive use of 3D models denotes that 3D models are simply used for further engineering analyses as input information or as visualization. In addition to the passive use, researchers have explored more active utilization of 3D models. A good example in the area of automated design is the "geometric reasoner" by Chinowsky and Reinschmidt (1995) where "qualitative spatial reasoning" was developed in order to embed the design knowledge into the graphic objects. For real-world BIM or CIC implementations, use of 3D models facilitates many different engineering analyses including structural or energy simulations. Furthermore, 3D models should be actively used for construction activities and facility management processes as well. In this context, five cases are introduced to illustrate how differently BIM/CIC was utilized by differently interacting with other PMIS components. The IS framework in Table 7-3 will be used to clearly indicate the comparative characteristics. Tables 7-4 and 7-5 offer side by side comparisons of the five projects implementing BIM.

Case I: Civil Infrastructure

The highway running through downtown Boston, known as the Boston Artery, carried more cars than any other highway in the United States. In order to resolve the problems caused by the congested highway, a 'big dig' was undertaken in 1991 and completed in December 2007. This project was initially scheduled for about ten years, and their early estimated cost was about 10 billion dollars. This complex megaproject included expressways (surface, elevated, underground), rebuilding five major interchanges, a cable-stayed bridge, and a tunnel. The project spans 160 lane miles. Keeping businesses open, maintaining traffic capacity and environmental concerns during the construction made this complex project more difficult to manage (MTA 1997; MTA 1998).

The project delivery method (E03) for the Boston Artery/Tunnel Project was multi-prime contracts with a CM for fee (CM-agent). A CM consortium of two large engineering and construction companies provided management consulting services for design and construction. About 25 designers or engineers and 100 different contractors had direct contracts with the owner. Therefore, the CM, as an

agent of the owner, had to coordinate and manage all the organizations from an extremely large project (P03) perspective.

Various information systems were effectively utilized in this project. For example, scheduling (F05) and cost control (F08) were integrated by utilization of the cost loaded critical path method (CLCPM). Standards for drawings (F03; S01) were set by the CM in order to easily share graphical data between relevant organizations. The utilization of advanced 3D systems was also notable. Three-dimensional graphical simulation was actively used for decision making in design, constructability review, construction scheduling, and training. Another important fact is the level of detail for the CM's management task (T01; T02), which is a very high level (with less details). This fact made it possible for the CM to develop large objects in BIM applications for easier integration with cost and schedule. Drawings were developed in 2D format by the engineering firms, and then the CM converted those drawings into high-level 3D CAD representations.

The integration of cost and schedule in this case study enhanced business performance by addressing indirect vertical integration under the fragmented contractual relationships (Jung and Gibson 1998b). However, this integration is more focused in terms of management (M02) than in terms of corporate strategy (M01). Data sharing between core computer systems was fairly well achieved by using CLCPM. Information technology (E04) utilized in this project was not the most advanced when compared with those used in the other case studies. They effectively utilized off-the-shelf products under temporary characteristics of a project. Nevertheless, proper selection of commercial software for the right applications on this project was very successful in oversight management of more than 130 organizations.

Case II: Industrial Plant

The most frequently benchmarked case of construction PMIS has been the integrated company-wide system (P02) for mainly industrial construction projects of a U.S. construction company. Their multi-dimensional CAD (nD-CAD) systems integrating EPC information (L02; L03; L04) in the early 1990's had achieved the first-mover strategic advantages in the global (E01) construction market (Jung and Gibson 1998b). The delivery method (E03) for these projects is usually design-build that encompasses engineering, procurement, and construction. Moreover, in-house engineers of the company perform all levels of transaction depth (T01~T05) for engineering and construction functions throughout the project life cycle.

This vertically integrated organizational structure, coupled with the capability of utilizing advanced IT, provided this company with a critical basis for implementing CIC. Data created at the beginning stage of the project smoothly flows through information systems. For example, 3D CAD (F03), quantity take-off (F04), construction planning (F01), scheduling (F05), materials management (F06), procurement (F07), and other information are processed in an integrated manner. Data sharing between such complex systems is carried out by way of an information exchange layer. Level of detail for this case is detailed enough to

Table 7-4. Five BIM implementation case studies

Variables	*Cases of BIM Implementation*				
	Case I	*Case II*	*Case III*	*Case IV*	*Case V*
Facility type	Civil infrastructure	Industrial plant	Office building	High-rise apartment	Industrialized housing
Project delivery method	Multi-prime	Design-build (EPC)	Design-bid-build	Design-bid-build	Design-bid-build
Nation	US	US	Japan	South Korea	South Korea
Project cost (million $)	>10,000 s	>1,000 s	>100 s	>100 s	>0.1 s
Number of organizations	About 130	Two (Owner & EPC)	Three	Three	Three
BIM Perspective	Owner/CM	Design builder	Contractor	Contractor	Individual or contractor
PMIS	Project-wide	Company-wide	Project-wide	Company-wide	Industry-wide
BIM-PMIS integration (physical)	Separate & linked (Partially)	Integrated (Strongly)	Integrated (Strongly)	Integrated (Strongly)	Separate & linked (Automatically)
BIM-PMIS integration (logical & functional)	• Limited to cost and schedule	• Comprehensive to estimating, cost, schedule, materials management etc.	• Comprehensive to many different functions, even for automated production and installation	• Comprehensive to estimating, cost, schedule, materials management etc.	• Comprehensive to estimating, cost, schedule, and specification

BIM level of details	• High (less details)	• Detailed enough for EPC vertical integration	• Very detail to handle each members (e.g. steel structure)	• Detailed enough for GC's outsourcing	• Very detail to handle each members of housing
PMIS configuration	• Maximum use of off-the-shelf packages	• Company developed and fully integrated	• Proposed and developed for a pilot project	• Proposed and developed for a pilot project	• Maximum use of off-the-shelf packages
Special features	• Cost loaded CPM • Fragmented contracts	• Typical EPC contractor • Vertically integration	• Robotized site construction • Automated factory & robotics	• Typical general contractor • Comprehending functions	• Industry-wide PNS • Automated object linking

Table 7-5. Comparison of five BIM cases based on IS variables

	Cases of BIM Implementation				
Variables	*Case I*	*Case II*	*Case III*	*Case IV*	*Case V*
Facility type	Civil infrastructure	Industrial plant	Office building	High-rise apartment	Industrialized housing
BIM Perspective	Owner/CM	Design builder	Contractor	Contractor	Individual
E: Project delivery method (E03)	Multi-prime	Design-build (EPC)	Design-bid-build	Design-bid-build	Design-bid-build
E: Technology (E04)	Off-the-shelf	Proprietary	Proprietary + Robotics	Proprietary	Off-the-shelf
P: Perspective	P03	P02	P03	P02	P01
L: Project Life Cycle	L02, L04	L02, L03, L04	L02, L03, L04	L04	L01
		F02, F04	F04	F02, F04	F04
F: Business Functions	F03, F05, F08	F03, F05, F08	F03, F05, F08	F03, F05, F08	F03, F05, F08
	F11	F06, F07, F09	F06, F09	F06, F07, F09	F06, F09
M: Implementation	*M02*	M01, M02, *M03*	*M01*, M02, M03	M01, *M02*, M03	M02
	T01	T01 (planning)	T01	T01	T01
	T02	T02 (review)	T02	T02	
T: Transaction Depth		T03 (operation)	T03	T03	
		T04 (inspection) T05 (settlement)	T04	T04	
S: Standards	S03	S01, S02, S03	S01, S02, S03	S01, S02, S03	S01, S02, S03

handle estimating and materials management, and 3D CAD systems are directly integrated into all relevant business functions.

The integrated information systems of this case study company have been developed over a long period of time and through continuous efforts. Not only the technology development but also business process re-engineering (M02, M03) were incorporated into the systems. Utilizing these systems, in part, has enabled the company to gain strategic advantages (M01) in domestic and international markets. It is also interesting that the company forms a thorough matrix organization that helps maximize the benefit of specialized firms. This matrix organization is also suitable for globalization. It is obvious that information systems play an important role in maintaining a complex matrix organization.

Case III: Office Building

A Japanese CIC project exploited a full-scale, on-site automation (E04) combining information systems and robotics all through design and construction. Although this effort had been implemented to test further development, three components including integrated design and construction planning system, construction site automation system, and factory automation system were combined through a shared common integrated project database. CIC implementation in Japan was concerned with the changing market environment (E02) including shortage of skilled labour and demand for improved quality. This motivation leads large Japanese construction companies to the development of automated technology (Miyatake and Kangari 1993).

The pilot building project featured 31 stories above ground and 74,927 square meters of total floor area. The project utilized an automated construction system. The traditional sequence of design-bid-build was the project delivery method (E03) for this case. The automated construction system consists of six major components. These components include a lift up system composed of jacking towers, an automated conveying system, an automated steel assembling system with specially designed steel connections, an automated welding system for structural steel members, an automated transportation and installation system for other prefabricated materials and equipment, and an information control system that manages the central database (Maeda 1994).

Miyatake and Kangari (1993) proposed a CIC model based on this automated construction system. Their CIC model consists of: 1) the integrated design/construction planning system, 2) the CIC central database, 3) the site automation system, and 4) the factory automation system. Their research concludes that the major benefit of automated systems, at present, is the improvement of the company's competitive advantage, rather than cost effectiveness in operations that would occur in the near future (Miyatake and Kangari 1993).

The case study company has applied the automated construction systems for two different commercial building projects since 1990. Emphasis on automation and strategic implementation (M01) for a specialized product make this project distinct. Even though it was a pilot project (P03), level of details in integrating

3D-CAD with other business functions are precise enough (T01∼T05) to automatically handle specific steel members to an exact location. This case showed a future direction how BIM or CIC can achieve fully automated utilization in an integrated way.

Case IV: High-rise Apartment Complex

The fourth case had developed fully-integrated CIC systems using two real-world projects (Jung and Gibson 1998a; Cho 2000) encompassing a full spectrum of construction business functions (F01∼F16). CIC systems developed by this project were tested in a high-rise apartment complex building and a grand suspension bridge. It is noteworthy that this Korean government-funded research project fully utilized state-of-the-art technologies coupled with newly researched management methodologies.

A fully integrated system of the fourth case tried to encompass 3D-CAD systems (F03) integrated with many different construction business functions including estimating (F04), scheduling (F05), cost control (F08), materials management (F06), and others. A commercial simulation packages were partially used in order to tightly combine the graphic (D01.1) and non-graphic (D01.2) data. Initially, the system was developed to encompass almost all business function of the case-company. However, after implementing a pilot project, it was found that managing PMIS data to fit the BIM objects on a certain level requires tremendous overhead efforts. Finally, it was decided to focus on the most promising areas including design, estimating, scheduling, and cost control.

Basically, the fourth case focused on BIM integrated PMIS for general contractors (GCs, P03). Therefore, more often than not, the 3D-CAD objects were generated based on 2D-CAD representations provided by designers for design-bid-build (DBB) delivery systems (E03). It was a less active use of 3D data comparing to Case II in terms of transaction depth (T), but it is also natural from a GC's perspective as they were outsourcing more, with less direct intra-organizational vertical integration. Even today, as of 2013, the owner's requirements for planning tasks or as-built purposes are the important motivation for GCs to utilize BIM applications. Other active BIM utilizations by major GC's are seen in extremely complex facilities or atypically designed buildings. Again, the integration of BIM with practical estimating, cost control, or other management functions on everyday work job sites are still limited in the real-world projects (Talyor and Bernstein 2009; Jung and Joo 2011).

Case V: Industrialized Housing

A comprehensive research effort in order to develop and disseminate modernized Korean traditional housing (Hanok) has recently been initiated by the Korean government. This large scale research project encompasses a wide spectrum of housing development including public policy, architectural plans, modules, construction materials and methods, prefabricated assemblies, automated production, construction management, and advanced information systems. For the

purpose of integrating and automating the whole process from an industry perspective (P01), it is of great importance to develop a standard classification system and project numbering system (PNS) for modernized Korean housing (Jung et al. 2012).

Case V has distinct characteristics in terms of PMIS. First, standard plans (F03), schedules (F05), and cost items (F08) developed will be used by many small business firms, unspecified individuals, or even do-it-yourself home owners. Therefore, those standard deliverables must be developed for easy use. Secondly, in order to organize a historical database, the whole system needs to be equipped with strict standard numbering systems for product (S01), process (S02), and classifications (S03). Thirdly, for the purpose of industrialized dissemination with low cost, advanced technologies including automated production, pre-modeled 3D-CAD objects, and pre-formatted construction documents should be useful separately as well as in an integrated way. These complex requirements make this project utilize the concept of interoperability, which is actively discussed in recent BIM research. In other words, the unspecified users do not need to know any construction IS, BIM, or standards. They will only use provided templates of estimate, cost reports, schedule, and 3D-objects. However, whenever those simple data (mostly in forms of spread sheet) return to a computer, all different properties will automatically connect to each other in order to summarize, analyze, and update the common standards.

As a solution to those BIM requirements, this case developed a geometry numbering system (GBS) pre-embedded in graphic objects as well as in cost sheets and schedules along with WBS and CBS. Unlike using WBS or CBS, it would significantly facilitate the manipulation of a large number of graphic objects in a systematic and automated way. Namely, considerations and requirements of formulating a PNS of a single type of facility (industrialized traditional housing) for multi-functional integration (e.g. object, cost, schedule and others) by unspecified architects, cost engineers, schedulers, and others are developed (Jung et al. 2013, US patent pending). This case looks similar to many other BIM practices, but it is more concentrated in automated linkage with cost estimating (F04), scheduling (F05), and cost control (F08) from an industry level (P01) for unspecified and BIM illiterate users.

COMPARISON OF FIVE CASES & IMPLICATIONS

This study was started with some practical questions. If there are 100 persons including architects, engineers, and construction managers within one specific construction project, how many of them use BIM tools for daily tasks? How often do they use data supported by BIM for cost and schedule control? More specific question is how many work items of an estimate can be automatically generated from BIM? BIM experts know exact answers and the reality. Even though everyone agrees that BIM is the future direction and the technology is out there,

BIM itself has been promoted with a lot of hype today. In order to utilize the BIM in a practical manner, it is important to understand how different techniques and methods were used in successful BIM cases. To answer these questions, this study introduced five different cases. Outlines of five cases are summarized in Table 7-4 with comparisons based on IS variables, those are listed in Table 7-5 and illustrated in Figure 7-1. Again, there is no single best way in utilizing BIM. Each of five cases in this study achieved its own benefits from BIM under different business environment.

Among many different variables listed in Table 7-3, the seven most influencing variables are discussed in following sections in order to compare different implementations for those variables.

Project Delivery Method (E03)

As the first variable of 'project delivery method (E03)', Case II under EPC contracts has the ideal environment for BIM because most of the data were generated and used within an organization. Unlike the other EPC firms, the company of Case II had strong vertical integration (with less outsourcing) for basic design, detail design, procurement, and construction works. The concept of integrated project delivery (IPD) tries to achieve this vertical integration in an indirect method, namely by contractual and partnering means. However, strong and direct integration inside an organization would be the best situation. Case I is an excellent example of how a CM firm manipulated this indirect integration by using common numbering systems (S03) within a project which was comprised of more than 130 different companies. BIM data in Case I did not have high level of details, but it was effective enough considering the attained benefits from actually spent man-hours. Case V is an extreme one in this sense, because the BIM developer cannot know who would use those BIM templates. Nevertheless, the BIM requirements for this specific type of housing plan were very definite and clear for the unspecified final users. Case V is totally different from the general standards making efforts such as Industry Foundation Classes (IFC).

Technology (E04)

When it comes to 'technology (E04)' variable, recent advances in commercially available BIM software packages greatly facilitate practical implementation. However, as seen in Cases II, III, and IV, in order to achieve gigantic integration of graphic and non-graphic information within PMIS, a lot of proprietary systems should be developed in-house. It can be economically feasible only if the company uses these proprietary systems repeatedly for many projects as shown in Case II. On the contrary, Case I effectively utilized the off-the-shelf applications for fragmented organizations. It is common that CM firms do not need to develop a thoroughly integrated system as each CM project may have totally different managerial requirements. This fact proves that the 'demand pull' is more important than 'technology push' in BIM. An interesting point is the Case III

of a Japanese company that attempted full integration of robotics for automated construction. This case gives an implication for future BIM implementation.

Perspective (P) & Project Life Cycle (L)

The 'perspective (P)' variable is closely related with project delivery methods (E03). However, as more owners are getting interested in BIM applications for their own interests, a construction company (P02) or a project (P03) should have the industry level (P01) perspective. From the owners' perspective, engineers or contractors may vary over their many construction projects. Therefore, more owners require engineering firms and contractors to use industry standards to keep the owners' data inter-operable. It was found that the 'project life cycle (L)' variable is also related to project delivery methods (E03). Nevertheless, it is interesting that the BIM 'usage with other business functions (F)' and the 'degree of transaction depth (T)' can vary throughout the project life cycle. For example, Case III is a design-bid-build project. However, the contractor used BIM data for factory automation to prefabricate building components. In Case II (EPC contract), BIM data was more actively used in design phase.

Business Function (F) & Transaction Depth (T)

Business function (F) is the most important variable for measuring BIM utilization (Jung and Joo 2011). Design (F03), scheduling (F05), and cost control (F08) were the most often used ones for all five cases, even though the transaction depth differs in each case. In Case I, cost and schedule information was already integrated in CPM schedules (i.e. earned value management system) on a higher level (less details) with strictly shared common numbering systems. Rough 3D-objects for CM was then connected to this integrated cost and scheduling system in order to implement 5D-CAD for on-site briefing for workers (F11), as well as to conduct interference check to review drawings from 30 different engineering firms. Case V utilizes similar concept as it provides pre-integrated cost and schedule information to 3D-objects. But, Case V has pre-embedded numbers of geometry breakdown structure (GBS), CBS, and WBS. Therefore, users do not need to input the whole different numbers. Case V also developed a numbering system for cost data collection purpose, thus up-to-date cost information can automatically update the templates.

Cases II, III, and IV conducted more comprehensive integration between 3D-CAD and other business functions including sales (F02), materials management (F06), contracting (F07), quality management (F09), and accounting (F12). It was possible because the companies in Cases II, III, IV were EPC or GC who needed to manipulate detail construction data in their organization with proprietary systems. As shown in Figure 7-1, Case II (EPC) largely utilized BIM in design phase, which would be ideal for up-front BIM setup. The transaction depth (T) for all these construction business functions (F) is also substantially comprehensive in Case II.

Implementation (M)

As discussed, utilizing BIM within PMIS for everyday practice is not easy task. The difficulty is mainly due to the cost required to run BIM applications (especially, efforts to input all different data into BIM), and it is not because of the technical skills required for using BIM. Even without having commercially available BIM software, companies in the case studies have already implemented complex and advanced BIM practice in 1990's. The same principle applies to today's BIM implementation. If BIM is found to be economically or strategically beneficial for a project, the construction practitioners will use it.

Therefore, it is meaningful to see the motivations for five Cases in this study. Cases I and II effectively used BIM for their everyday management (M02). In addition, Case II achieved competitive advantages (M01) by developing and using BIM/CIC system as the first mover in the market. As for Case III and Case IV, strategic advantages were the most important BIM driver. Their technical capabilities in CIC/BIM were recognized in the industry as well as in the academia. By using the results from these experiments, they developed many other applications for practical uses. For Case III, in their CIC/BIM development process, they also conducted company-wide redesign of management information systems (MIS/ERP) with improved procedures. For all companies in Case I through IV, procedures (M03) and manuals (M04) must be developed at the same time. Finally, Case V is a very special one, because the government initiated an industry-level research to disseminate the traditional housing. It can be also interpreted as a strategy (M01) of a nation.

Defining the project objectives and requirements from strategic (M01) and managerial (M02) perspectives would make BIM more viable. Of course, using BIM in design firms at the design phase is important aspect. However, this study focuses on 'active use of practical BIM' throughout project life cycle.

CONCLUSIONS

It is notable that both curtailing CIC and expanding BIM research commonly explore practical effectiveness. In general, this reciprocal convergence of CIC and BIM implies the needs and issues of optimizing mechanisms for maximum effectiveness of IS in construction. Nevertheless, these two acronyms seem to be in different perspectives in terms of the level of application. While CIC is more project-oriented or organization-oriented, BIM is focusing more on the industry perspective (Jung and Joo 2011).

Based on the CIC and BIM frameworks, this study investigated a further extended IS framework for PMIS in the construction industry. As discussed, in order to have maximum benefits from BIM, it is required to assess the role of nD-CAD applications in different PMIS environments. It is found that utilizing 3D-CAD systems within a PMIS environment is very dependent on the project characteristics including project delivery methods, life cycle of the facilities,

construction business functions, and others. Among these variables, perspective (P), project life cycle (L), and construction business function (F) are well representing the characteristics of BIM implantation. Based on these three variables, implementation (M) plan should incorporate the strategic (M01) and managerial (M02) requirements for successful BIM.

At the present time, the integration in between 3D-CAD and PMIS in practice is not fully utilized yet, however, as observed in Case II and Case III, this integration in full spectrum is practically beneficial for large organizations under certain conditions (e.g. project delivery methods and vertical integration). In addition, expanding the use of 3D-CAD in engineering firms (relatively small organizations with limited business functions) is obviously encouraged. In order to boost more advanced and more effective construction information systems, it is necessary to research and develop BIM and PMIS in a comprehensive manner. Even though the number of cases is limited and interpretations can be somewhat subjective, this study tried to provide implications and a starting point for future research by developing a systematic method for comparing BIM cases.

APPENDIX: GLOSSARY

2D-CAD: two-dimensional computer aided design
3D-CAD: three-dimensional computer aided design
nD-CAD: multi-dimensional computer aided design
BIM: building information modeling
BPR: business process reengineering
CAD: computer aided design
CALS: continuous acquisition and life-cycle support
CBS: cost breakdown structure
CIC: computer integrated construction
CM: construction management
DAT: data acquisition technology
EPC: engineering-procurement-construction
ERP: enterprise resource planning
GBS: geometry breakdown structure
GC: general contractor
ICT: information and communication technology
IFC: industry foundation classes
IPD: integrated project delivery
IS: information systems
IT: information technology
M&O: maintenance and operation
MIS: management information system
PDM: project delivery method
PI: process innovation

PMIS: project management information system
PNS: project numbering system
R&D: research and development
SC: supply chain
SIS: strategic information systems
WBS: work breakdown structure

ACKNOWLEDGMENTS

This research was supported by '*Basic Science Research Program*' through the National Research Foundation of Korea (NRF) jointly funded by the Ministry of Education under Grant No. 2011-0022900 and by the Ministry of Science, ICT, and Future Planning under Grant No. 2014R1A2A2A01006984.

References

Betts, M. (1995). "Technology Planning Frameworks to Guide National IT Policy in Construction," *Automation in Construction*, 3(4), 251–166.

Chinowsky, P. S. and Reinschmidt, K. F. (1995). "Qualitative Geometric Reasoner for Integrated Design." *Journal of Computing in Civil Engineering, ASCE*, 9(4), 250–258.

Cho, M. (2000). Development of Construction Project Management, Final research report to Korean Ministry of Science and Technology, Project: 98-NE-04-03-A, Seoul, Korea.

CSI. (2004). MasterFormat: Master List of Numbers and Titles for the Construction Industry, The Construction Specifications Institute (CSI), Alexandria, VA, USA.

Earl, M. J. (1989). *Management Strategies for Information Technology*, London: Prentice Hall.

Hendrickson, C. and Au, T. (1989). *Project Management for Construction*, New Jersey: Prentice Hall.

International Organization for Standardization (ISO). (1994). *Classification of information in the construction industry*, Technical Report 14177, Geneva, Switzerland.

Ives, B., Hamilton, S., and Davis, G.B. (1980). "A Framework for Research in Computer-Based Management Information Systems," *Management Science*, 26(9), 910–934.

Jung, Y. and Gibson, G. E. (1998a). "Data Sharing Effectiveness for Computer Integrated Construction," *Journal of the Architectural Institute of Korea*, 14(5), 371–377.

Jung, Y. and Gibson, G. E. (1998b). "Variation in CIC Driving Factors based upon Types of Construction Contracts," *Proceedings of The Fifth International Conference on Automation Technology*, Taipei, Taiwan, 199-.

Jung, Y. and Gibson, G. E. (1999). "Planning for Computer Integrated Construction," *Journal of Computing in Civil Engineering, ASCE*, 13(4), 217–225.

Jung, Y. and Joo, M. (2011). "Building Information Modeling (BIM) Framework for Practical Implementation," *Automation in Construction, Elsevier*, 20(2). 126–133.

Jung, Y. and Woo, S. (2004). "Flexible Work Breakdown Structure for Integrated Cost and Schedule Control," *Journal of Construction Engineering and Management, ASCE*, 130(5), 616–625.

Jung, Y. and Kang, S. (2007). "Knowledge-Based Standard Progress Measurement for Integrated Cost and Schedule Performance Control," *Journal of Construction Engineering and Management, ASCE*, 133(1), 10–21,

Jung, Y., Chin, S., and Kim, K. (2004). "Informatization Index for the Construction Industry," *Journal of Computing in Civil Engineering, ASCE*, 18(3), 267–276

Jung, Y., Joo, M., and Kim, H. (2011). "Project Management Information Systems for Construction Managers: Current Constituents and Future Extensions," *Proceedings of the 28th International Symposium on Automation and Robotics in Construction (ISARC 2011)*, Seoul, Korea, 597–602.

Jung, Y., Kim, W., and Ha, J. (2012). "Standard Classifications and Project Numbering System for Integrated Construction Management of Modernized Korean Housing (Hanok)." *Transactions of the Society of CAD/CAM Engineers*, 17(4), 225–233.

Jung, Y., Lee, Y., Kim, Y., and Kim, M. (2013). System and Method for Creating Building Information Modeling (BIM) Geometry Breakdown Structure (GBS), Korean Patent Registration: 10-1293662: US Patent Pending: 13/830, 705.

Lee, B. N., Kim, D. H., Woo, S., and Jung, Y. (2001). "Determination of CM Cost in Korean Domestic Public Construction Projects." *Journal of the Korea Society of Civil Engineers*, 21(5-D), 725–735.

Maeda, J. (1994). "Development and Application of the SMART System," *Proceedings of the 11th International Symposium on Automation and Robotics in Construction (ISARC 1994)*, 457–464.

Miyatake, Y. and Kangari, R. (1993). "Experiencing Computer Integrated Construction," *Journal of Construction Engineering and Management, ASCE*, 119(2), 307–322.

MTA: Massachusetts Turnpike Authority. (1997). The Future: Now Under Construction, Project Brochure, Massachusetts Turnpike Authority.

MTA: Massachusetts Turnpike Authority. (1998). Central Artery/Tunnel Project, Web Site (www.bigdig.com), Massachusetts Turnpike Authority.

PMBOK. (1996). *A Guide to Project Management Body of Knowledge. Upper Darby*, Pennsylvania: Project Management Institute.

Sanvido, V. E. and Medeiros, D. J. (1990). "Applying Computer-Integrated Manufacturing Concepts to Construction," *Journal of Construction Engineering and Management, ASCE*, 116(2), 365–379.

Taylor, J. E. and Bernstein, P. G. (2009). "Paradigm Trajectories of Building Information Modelling Practice in Project Networks," *Journal of Management in Engineering, ASCE*, 25(2), 69–76.

Tobin, J. (2008). "atomicBIM: Splitting Data to Unleash BIM's Power," available at: http://www.aecbytes.com/buildingthefuture/2008/atomicBIM.html"

Uniclass: Unified classification for the construction industry. (1997). Royal Institute of British Architects (RIBA) Publications, London, UK.

This page intentionally left blank

CHAPTER 8

An Adaptive Cyber-Physical System's Approach to Construction Progress Monitoring and Control

Oluwole Alfred Olatunji*
Abiola Abosede Akanmu†

Abstract: *This chapter proposes an approach to deploying an adaptive cyber-physical system (aCPS) for project monitoring and control. In developing the system, we use a prototype platform which employs a radio frequency identification system that is capable of real-time location sensing to track construction processes and resources within spatially mapped activity areas. Data from the system are fed into BIM-based construction models such that project statuses are tracked and aligned with project schedule in an interactive manner. Outcomes of the procedure are primed on the impact of real time status tracking as project stakeholders are able to continuously create quick and preventive solutions against schedule delays and disruptions before overruns occur. Compared to existing project monitoring and control systems, extant approaches are susceptible to the limitations of manual approaches where data gathering and their syntheses are non-adaptive. Our findings also show that, in a data intensive environment as construction, satisfactory project outcomes are driven only by effective interactions between cyber and physical systems. We conclude that, to maximize system deliverables through cross-domain technologies – particularly to swiftly aid decision-making, autonomous systems must be able to shift boundaries dynamically, be context-adaptive and be capable of generating real-time information.*

*Department of Construction Management, School of Built Environment, Faculty of Humanities, Curtin University of Technology, Perth, Western Australia, 6102, Australia; PH +61 8 9266 7492; FAX +61 8 9266 2711; email: oluwole.olatunji@curtin.edu.au

†Department of Civil and Construction Engineering, College of Engineering and Applied Sciences, Western Michigan University, Kalamazoo, Michigan, United States; PH (269) 276-3201; email: abiola.akanmu@wmich.edu

INTRODUCTION

Project success is usually primed on the integration of virtual-computational and actual construction data. Computational data, such as design and pre-contract estimate data, are meant to inform decision-making in actual construction systems e.g. to manage project schedule, control costs and enhance value (Bowen et al. 2010; Cha and O'Connor 2005; Kelly and Hunter 2003). Likewise, construction data are used to appraise computational systems such that design deliverables can reliably predict project outcomes (Acharya et al. 2006; Barton 2000; Daschbach and Apgar 1988). As data from each of these domains are developed through many sources in different lifecycle stages, they are often complex and difficult to integrate; especially in real times, and with sufficient integrity to prevent misleading outcomes from jeopardizing project outcomes (Boddy et al. 2007). Several studies have shown unequivocally that when virtual and actual construction data are unable to integrate, errors and overruns may not be detected until they have occurred and have escalated obstinate conflicts between design and construction deliverables (Hinze et al. 1992; Jergeas and Ruwanpura 2010; Love et al. 2013). Construction management literature is already inundated with observable outcomes when these happen: they create friction in project relationships (Reichelt and Lyneis 1999); expose stakeholders to pressure as they try to catch-up on lost schedules and re-engineer project deliverables (Jergeas 2008); jeopardize project outcomes (Pinto and Mantel 1990).

Regardless of sources and integration issues, one of the main challenges is that these data should be generated, captured, shared, synthesized, adopted, stored and metamorphosed seamlessly and appropriately without significant dissipation (El-Omari and Moselhi 2009). As a key approach in facilitating this, Akanmu (2011) has demonstrated the cyber-physical system (CPS) as an approach that could be used to engineer how construction data are captured and integrated across the different source domains in real time. The purpose of this chapter is to elicit an adaptive approach to CPS – this will be referred to aCPS in this chapter forthwith. The objectives are:

1. By way of literature analysis, to describe an approach to the adaptive cyber-physical system (aCPS) through a procedure for using sensors such as the radio frequency identification technology that is capable of real time location sensing (RFID-RTLS) for tracking construction processes and resourcing within spatially mapped activity areas.
2. To describe how data from the radio frequency identification technology that is capable of real time location sensing (RFID-RTLS), which are fed into design and construction models, are able to generate real-time adaptive outcomes.
3. To create a robust framework for deploying an adaptive cyber-physical system (aCPS).

CYBER AND PHYSICAL SYSTEMS (CPS)

Definition of Cyber Physical Systems

According to Rajkumar et al. (2010), cyber-physical systems (CPS) are physical and engineered systems, the operations of which are monitored, coordinated, controlled and integrated by a computing and communication core. Wu et al. (2011) have added another perspective to this: CPS supports the tight integration and coordination between virtual resources and, physical processes and components. In context, virtual resources include sensing systems, applications, virtual models, databases and actuators, which could generate automated outcomes when combined appropriately. On the other hand, the physical component of the CPS include construction activities and physical resources whether in-situ or preformed. Technologies such as radio frequency identification (RFID), photographic methods and laser scanning have been used for several years to capture data on construction systems (Bennett 2009; Golparvar-Fard et al. 2009).

Domains and Forms of CPS Application

Capturing and integrating data from both cyber and physical systems have evolved as a result of advances in computing systems and the need to enhance control of physical processes. With considerable rewards which can be replicated in construction, the CPS control mechanisms have been applied in the healthcare, transportation, manufacturing and defense industries (Talcott 2008). In such applications, it has been categorized as open and closed CPS, and such had depended mainly on the nature of interaction between the computational and physical systems. An open CPS refers to systems where computing protocols and systems interact with complex physical systems to facilitate reasonable predictions of outcomes. An example of early open CPS is the networked navigation software which uses mobile communication data to deduce information on traffic jams from current movement profiles for improved route guidance (Weigel et al. 2010). Ahmadi et al. (2011) have demonstrated another example in which "the Green GPS" was developed and used for reducing fuel consumption and carbon footprint.

As defined by Talcott (2008), a Closed CPS occurs within closed physical locations where dedicated networks operate through computational boundaries. In such situation, physical processes and systems are affected by spatio-temporal systems. Together they form some closed loops as feedback mechanisms, requiring physical actuation or control of the physical systems.

What Makes a CPS – Some Key Features?

According to Wu et al. (2011), a system cannot be considered a CPS unless it is be able to bridge the virtual design to the physical world through sensors, storage and applications, intelligent and decision systems, and actuators – see Figure 8-1:

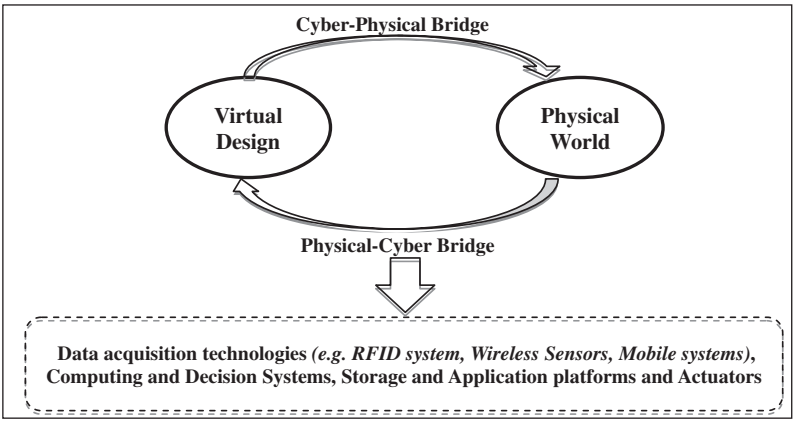


Figure 8-1. Interactions between the virtual and physical worlds (Xia et al. 2011).

- **The Physical to Cyber Bridge,** which is the sensing process. It involves using sensors and data acquisition technologies to acquire information about processes and physical components or phenomena.
- **The Cyber to Physical Bridge,** which represents the actuation and shows how the sensed information affects the system. In this context, actuation is taken to mean making control decisions from the sensed information and/or using the sensed information to physically control construction project's components.

Characteristics of Cyber-Physical Systems

CPS aims to integrate the virtual design and the physical system; particularly in ways that are entirely different from wireless sensor networks, embedded, real-time systems, traditional desktop computing and the similar. Its defining characteristics include:

- *Context-adaptive component:* The context of the physical environments must be understood by the virtual design, and defined by the level of interaction between the virtual design and the physical system. It is worthy of note that such interaction is often enhanced by an integrating software.
- *Real-time capability:* The system requires close monitoring to capture context-relevant and time-critical information. More importantly, data retrieval, aggregation, processing and communication must occur before critical information becomes obsolete or is replaced by new or contradicting content.
- *High-level automation:* CPS can be partially or completely autonomous. The level of automation defines the efficiency of the system.

ADAPTIVE CYBER-PHYSICAL SYSTEMS (aCPS)

Increased investigations have focused on the development of new sensors which offers opportunities for enhancing the level of automation and adaptivity between the virtual design and the physical systems – as required conventionally by CPS. An example of such developments includes that of the radio frequency identification which is capable of real-time location sensing system i.e. the RFID-RTLS. The RFID-RTLS provides real-time location tracking of tagged components, and this markedly reduces the computational effort required to track the previous RFID tags (Lee et al., 2012). In addition, RFID-RTLS promotes constricted integration, rather in an adaptive way, of physical components with their corresponding virtual representation in the model by using purpose-made software applications. Meanwhile, other high precision real-time sensors have been listed by Behzadan et al. (2008) to include tracking based on Wireless Local Area Network (WLAN), Bluetooth transmission and Dedicated Spectrums. The system resulting from this has also been referred to as the adaptive cyber-physical system (aCPS) by many authors, including Marstaller et al. (2012).

What Does an Adaptive Cyber-Physical System Mean to Construction?

There are two perspectives to the applications of aCPS to construction. For example, there is the compositional-level perspective which includes other perceptions outside the designer-controlled view of the CPS. There is also the component-level perspective which is a designer-controlled view of the structure and operation of the CPS, with a view to determine which components come to life at a time, regardless of size (Al-Kuwaiti 2008). Considering the latter, studies have shown that construction site personnel spend considerably critical time tracking and recording progress data manually (Navon and Sacks 2007). As identified by Ergen et al. (2007), the data collected using manual methods are usually prone to human errors. No amount of this is excusable: the management of construction operations requires an efficient tracking of construction progress data.

Over the years, researchers have observed the transitioning from isolated use of radio frequency identification (RFID) tags to the use of integrated approaches involving conventional RFID tags and virtual models (Chin et al. 2008; Sørensen et al. 2009). Embedding status information manually into the tags has been the Achilles Heels in this approach. As such, construction personnel spend significant amount of time on the manual process as well as in using multiple technologies to gather data and accomplish target tasks. These limitations have been documented by Sørensen et al. (2009) and Chin et al. (2008): construction crew need to scan installed tagged steel or precast concrete components manually to record components' installation status while using real time sensors for progress tracking. This means such worker requires motivation to collect and record appropriate progress data. Moreover, the approach does not reduce the concerns that may

arise on the reliability of such systems. Another drawback is that access to real-time information is not as possible in manual system as when adaptive sensors (e.g. RFID-RTLS, WLAN, Bluetooth, Dedicated Spectrums) are used. aCPS impacts these limitations. Some of the values it adds to project control are highlighted below.

The Values of Adaptive Cyber-Physical System to Project Monitoring and Control

The use of information technologies in construction is to simplify the complexity and reduce the burdens that associate with existing construction practices; at least, its goal is not to contribute to such negative indicators (Grau et al. 2009). In the case of aCPS, several outcomes have added value to conventional practices:

- ***Remote access:*** With aCPS, data from both the physical and cyber domains flow adaptively into project repositories in real time. This occurs regardless of the physical constraints in the spatial distribution of project components. Moreover, data retrieval within the aCPS exists in its purest forms; the data are captured and integrated into project control systems without marked dissipation. Invariably, this deliverable facilitates efficient decision making project control processes. In addition to these, an area of significant interest to construction management research and practice is the capability to store these data digitally throughout project lifecycle (Arayici et al. 2012; Olatunji 2012).
- ***Real-time data integration:*** System integration has been a major issue in construction. As elicited by Anumba (1996), the functionality of design platforms often struggle to integrate. It is impossible for them to create, retain and transmit data adaptively across different CAD platforms. Although there are indications that these are being resolved through the building information modeling (BIM) (see the Section on BIM), aCPS offers the opportunity to integrate data from construction resources into project cyber systems (Akanmu et al. 2011). This creates a basis for objectivity in project control judgments, and at the same time, promotes the availability of highly robust data which are adaptive in real time, and across different software platforms.
- ***Multi-domain interaction:*** As indicated earlier, aCPS serves as a bridge in a bi-directional flow of data and processes between the computing and physical domains. The effect of this interaction is critical to project monitoring and control outcomes. Previous studies have underlined the value of such effect. It is sufficiently evident in the work of Acharya et al. (2006) that conflicts and a lack of digital co-ordination of data from the two domains – i.e. the physical and the cyber domains – have triggered dire consequences on project outcomes. Such include dysfunctional contractual relationships and poor project performance as a result of cross-domain data integration and integrity issues.

- ***Automated project monitoring and control:*** Sensors, actuators and integration platforms are in aCPS to facilitate automation and simplify data processing across the Cyber-to-Physical (C-P) and Physical-to-Cyber (P-C) boundaries. Invariably therefore, some benefits are offered to the project deliverables as project databases become self-adaptive, rendering data engineering more simplified for controlling construction resources and costs. This is especially so by avoiding some of the limitations and sophistications of conventional procedures. Sufficient evidence supporting this view has been elicited comprehensively by Navon and Sacks (2007); Popov et al. (2010); Whyte et al. (2000).
- ***Accuracy in data collection:*** Completeness and integrity of data from both C-P and P-C domains matter in aCPS project control processes. There are not many ways to capture, integrate and synthesize data on construction project implementation across naturally occurring domains, in real time, in their purest forms and without dissipation and accuracy issues. With the exception of system error and failure (see Behzadan et al, 2008), aCPS offers the opportunities to overcome these limitations. The outcomes are considerable: decision making regarding progress monitoring and control are based on robust and accurate data. Similarly, visualizations in both virtual and physical domain are reactive in real time.
- ***Attenuation of human error:*** Construction is impossible without human actors who design, implement designs and manage projects. Human errors, and the attendant effects, seem inevitable (Lowe and Skitmore 2001; Yang et al. 2004). aCPS limits human errors through augmented remote sensing, actuation and automation. The benefits of these to project implementation include the time saving approach in aCPS, the quality of data upon which objective judgments are based, and the ability to sustain same throughout project life.

BI-DIRECTIONAL DATA DEVELOPMENT AND INTEGRATION FOR PROJECT MONITORING AND CONTROL

Building information modeling (BIM) is currently the most popular system for developing and storing project integrated data throughout project life. The philosophy underpinning the robustness of its data, their adaptivity and multi-disciplinary applications have been documented (Abdelkarim 2010; Arayici et al. 2012; Eastman et al. 2011). This section looks into BIM – its forms, the methodologies underlying its interactions with data from the physical domains and how this facilitates automated outcomes. For example, BIM models occur in diverse forms in design and construction domains (Olatunji 2012). What are the relationships between these, and which form of BIM models are most suitable for aCPS? Answers are provided in the following sub-section.

Forms of Building Information Models

BIM is a multi-dimensional (nD) platform that applies differently to the many professional practices in project's lifecycle. Like design, BIM applies to non-design disciplines variously too. For example, Yesilbas and Lombard (2004) have observed how *n*D modelling works in sensitivity analysis of a proposed construction project. Isikdag, et al, (2007) have also identified similar opportunities in disaster mitigation and emergency response. This proves that as BIM is used to create design data, it also applies to non-design disciplines for diverse synthesis e.g. data development through estimation, scheduling, contract administration and project management. Olatunji (2012) has identified the different forms of project models and how they are put to use in construction project lifecycle stages. These are visualization, prefabrication and construction models, and models for design analysis. Others are procurement models, and facilities management and simulation models. How do these apply to aCPS? Specific aCPS applications in the different forms of building information models are discussed below:

- ***Design Visualization Model:*** Either as architectural or engineering design models, both raster and vector representations can be visualized and manipulated seamlessly, from 3D to 2D and vice versa. Both forms are also made from data-rich objects, which usually contain robust information (Munzner 2009). However, there are distinctive features in what both forms of representation contain. Unlike working drawings, the objective of presentation drawings is to aid design presentation, visualization and analysis. They are often devoid of reference to materials, construction methods or measurement details such as accurate scale and measures (Leupen et al. 1997). Understandably, BIM models in parametric vector forms are more attractive to aCPS processes than raster representation. However, as argued by Golparvar-Fard et al. (2009), construction status data can also be fed into project databases through raster models. The typology for this communication arrangement has been indicated as Figure 8-2.

  An appropriate question is how does a design visualization model work for or with aCPS? Figure 8-3, culled from Golparvar-Fard et al. (2009),

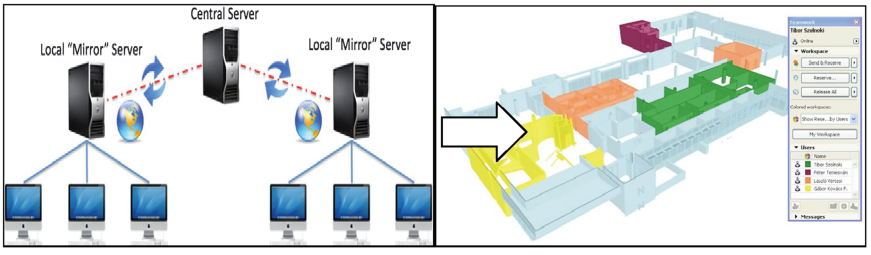


Figure 8-2. System typology and simultaneous access to design visualization model (Olatunji, 2012).

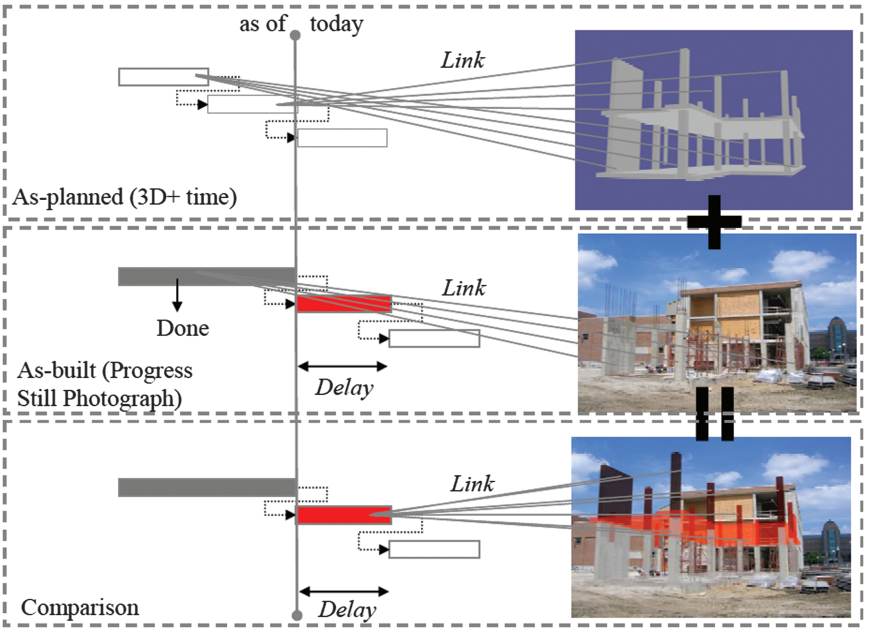


Figure 8-3. Augmented reality approach to construction progress monitoring through design visualization model (Golparvar-Fard et al. 2009).

answers this. This approach focuses on the relationship between project schedules and design visualization models by using independent still photographs to gather data on actual construction progress. The photographs are then used to populate alternative visualization models which can be compared to as-designed-and-as-scheduled models to monitor work progress and design control measures.

There are some forms of design visualization models that are relative to the procedure described above, including:

- ***Design Analysis Model,*** which is derived from analyzing design models for ease of use, transferability to other platforms and their ability to support project goals. They also reflect strength of the data upon which design models are based and whether such data can be maintained over a long period of time without compromising the correctness, accuracy and completeness both in the data themselves and when they interact with other data models (Amor et al. 2007).
- ***Prefabrication Model,*** which is targeted at standardizing component designing, modularization and integration of forms, functions and construction. Models made in 3D facilitate multi-perspective manipulation and visualization, and contain robust metadata on design, sourcing, fabrication, installation and other necessary information which is often

absent in geometric-data-only (GDO) CAD (Alwisy and Al-Hussein 2010).

– ***As-Built and Facility Simulation Model,*** which makes it increasingly easier to transfer extremely large data showing all stages of a project history on one single model, from conception through to design, procurement, fabrication, construction and delivery. As the demand for intelligent construction has increased markedly in the past decades, many neo-classical facilities now have sensors and actuators that make them behave intelligently. Moreover, through this form of model, situation reports on facilities operation can be generated automatically, assets can be tracked and facilities can alert users when maintenance actions are required. Similarly, the behaviors of intelligent and human actors can be simulated, analyzed and optimized.

In what ways do these models affect aCPS? Design analysis models add value to construction processes, including through value engineering procedures. Likewise, as-built and FM simulation models integrate information that had existed on a project with a view to informing FM solutions' providers regarding the original rationales behind design decisions. This also includes information on components' performance, space creation and allocation. Data from prefabrication models also assist in modeling and sourcing replacements e.g. for future alterations, modernization, conversions and rehabilitation efforts. The implication of these applications of model data is that they offer opportunities to underpin post-construction use of project model through the intelligence, and this aligns with the operational principles of aCPS platforms.

- **Construction Process Model:** Design models are usually static – this is because they are usually aimed at showing how the final product will appear when constructed. However, there are specific construction processes underlying how the final construction products are achieved. As shown in Figure 8-4, such processes involve some strategic combination of human, materials and plant resources. Norberg (2008) used BIM, location-based planning, 4D modeling and Field Force Automation to illustrate how design models can synchronize coordinated process agents (CPAs) in a particular work-flow pattern. The outcome of the research is such that project models are rendered interactive and motional. This procedure is popularly known as Virtual Reality (VR), Virtual Construction (VC), Virtual Design and Construction (VDC) or Virtual Prototyping (Huang et al. 2009). There are some benefits in this. In a clear demonstration by Nasios (2001), virtual reality is used to mitigate risks and uncertainties through on-site training. Lucas and Thabet (2007), among others, have also demonstrated how virtual reality exposes non-value adding activities during construction, improves resource efficiency and gives project stakeholders the opportunity to visualize the values of alternative options in project planning. In the view of Popov et al. (2010), these achievements are the Achilles heel in conventional CAD systems.

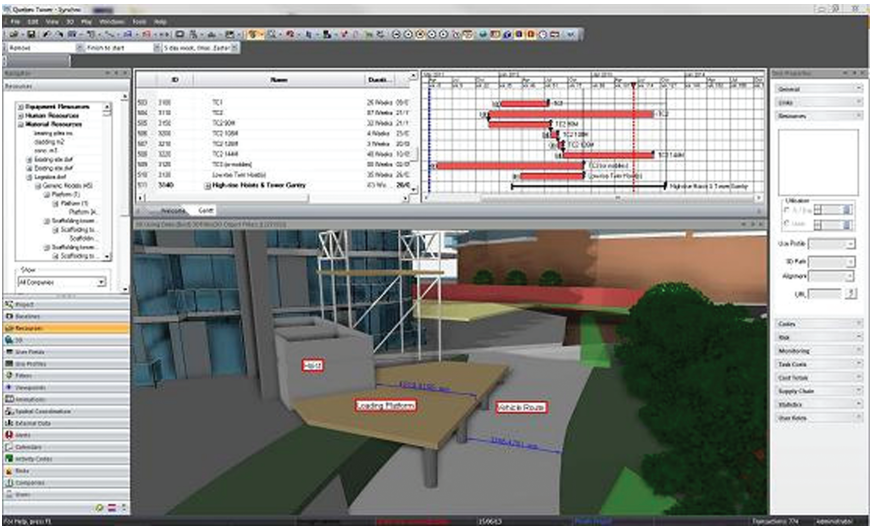


Figure 8-4. A synchronized construction process modeling (www.synchroltd.com).

In modes similar to construction process models, there are other deliverables of BIM that relate to decision-making during project monitoring and control. These include:

– ***Process Optimization Models***, which are developed to improve process efficiency, save resource input and improve product performance. Applicable concepts in this direction include lean construction (Camarinha-Matos et al. 2009), process re-engineering and strategic business management (Oyegoke 2007), knowledge visualization (Burkhard 2005), material management (Georgy and Basily 2001) and value management (Cha and O'Connor 2005).

The overarching difference between the main construction model and construction process optimization model is that the former presents a particular perspective to executing the construction project in relation to the contractual schedule. The latter focuses on improving selected components of the construction project through different alternative approaches to meet specific goals.

So, how do construction models work for aCPS, considering the in-situ and preformed nature of construction works? First, mapped construction processes require some form of performance measurement and benchmarking. Second, as an alternative to photographic methods, construction models are able to signal contractor's approach to resource management and control. For example, material inventories can be created through tagged materials which are tracked and automatically reported when they have been manufactured, being transported, when they have arrived site and where

they have been stored. When supplies are unable to meet consumption and such can jeopardize planned project schedule, automatic alert systems could signal this. Third, in combination with video data, resource utilization and the entire construction processes can be re-modeled and compared with the pre-contract construction model (Olatunji 2012). The resultant model helps contractors in terms of training, documentation, innovation trials and in creating knowledge databases for future projects. The client also benefits: it is an exceptional approach to contract administration which tells clients how contractors have complied with process and resource specification, and could serve as early signaling platform for schedule disruptions. Thus, it enables project stakeholders to respond to schedule disruptions even before they are noticed.

Whether in the form of design models or as construction models, there are different automated aCPS approaches to construction data collection. The subsection below shows how RFID-RTLS system works with BIM. Thereafter, an approach to aCPS in BIM is discussed.

The RFID-RTLS System: An Overview

A RFID-RTLS enables the tracking of tagged components within spatially mapped areas. It is made up of a master reader, some slave readers, RTLS tags and software. A system configuration showing the relationships between these components is shown in Figure 8-5. The process for the data-capture starts with battery-powered tags. Once active, the tags are usually attached to assets and personnel being

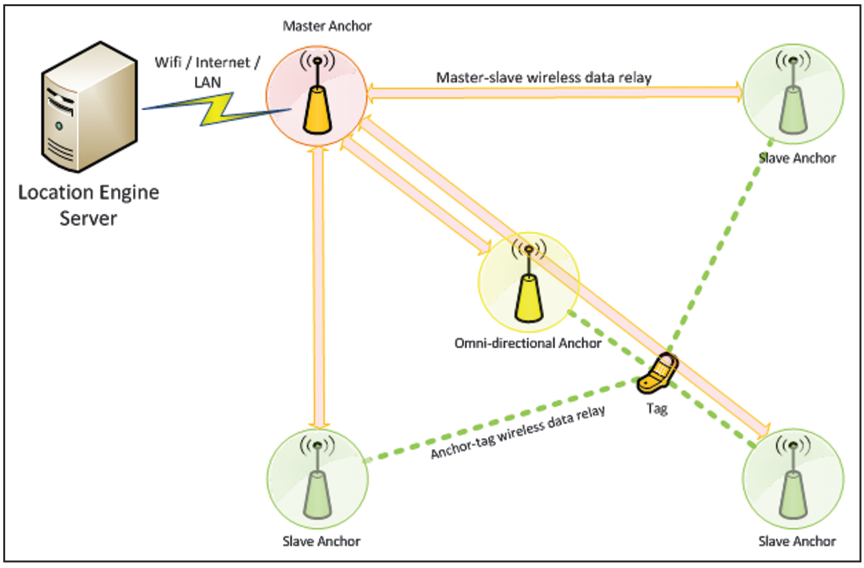


Figure 8-5. Component overview of the RFID-RTLS system.

tracked. The tags then relay location information every cycle time to the master and slave readers, which are positioned at the boundaries of areas of interest. Slave readers are purposed to determine and relay tags' ranges to the master reader, which also captures location data from each slave reader and relays them to the location engine software already installed in an associated computer system. Based on time-of-arrival (TOA) of radio frequency signal from the tags to the reader, the distance between tags and readers is determined in the location engine software on the basis of round-trip time of the signal travelling between the two entities.

Prototype System Development

System Architecture

Figure 8-6 shows the system architecture consisting of RFID-RTLS system, BIM, MySQL database, all integrated using a middleware written in Visual Studio.Net (C#). The process starts with tagged resources, such as material, labor or equipment which are ranged by the slave anchors. Along with the received signal strength indicators (RSSI), ranged data are sent wirelessly to the master anchor by the slave anchors, which also relays the information of the slave anchors to the Location Engine Server, and sort them by the RSSI value on each tag. The range data with the highest RSSI value are then given the most priority bases on location computation. Following this, computed tag locations are forwarded to the middleware.

Two middleware were developed within the RFID-RTLS Location Engine Server and Autodesk Navisworks. These are called the RTLS-DB-EVM and EVMPanel. Both middleware were developed using Visual Studio.Net 2010 (C#). EVMPanel was developed as a plugin for Autodesk Navisworks using the software's. NET API. Both middleware were connected to the MySQL database which acted as a bridge to exchange information between the RFID-RTLS and BIM.

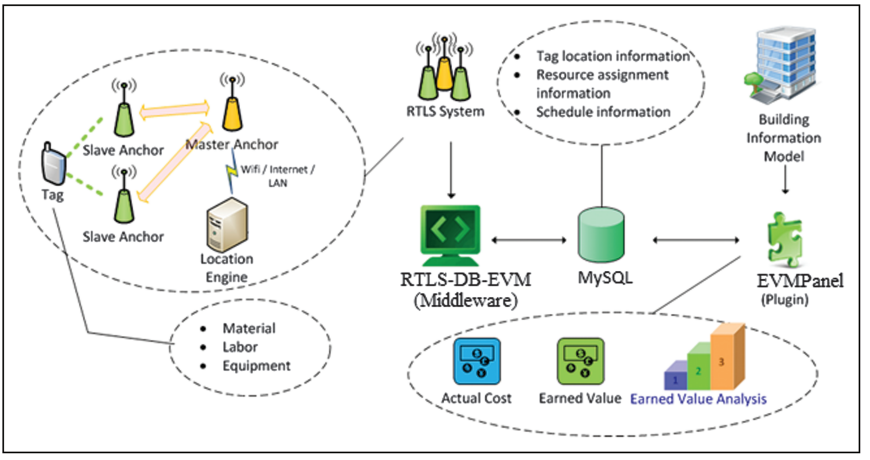


Figure 8-6. System architecture for the developed aCPS.

EVMPanel captures the user defined resource type, cost, and activity assigned to a particular tag from a custom graphical user interface (GUI). This plugin also extracts the schedule details, the list and planned cost of activities to be performed. All of the data are collected in the database; where the RTLS-DB picks up and processes the cost data. EVMPanel captures the user defined resource type, cost, and activity assigned to a particular tag from a custom graphical user interface (GUI). This plugin also extracts the schedule details from Autodesk Navisworks, the list and planned cost of activities to be performed. These data are collected in the database; where the RTLS-DB picks up and processes the cost data. RTLS-DB-EVM checks for the current activity (by comparing the actual start and current date of each activity in the database) and lists all the defined resources associated with that activity. EVMPanel computes the probable costs of resources based on the location of the attached tag. The computation of cost data is as follows:

- If a resource type is material, the probable cost is computed as the material is tracked to its installed location. The cost per unit quantity/time is defined in the database and is the actual cost incurred based on the resource type (material, labor/equipment) – see equation 8-1.

$$Probable\ Cost\ (Material) = Quantity/Time \times Unit\ Price \quad \text{Eq. (8-1)}$$

- If a resource type is labor, it is assumed that the labor is working when they are within the vicinity of the installation zone (known as the 'Labor' zone). RTLS-DB-EVM computes the total time spent by the labor tag, when it is within the 'Labor' zone. The probable cost is calculated when the labor moves out from the work zone i.e. by multiplying the time spent by the unit cost defined in the database – see Equation 8-2.

$$Propable\ Cost\ (labor) = Time\ spent \times Unit\ Price \quad \text{Eq. (8-2)}$$

- In ways akin to Harris et al.'s (2006) description of operational cost estimation, if an equipment is required for an activity, it is assumed that the equipment is working only when it moves between the storage and installation location of components or when the equipment moves between the activity's associate facilities. In the case of the former, RTLS-DB-EVM computes the total time spent by the equipment as it moves between the 'Storage' zone and the 'Installation' zone, and this is used to calculate the actual construction cost of the activity that the equipment is involved in. The probable cost is calculated in a similar way as the labor by multiplying the time by the unit cost defined in the database by Equation 8-3.

$$Probable\ Cost\ (Equipment) = Time\ spent \times Unit\ Price \quad \text{Eq. (8-3)}$$

After computing the actual cost, the RTLS-DB-EVM stores the data and the timing information in the database. EVMPanel extracts the cost information from

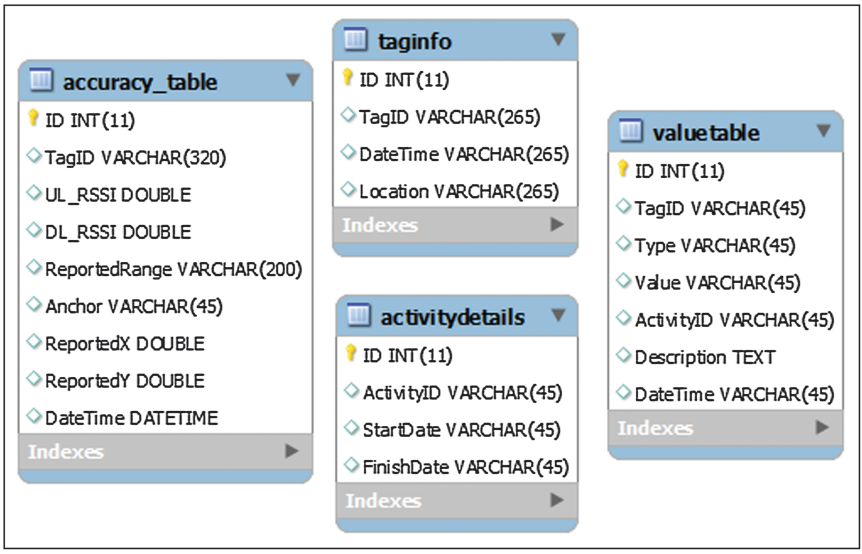


Figure 8-7. Database table structure.

the database and presents it visually in real-time on a graph via a custom GUI developed within the plugin.

Software Architecture

The software architecture shown in Figure 8-7 is for a developed prototype, distributed over two middleware. Both middleware are connected to a centralized database and acts as a bridge to relay information between both RFID-RTLS software and Autodesk Navisworks. The database is installed on a workstation where a database schema is setup. Four database tables are modeled to capture the following information: 'accuracy_table', 'taginfo', 'activitydetails' and 'tagdetail'. The accuracy_table' stores the Tag IDs, RSSIs, reported ranges from each anchor to the tag and reported location from the system. The 'taginfo' stores the TagIDs, last known zone within which the tag is reported, the date and time for each capture is also added. The 'activitydetails' table stores the Activity ID and their associated actual start and end dates. The 'tagdetail' stores the resource type, resource cost, activity, and description. This information is assigned to a particular Tag ID which is also defined in this table.

As shown in Figure 8-8, the RTLS-DB-EVM is developed to capture location information and all associated data such as tag IDs, reported locations from the RFID-RTLS location engine software. It also serves as a terminal for users to input the zoning information (such as the workspace name, size and location) into the system. By checking for the current activity stored in the 'activitydetails' database, the RTLS-DB- EVM compares the current and the actual dates (start and end) of the activities. Actual costs are determined by the middleware based on the

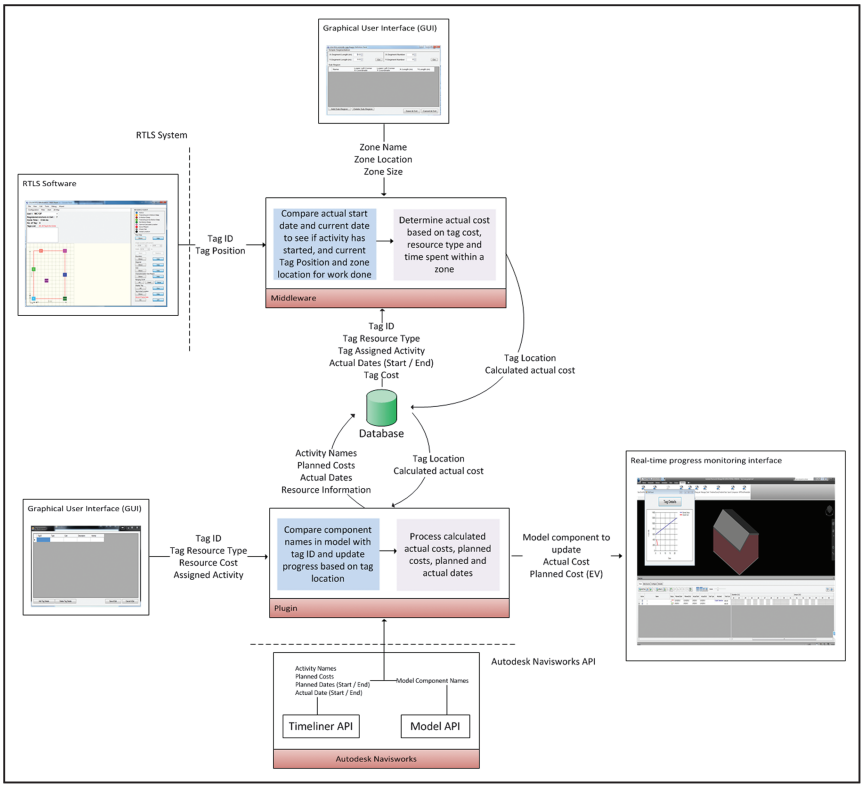


Figure 8-8. Brief software architecture for the project control prototype.

location of resource tags associated with the current activity (as discussed in Equations 8-1–8-3 under *System Architecture*), and the information is stored in the database.

EVMPanel is also connected to the database. It uses the timer function to scan the database 'taginfo' for specific information. As soon as the tag ID is populated in the database, the plugin launches a search query within the Navisworks for a 3D component with the matching tag ID. Based on the zone reported in the database, the plugin automatically updates the color of the searched 3D component. If a reported zone is empty (on-site), the component color is changed to red; to white if a reported zone is 'Storage'; and to green if a reported zone is 'Installed'. Using the timer function, this plugin scans for changes in the 'valuetable' component of the database. By using associated activity, it captures all the cost data, processes and presents them in a graphical form. In addition to this, it also stores information in the database, including schedule details (Activity ID, actual start and end dates) in the 'activitydetail' table of the database. Through a custom GUI, user-defined resource type, resource cost, and activity assigned to a particular tag can be captured and stored in the 'tagdetail' component of the database.

CASE STUDY

This section illustrates a case study on the application of the aCPS. The goal of the aCPS in the implementation project is to automatically and continuously generate site layouts through BIM, based on the project schedule and space availability. In addition, the outcomes generated by the system also consider optimal layout solutions that are primed on the probable minimal total cost for resource transportation, facility setup and shifting. To achieve this, the aCPS integrates the RFID-RTLS system and Genetic Algorithm (GA) as detailed in the architectures discussed above. During the implementation, the RFID-RTLS system serves two functions: (1) it tracks the context of site spaces and construction personnel, and; (2) it provides a graphical user interface (GUI) for visualizing the generated layout. To compliment this, the GA serves as the search algorithm for achieving the optimal layout solutions.

The implementation case study was observed on the Western View Apartment Project of the Western Michigan University. Located on the main campus, the total area of the project site is 136,800 ft^2 (15,200 m^2), which includes a parking lot area of 59,535 ft^2 (6,615 m^2) – we have targeted parking lot area for our site layout scenarios. Although we did not observe any critical limitations in the contractors' applications of the aCPS on any part of the project, for the purpose of this report, we have limited our observation to a site boundary of 6.3 m × 10.5 m (66.1 m^2). As shown in Figure 8-9, by using the RFID-RTLS

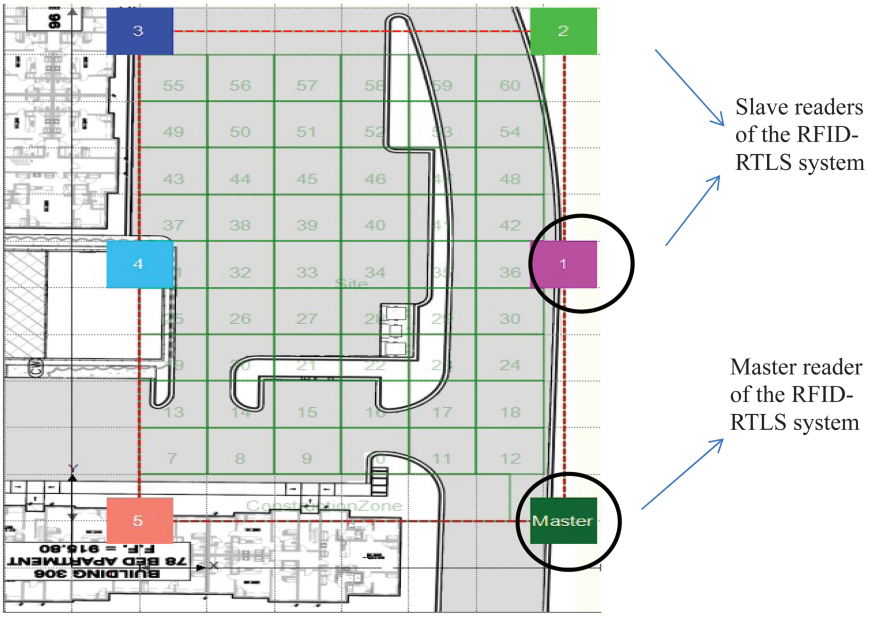


Figure 8-9. Possible locations layout in RFID-RTLS system interface.

system, the layout was divided into 60 locations. Each location has an area of 1 m^2. Of these, 6 locations were not available for tagging because they overlapped with the main building. The remaining 54 locations served as inputs to the RFID-RTLS system. Once this information was entered into the RFID-RTLS system, the coordinates (X, Y) of each possible location was calculated and embedded in the database. The GA then extracts the information to create distances matrix between the locations – as noted earlier, this matrix is required for computing the objective function.

Based on the project schedule generated in Autodesk Navisworks, and shown as Figure 8-10, 18 temporary facilities are required for our observation. Accordingly, there were different tasks to be executed, each of which requires at least one facility to move within at least one construction stage. Moreover, this also requires efforts from the construction personnel who had been tagged.

Identification details of the 18 facilities involved in the observation project are shown in the first two columns of Table 8-1, while the distribution of the facilities in each of the three construction stages is shown in Table 8-2.

As all the 18 temporary facilities interact, GA only calls out the frequency values of facilities within a current stage. For example, Stage 1 has 8 temporary facilities, numbered 1 to 8. Consequently, 8 × 8 matrixes apply to the frequency of trips for the Stage. For the entire 18 facilities, an 18 × 18 matrix applies. Table 8-3 shows the frequency of trip matrix per day as each tagged personnel and facilities moved.

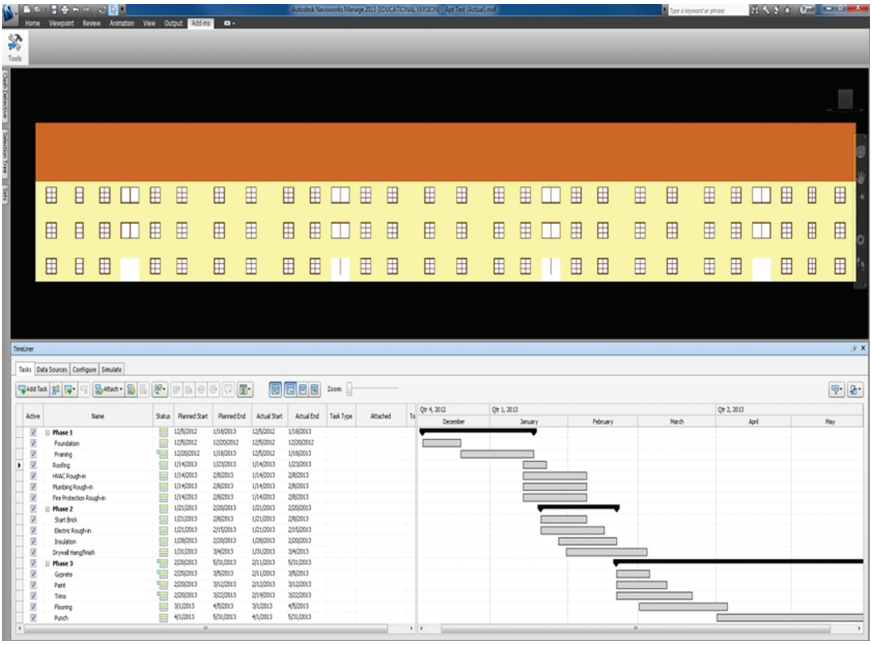


Figure 8-10. Building model with project schedule in navisworks manage.

Table 8-1. Setup cost of temporary facilities, as observed

ID	*Name*	*Setup Cost ($)*	*Labor (persons)*	*Cost ($)*
1	Concrete Element storage area	200	4	88
2	Rebar bending yard	150	3	66
3	Carpentry workshop	200	4	88
4	Moulding board storage area	200	4	88
5	Storage Container	130	4	88
6	Material delivery storage area	110	3	66
7	Mechanical equipment storage	125	3	66
8	Raw material container	120	5	110
9	Material hoist	100	2	44
10	Brick Yard	160	6	132
11	Electrical equipment storage area	145	3	66
12	Insulation material area	135	4	88
13	Drywall sheet storage	160	3	66
14	Concrete pour equipment	165	5	110
15	Paint storage	170	3	66
16	Finishing equipment storage	120	5	110
17	Carpet/interior material storage	130	4	88
18	Cleaning equipment	100	2	44

Table 8-2. List of temporary facilities involving in each construction stage

	Stage 1	*Stage 2*	*Stage 3*
Temporary Facilities	1	3	13
	2	4	14
	3	5	15
	4	6	16
	5	7	17
	6	8	18
	7	9	
	8	10	
		11	
		12	
		13	

It is important to note that the cost data used by the construction company handling the project was used to develop the set-up costs shown in the last three columns of Table 8-1. For confidentiality reasons, the specific approaches underlying these are not disclosed here. Nevertheless, the works of Akintoye and

Table 8-3. Frequency of trips between facilities

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
1	0	7	23	16	7	7	6	11	21	15	10	11	9	12	12	7	11	5
2	7	0	25	21	24	23	17	10	17	25	8	16	9	17	6	24	5	5
3	23	25	0	14	8	22	10	7	13	9	9	14	24	10	24	9	6	22
4	16	21	14	0	9	14	10	8	13	10	17	20	21	5	19	24	11	21
5	7	24	8	9	0	7	10	20	9	11	22	24	5	16	22	17	14	21
6	7	23	22	14	7	0	20	17	9	14	8	8	10	9	15	9	13	21
7	6	17	10	10	10	20	0	7	18	19	15	8	10	19	9	20	24	9
8	11	10	7	8	20	17	7	0	8	6	7	9	17	10	20	8	13	6
9	21	17	13	13	9	9	18	8	0	14	12	20	9	20	15	12	14	18
10	15	25	9	10	11	14	19	6	14	0	23	10	22	9	23	21	25	19
11	10	8	9	17	22	8	15	7	12	23	0	21	11	11	12	11	22	8
12	11	16	14	20	24	8	8	9	20	10	21	0	7	18	12	12	15	21
13	9	9	24	21	5	10	10	17	9	22	11	7	0	9	18	8	17	18
14	12	17	10	5	16	9	19	10	20	9	11	18	9	0	7	18	22	8
15	12	6	24	19	22	15	9	20	15	23	12	12	18	7	0	10	6	14
16	7	24	9	24	17	9	20	8	12	21	11	12	8	18	10	0	15	11
17	11	5	6	11	14	13	24	13	14	25	22	15	17	22	6	15	0	20
18	5	5	22	21	21	21	9	6	18	19	8	21	18	8	14	11	20	0

Table 8-4. Total cost of each site layout generation

Phase	*Layout Cost ($)*	*Setup cost ($)*	*Shifting Cost ($)*	*Total cost ($)*
1	157.9	1235	—	1392.9
2	128.4	700	154	982.4
3	155.9	685	836	1676.9

Skitmore (1992), Skitmore and Wilcock (1994) and Olatunji (2012) are relevant to construction costing methods.

According to the project schedule, and shown in the facilities schedule tables (Tables 8-1 and 8-2), a total of 8 facilities were setup at the beginning of Stage 1. As shown in Table 8-4, GA generated a site layout with total cost of $1392.9; representing layout and setup costs of $157.9 and $1235 respectively. There was no shifting cost of temporary facilities in Stage 1 since the stage has no preceding stage. Thus, layout of the temporary facilities was produced and input into the RFID-RTLS system without considering variability of locations prior to this stage.

Figure 8-11 shows the first layout on the graphical user interface (GUI) of the RFID-RTLS system. After generating the site layout for Stage 1, the RFID-RTLS system monitored the movement of all tagged resources within the layout spaces on site. As shown in the project schedule (refer to Figure 8-10), the last 4 tasks in Stage 1 extend to Stage 2. Consequently, all the facilities associated with these 4 tasks are

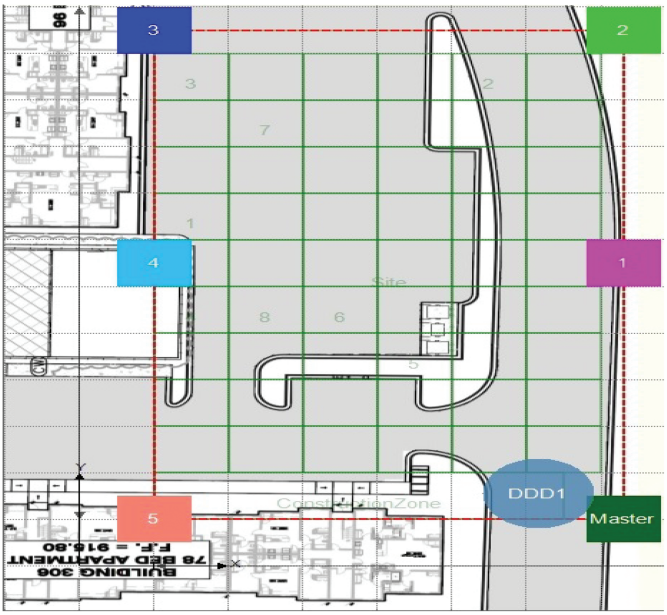


Figure 8-11. Site layout of phase 1 in RFID-RTLS system interface.

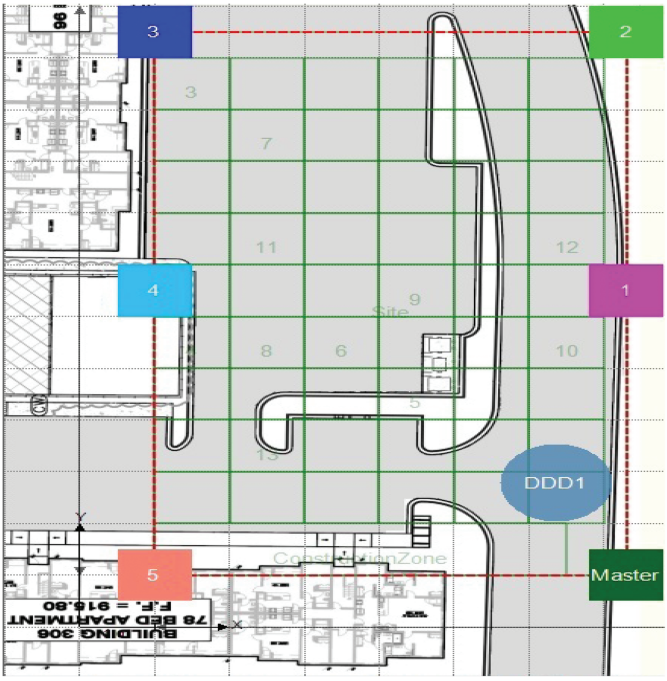


Figure 8-12. Site layout of stage 2 in RFID-RTLS system interface.

considered fixed, as they are being monitored in the system. Simply put, as the 4 tasks have commenced in Stage 1, and have continued to Stage 2, their entries have been adopted in Stage 2 as they were entered at the beginning of Stage 1.

When Stage 1 ended, BIM triggered GA for new site layout. By taking the fixed facilities into account, GA only generated site layout based on the new facilities for Stage 2 (shown in Figure 8-12). $982.4 was the total cost of site layout of Stage 2 (refer to Table 8-4). This includes layout cost, setup cost and shifting cost, calculated as $128.4, $700 and $154, respectively. Setup cost represents the cost of setting up facilities 9 to 13 since they are new items in Stage 2. Where a facility which is not in use in a Stage is to be moved, the removal cost will be added to the shifting cost.

The same procedures in Stages 1 and 2 were applied to Stage 3.According to the project schedule, Facility 13 was not moved since the associated task started in Stage 2 and was carried over to Stage 3. Figure 8-13 shows the site layout generated for Stage 3 as BIM triggered GA for an output. $1676.9 is the total cost of the site layout for Stage 3 as generated: the corresponding layout, setup and shifting cost are $155.9, $685 and $836 respectively. In this case, the setup cost includes the cost of setting up facilities 14 to 18 and the cost of shifting or moving facilities 3 to 12. Thus, the total cost depends on the number of facilities associated with each phase and the number of facilities that are shifted.

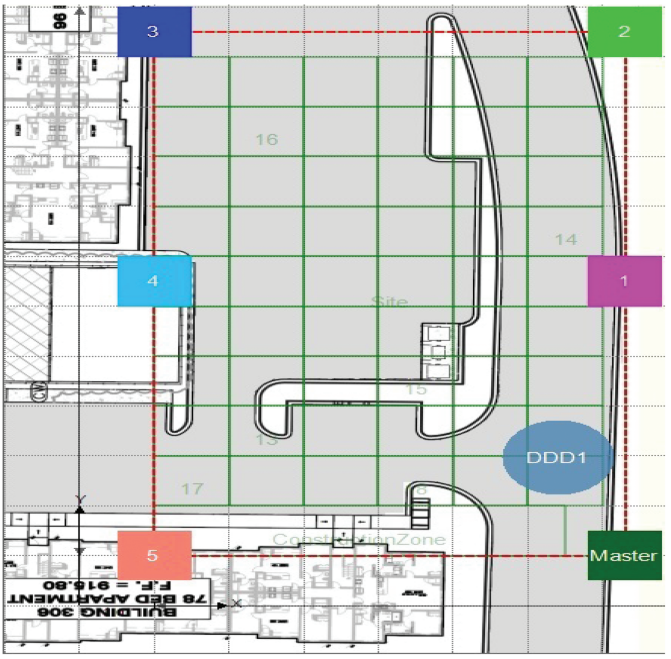


Figure 8-13. Site layout of stage 3 in RFID-RTLS system interface.

CONCLUSION ON THE DELIVERABLES OF ADAPTIVE CPS

An adaptive cyber-physical system promises a bi-directional platform for sensing and actuating data capturing in construction systems. It also promotes automation of information gathering between construction physical systems and design virtual systems towards intelligent project monitoring and control protocols. The approach described in this chapter shows how a RFID-RTLS captures data on construction resources in real time, and feed the data into an integrated design platform such as BIM, which triggers a genetic algorithm to generate site layouts and their cost implications. The values in this system are discussed below:

- A project design that is generated through collaborative platform such as BIM promises multi-disciplinary integration, particularly involving design and construction disciplines. This integration has been one of the main contributions of this work. Although other studies (including Lee et al. (2012); Norberg (2008)) have explored CPS, they have not included automated cost management processes in real time. Where cost management has been studied (e.g. Arayici et al. 2012), one of the main challenges was how to use appropriate technologies to capture data from remote sites in real time. As a key solution delivered in this study, we contend that using RFID-RTLS

limits human errors, promotes multi-domain integration and protects data integrity.

- Integrating the adaptive nature of physical and virtual systems is not new, but relating the adaptivity between the two to cost data in real time is novel. For example, in the data capture approach using still photography described by Golparvar-Fard et al. (2009), schedule overruns are detectable. However the process does not determine the cost implication of schedule overruns, neither does it encourage the synthesis of cost implications for resource control and time savings. As elicited in this chapter, aCPS is able to achieve these.

As per the procedures presented in this chapter – to promote the impact of cyber-physical systems – it is pertinent that technologies across domains are able to shift boundaries dynamically and be context-adaptive, autonomous and capable of generating real-time information for aiding swift cost management decision-making. This is because the outcomes reported in this chapter relate to a well-defined approach to cost management from construction project management perspective, usable by clients for cost control and contract management purposes, and by contractors for production control measures.

References

Abdelkarim, M. (2010) "BIM, ERP and Field Mobility in Construction - Technology and Strategy in the 21st Century." *Keynote of the 27th International Conference on Aplications of IT in the AEC Industry*, Cairo, Egypt. The International Council for Research and Innovation in Building and Construction, Rotterdam, The Netherlands.

Acharya, N. K., Lee, Y. D., and Im, H. M. (2006). "Conflicting factors in construction projects: Korean perspective." *Engineering, Construction and Architectural Management*, 13(6), 543–566.

Ahmadi, H., Abdelzaher, T., Han, J., Pham, N., and Ganti, R. K. (2011). "The sparse regression cube: A reliable modeling technique for open cyber-physical systems." *Proc. Cyber-Physical Systems (ICCPS), 2011 IEEE/ACM International Conference*, IEEE Computer Society, Chicago, 87–96.

Akanmu, A. (2011). "A Cyber-Physical Systems Approach to Construction." PhD PhD Dissertation, Penn State University.

Akanmu, A., Anumba, C., and Messner, J. "Mechanisms for bi-directional coordination between virtual design and the physical construction." *Proc., Proceedings of the CIB-W78 28th International Conference on Information Technology in Construction*.

Akintoye, A. and Skitmore, M. (1992). "Pricing approaches in the construction industry." *Industrial Marketing Management*, 21(4), 311–318.

Al-Kuwaiti, M. H. H. (2008). *Performance of Information Infrastructures: A Concept Comparison Framework*, ProQuest Information and Learning Company, Ann Arbor, MI.

Alwisy, A., and Al-Hussein, M. (2010). Automation in drafting and design for modular construction manufacturing utilizing 2D and parametric modeling. *Proc. International Conference on Computing in Civil and Building Engineering*, W. Tizani, (Ed.), University of Nottingham, Nottingham, UK. <http://www.engineering.nottingham.ac.uk/icccbe/proceedings/pdf/pf167.pdf>.

Amor, R., Jiang, Y., and Chen, X. (2007). BIM in 2007– are we there yet? *Proc.CIB International Conference on the Applications of IT in Construction (CIB-W78): knowledge to work*, RebolјD. (Ed.), Maribor, Slovenia. The International Council for Research and Innovation in Building and Construction, Rotterdam, The Netherlands, <http://www.cs.auckland.ac.nz/~trebor/papers/AMOR07B.pdf>, 159–162.

Anumba, C. J. (1996). "Functional integration in CAD systems." *Advances in Engineering Software*, 25(2-3), 103–109.

Arayici, Y., Egbu, C., and Coates, P. (2012). "Building information modelling (BIM) implementation and remote construction projects: Issues, Challenges and Critiques." *Journal of Information Technology in Construction*, 17 (Special Issue Management of remote construction sites and the role of IT Systems), 75–92.

Barton, R. T. (2000). "Soft value management methodology for use in project initiation: a learning journey." *Journal of Construction Research*, 1(2), 109–122.

Behzadan, A. H., Aziz, Z., Anumba, C. J., and Kamat, V. R. (2008). "Ubiquitous location tracking for context-specific information delivery on construction sites." *Automation in Construction*, 17, 737–748.

Bennett, T. D. (2009). "BIM and Laser Scanning for As-built and Adaptive Reuse Projects: The Opportunity for Surveyors." *The American Surveyor(July)*, 32–37.

Boddy, S., Rezgui, Y., Cooper, G., and Wetherill, M. (2007). "Computer integrated construction: A review and proposals for future direction." *Advances in Engineering Software*, 38(10), 677–687.

Bowen, P. A., Cattell, K., Edwards, P., and Jay, I. (2010). "Value Management practice by South African quantity surveyors." *Facilities*, 28(1/2), 46–63.

Burkhard, R. (2005). "Towards a Framework and a Model for Knowledge Visualization: Synergies between Information and Knowledge Visualization"; Knowledge and Information Visualization: Searching for Synergies (2005)." *Lecture Notes in Computer Science*, S.-O. Tergan and T. Keller, eds., Springer Heidelberg: New York.

Camarinha-Matos, L. M., Afsarmanesh, H., Galeano, N., and Molina, A. (2009). "Collaborative networked organizations - Concepts and practice in manufacturing enterprises." *Computers & Industrial Engineering*, 57(1), 46–60.

Cha, H. S. and O'Connor, J. T. (2005). "Optimizing Implementation of Value Management Processes for Capital Projects." *Journal of Construction Engineering and Management*, 131(2), 239–251.

Chin, S., Yoon, S., Choi, C., and Cho, C. (2008). "RFID+ 4 D CAD for Progress Management of Structural Steel Works in High-Rise Buildings." *Journal of Computing in Civil Engineering*, 22(2), 74–89.

Daschbach, J. M. and Apgar, H. (1988). "Design analysis through techniques of parametric cost estimating." *Engineering Costs and Production Economics*, 14, 87–93.

Eastman, C., Liston, K., Sacks, R., and Teicholz, P. (2011). *A BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*., Wiley, New York, NY.

El-Omari, S., and Moselhi, O. (2009). "Integrating automated data acquisition technologies for progress reporting of construction projects." *Proc. 26th International Symposium on Automation and Robotics in Construction (ISARC 2009)*. International Association for Automation and Robotics in Construction, Austin, TX, 86–94.

Ergen, E., Akinci, B., and Sacks, R. (2007). "Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS." *Automation in Construction*, 16(3), 354–367.

Georgy, M. and Basily, S. Y. (2001). "Using genetic algorithms in optimizing construction material delivery schedules." *Construction Innovation*, 8(1), 23–45.

Golparvar-Fard, M., Pena-Mora, F., and Savarese, S. (2009). "Application of D4AR - A 4-Dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication." *Journal of Information Technology in Construction (ITcon), Special Issue Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning*, 14, 129–153.

Grau, D., Caldas, C. H., Haas, C. T., Goodrum, P. M., and Gong, J. (2009). "Assessing the impact of materials tracking technologies on construction craft productivity." *Automation in Construction*, 18(7), 903–911.

Harris, F., McCaffer, R., and Edum-Fotwe, F. (2006). *Modern Construction Management*, Blackwell Publishing, Oxford, UK.

Hinze, J., Selstad, G., and Mahoney, J. P. (1992). "Cost overruns on State of Washington construction contracts." *Transportation Research Records*, 1351, 87–93.

Huang, T., Li, H., Guo, H., Chan, N., Kong, S., and Skitmore, M. (2009). "Construction virtual prototyping: a survey of use." *Construction Innovation: Information, Process, Management*, 9(4), 420–433.

Isikdag, U., Underwood, J., Aouad, G., and Trodd, N. (2007). "Investigating the Role of Building Information Models as a Part of an Integrated Data Layer: A Fire Response Management Case." *Journal of Architectural Engineering and Design Management*, 3, 124–142.

Jergeas, G. (2008). "Analysis of the front-end loading of Alberta mega oil sands projects." *Project Management Journal*, 39(4), 95–104.

Jergeas, G. and Ruwanpura, J. (2010). "Why Cost and Schedule Overruns on Mega Oil Sands Projects?" *Practice Periodical on Structural Design and Construction*, 15(1), 40–43.

Kelly, J. and Hunter, K. (2003). "The three Wheels of Best Value." *CIB Research Series*, 4(23).

Lee, H., Lee, K., Park, M., Baek, Y., and Lee, S. (2012). "RFID-Based Real-Time Locating System for Construction Safety Management." *Journal of Computing in Civil Engineering*, 26(3), 366–377.

Leupen, B., Grafe, C., Kornig, N., Lampe, M., and de Zeeuw, P. (1997). *Design and Analysis*, OIO Publishers, Rotterdam, Netherlands.

Love, P. E. D., Sing, C.-P., Wang, X., Edwards, D. J., and Odeyinka, H. (2013). "Probability distribution fitting of schedule overruns in construction projects." *Journal of the Operational Research Society*, 64, 1231–1247.

Lowe, D. J. and Skitmore, M. (2001). "Human effects in construction contract price forecasting: experience and experiential learning styles." *Journal of Construction Engineering and Management*, 127(6).

Lucas, J., and Thabet, W. (2007). "Benchmarking User Performance By Using Virtual For Task-Based Training." *Proc. 7th International Conference on Construction Applications of Virtual Reality*, Penn State University, University Park, PA, 70–79.

Marstaller, L., Hintze, A., and Adami, C. (2012). "Cognitive systems evolve complex representations for adaptive behavior." arXiv preprint arXiv:1206.5771.

Munzner, T. (2009). "A Nested Model for Visualization Design and Validation." *IEEE Transaction on visualization and computer graphics*, 15(6), 921–928.

Nasios, K. (2001). "Improving chemical plant safety training using virtual reality" *Doctor of Philosophy*, University of Nottingham, UK.

Navon, R. and Sacks, R. (2007). "Assessing research issues in automated project performance control (APPC)." *Automation in Construction*, 16(4), 474–484.

Norberg, H. (2008). "On-Site Production Synchronization: Improving the Resource-Flow in Construction Projects."Licenciate Thesis, Luleå University of Technology, Luleå, Sweden

Olatunji, O. A. (2012). "The Impact of building information modelling on estimating practice: analysis of perspectives from four organizational business models." Doctor of Philosophy Dissertation, University of Newcastle, Newcastle, Australia.

Oyegoke, A. S. (2007). "Specialist task organizations procurement approach for re-engineering construction project processes." PhD PhD Dissertation, Helsinki University of Technology Espoo, Finland.

Pinto, J. K. and Mantel, S. J., Jr. (1990). "The causes of project failure." *Engineering Management, IEEE Transactions on*, 37(4), 269–276.

Popov, V., Juocevicius, V., Migilinskas, D., Ustinovichius, L., and Mikalauskas, S. (2010). "The use of a virtual building design and construction model for developing an effective project concept in 5D environment." *Automation in Construction*, 19(3), 357–367.

Rajkumar, R. R., Lee, I., Sha, L., and Stankovic, J. (2010). "Cyber-physical systems: the next computing revolution." *Proceedings of the 47th Design Automation Conference*, ACM, Anaheim, CA, 731–736.

Reichelt, K. and Lyneis, J. (1999). "The Dynamics of Project Performance: Benchmarking the Drivers of Cost and Schedule Overrun." *European Management Journal*, 17(2), 135–150.

Skitmore, M. and Wilcock, J. (1994). "Estimating processes of smaller builders." *Construction Management and Economics*, 12(2), 139–154.

Sørensen, K. B., Christiansson, P., and Svidt, K. (2009). "Ontologies to Support RFID-Based Link between Virtual Models and Construction Components." *Computer-Aided Civil and Infrastructure Engineering*, 25(4), 285–302.

Talcott, C. (2008). "Cyber-Physical Systems and Events." *Software-Intensive Systems*, M. Wirsing, et al., ed., Springer-Verlag, Berlin Heidelberg, 101–115.

Weigel, M., Preuss, T., Br, J., #252, and stel (2010). "Generating Navigation Capable Maps from User Provided Data with Woodtracker." *Proceedings of the 2010 International Conference on Complex, Intelligent and Software Intensive Systems*, IEEE Computer Society, 544–548.

Whyte, J., Bouchlaghem, N., Thorpe, A., and McCaffer, R. (2000). "From CAD to virtual reality: modelling approaches, data exchange and interactive 3D building design tools." *Automation in Construction*, 10(1), 43–55.

Wu, F.-J., Kao, Y.-F., and Tseng, Y.-C. (2011). "From wireless sensor networks towards cyber physical systems." *Pervasive and Mobile Computing*, 7(4), 397–413.

Xia, F., Vinel, A., Gao, R., Wang, L., and Qiu, T. (2011). "Evaluating IEEE 802.15. 4 for cyber-physical systems." *EURASIP Journal on Wireless Communications and Networking*, 2011(1), 596397.

Yang, B., Watkins, K. E., and Marsick, V. J. (2004). "The Construct of the Learning Organization: Dimensions, Measurement, and Validation." *Human Resource Development Quarterly*, 15(1), 31–55.

Yesilbas, L. G. and Lombard, M. (2004). "Towards a knowledge repository for collaborative design process: focus on conflict management." *Computers in Industry*, 55(3), 335–350.

This page intentionally left blank

CHAPTER 9

Building Information Modeling for Facilities Management: Current practices and future prospects

Arundhati Ghosh*
Allan D. Chasey†
Mark Mergenschroer‡

Abstract: *Building Information Modeling (BIM) has demonstrated important functional applications for architects, engineers and constructors, as both a tool and a process. However, its relative value for Facility Management (FM) has been widely debated in the industry. By leveraging the data resident in the geometric models, it can be reasoned that using BIM for FM is a valuable function of information management. The potential impact BIM has on cost reduction coupled with increased facility life cycle efficiencies are compelling arguments to keep developing and refining BIM for FM. As it continues to develop, BIM will facilitate efficiency gains in facility operations, ultimately yielding a more sustainable built environment. This chapter is a literature review of the current efforts in academia and industry that have looked at synthesizing the collection, dissemination and distribution of information through a project lifecycle and critically analyses how BIM can aid this process. It also describes the current technology that enables the said processes to occur. In conclusion, the authors present recommendations for future avenues of research.*

*PhD student and Research Assistant, Del E. Webb School of Construction, School of Sustainable Engineering and the Built Environment, Ira A. Fulton Schools of Engineering, Arizona State University, Tempe, AZ; email: aghosh9@asu.edu

†Professor and Program Chair, Del E. Webb School of Construction, School of Sustainable Engineering and the Built Environment, Ira A. Fulton Schools of Engineering, Arizona State University, Tempe, AZ; email: achasey@asu.edu

‡BIM Innovation Services Manager, TME, Inc., 800 Evergreen Drive, Little Rock, AR; email: MMergenschroer@tmecorp.com

INTRODUCTION

All facility owners share a common theme in their organizational goals that is ensuring that the end users are effectively receiving the services for which the facility has been designed. The day-to-day management of the facility, including operations and maintenance (O&M) contribute to this goal. There is a growing recognition that FM contributes to the health and well-being of the buildings occupants, thereby benefiting efficiency, productivity and profitability of the people and the organization. Thus, the role of the FM team is to maintain the facility, optimize operational costs and efficiently manage all systems, while assessing its impact on people and processes within the facility. Complex building systems and controls increasingly offer opportunities as well as challenges for the profession. As the facilities and building systems reach and exceed their expected operating lives, significant issues of repair or replace become prominent. The revolution in building O&M is being fueled by a parallel revolution in information technology. New technologies bring opportunities for optimizing facility performance. Thus, the skills of a FM team have to expand to include knowledge about complex systems, technology and organizational impacts of maintenance management.

Facilities' of all types, sizes and complexities are dependent on the information they create. This could be information about the facilities existing features, space, materials, equipment and their performance, engineering, energy consumption amongst others. To perform his/her work of operating and maintaining the facility, the facility manager requires easy access to this information. Digitization of building information is accompanied with the hope that it is more accessible, accurate and easily communicated (Anderson et al. 2012). Hence, an ideal technological vision is that of a central database, such as a BIM, that supports open access to information when and where required across the FM organization. BIM allows facility managers access to information about the facility within minutes, when previously it could take hours of research to obtain the same information.

This chapter will approach the topic of BIM and FM from the perspective of information management while emphasizing the importance of the accuracy and relevance of the most critical variable i.e. information. Instead of looking at BIM as a tool in isolation, BIM for FM is an approach that is part of a system that includes people, processes and data (see Figure 9-1). BIM serves as the information backbone for FM systems, which can be combined with advanced technologies to gain greater efficiencies in operational workflows. The chapter flows from general to specific, covering the following topics; a brief overview of the FM industry, definitions of commonly used FM acronyms, information exchange standards, data handover including references to owners project requirements, standards and contracts, building commissioning, an overview of other technologies used in conjunction with BIM and concludes with the current challenges faced by the FM industry and suggested avenues for further research.

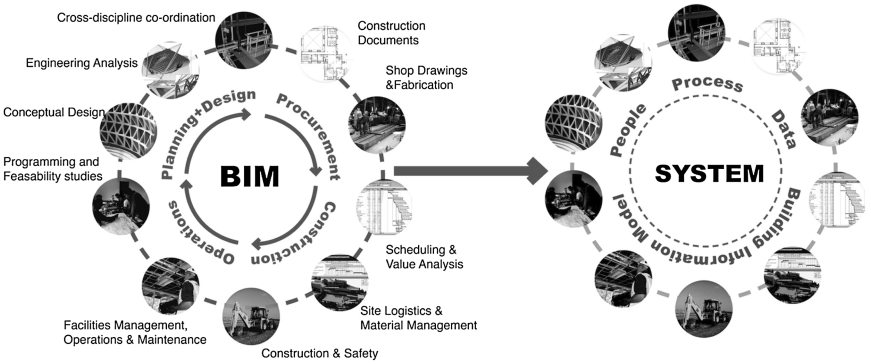


Figure 9-1. BIM as a system.

AN OVERVIEW OF THE FM INDUSTRY

Until about half a century ago, Facility Management (FM) was known as public works and generally referred to as maintenance, cleaning and repairs. Over the years, the functions of FM have evolved from meaning just operations and maintenance to include business functions, performance functions and financial management. According to Cotts et al. (2009), a well-managed facility creates a favorable work environment by having a direct impact on its employees' quality of life, health and safety. It is therefore pertinent for a facility to function as a healthy living organism in order to add strategic value to an organization.

The International Facility Management Association (IFMA 2013) defines facilities management as, "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology". This definition is broad enough to illustrate the multiple interdisciplinary functions that facility owners can tailor to their organizations infrastructure and business philosophies. The objective is that these integrative themes perform together for the holistic purpose of reducing operating costs, improving energy efficiency, supporting sustainability objectives and improving the quality of the facilities. When planned and executed efficiently, the expected results can be more than just cost savings. According to Shear (1983), a well-managed facility ensures "maximum savings on investment through optimum efficiency of operations, preventing emergency breakdowns, saving on replacement costs, improving occupant comfort and develops a competent management team".

"The Facility Management Handbook" lists 14 common functions based on tasks or activities that the Facility Manager is responsible for, not necessarily individually (Cotts et al. 2009). They encompass a variety of themes ranging from management, planning, construction, and finance to technology, O&M, telecom, security and other administrative services. These themes can be represented as FM roles and responsibilities in a popularly known visual; the FM Pie (Theriault 2010).

In most organizations, FM departments are created to manage the number, size and complexity of the facilities along with the development of new construction projects. The different strategic organizational models for facilities management are:

- In house management,
- Management by an agent or consultant,
- Direct outsourcing,
- Management by a contractor and,
- Integrated FM.

The type is developed considering the specialization or complexity of the non-core processes (maintenance, repair, technical assistance etc.), the focus on core processes (financial and human resource management), inclination to outsourcing, and desired level of autonomy in relation to the non-core process management (De Toni et al. 2012). A survey conducted by IFMA (2013) in 2001 on 'Designing the Facility Management Organization', at a response rate of 22% highlighted some popular organizational trends:

- 54% of all FM divisions are structured as a separate department of the organization, 42% are part of a larger department (usually Administration, HR, Finance, Operations, or Real Estate), and 4% are split across various departments,
- FM departments most frequently include maintenance and operations (91%), facility planning (88%), space management (75%), environmental health and safety (58%), real estate management (56%), and administrative services (52%). Only 8% of departments directly supervise the information technology function,
- 14% handle all services internally, 80% use out-tasking and 6% out-source.

Considering the general functions and organizational structures, it is evident that FM departments include personnel from various different backgrounds and expertise and tend to be spread both horizontally than vertically. With the various different departments and people exchanging information, it is likely to get entangled in a web of redundant and unnecessary information. Before we look at ways for making sense of the information, the next section gives a brief overview of the common FM terminologies.

Commonly Used FM Acronyms

Reactive Maintenance

The traditional method of maintenance is the 'run to failure' reactive maintenance approach where a part is replaced only when it fails.

Preventive Maintenance (PM)

Preventive maintenance is the time-based scheduling of maintenance activities effecting repairs before a failure occurs. The objective here is to eliminate or significantly reduce actual failures and breakdowns. PM introduces control and

ensures higher reliability while reducing costs through balancing work and downtime (Lewis and Payant 2007).

Predictive Maintenance (PdM)

Predictive Maintenance is a maintenance philosophy in which condition is monitored at appropriate intervals to enable accurate evaluation of equipment (Lewis and Payant 2007). PdM is a proactive method of condition monitoring, which helps predict when maintenance has to be performed. Previous knowledge of the equipment's condition helps in anticipating needs for repairs, schedule appropriate resources, order required parts only when needed, eliminating wasted efforts and leading to an overall lean process.

Computerized Maintenance Management Systems (CMMS)

CMMS is a computer software tool used by facility managers to store complete information about all assets within a facility and use-modules such as work order control, preventive and predictive maintenance, inventory control etc. The program behaves like a cross linked series of databases. Work orders can be generated, updated and archived in a CMMS. While some of the information is feasible to be captured within a geometric model, some of the information comes from separate sources such as commissioning reports and vendor data. A new asset in a CMMS will consist of at a minimum the following information (Foster 2012):

- Classification type (asset number, equipment group, criticality) and attributes (dimensions, weight, power, energy consumption),
- Manufacturer name and vendor data including model number, serial number, specifications, warranties, performance data, replacement parts information, O&M manuals, and installation date,
- Real property information such as building name, floor and room numbers, quadrant of the room,
- Installed equipment's operating parameters.

BIM can assist in automating the process of data transfer and update. If the relevant data is captured as a part of the BIM attributes during design and construction, previous labor-intensive data entry processes can be avoided when transferring the attributes to a CMMS. Some application areas of BIM-CMMS include:

- Visualization of spaces and easy location of systems and components during emergencies,
- Facilitating maintainability studies focusing on the desired performance at various stages of a facilities lifecycle (Becerik-Gerber et al. 2012),
- Prioritization of maintenance activities based on historical trends: A case study conducted by Ackamete et al. (2010), interfaces the history of changes captured from work orders archived in a CMMS with BIM. This exercise helps in identifying spatial trends and relationships for each type of repair activity. Through this visual and spatial analysis of maintenance and repair

work performed over a period of time, the facility manager can identify a pattern or a trend that helps the prioritization of maintenance activities. Such analysis leverages the 3D geometric data from the BIM, with the current and past data stored in the CMMS.

Computer Aided Facilities Management (CAFM)

CAFM is a software used by facility managers to track and plan events occurring in the department and analyze areas for cost savings. This tool gives the facility manager the ability to automate many of the data-intensive functions that typically result in continuous cost savings and improved utilization of assets throughout their entire lifecycle (Watson and Watson 2011). A variety of companies provide CAFM solutions, which can be client-server or cloud based. All CAFM tools will have at least an interactive relational database, an interactive graphics module and a user-friendly interface with data management functions such as data input, analysis and editing. A CAFM system will provide the following functionalities (Watson and Watson 2011):

- Strategic Planning for improved capital planning of new and remodel assets considering analyses of property and space,
- Space Inventory and Management including defining and standardizing space attributes and physical asset inventories for managing space during occupancy and move.
- Asset Management using bar codes or Radio Frequency Identification (RFID) tags to track all movable assets and equipment.
- Portfolio Management including lease management, portfolio performance and rent and contract management for multiple properties.
- Operations including tracking energy consumption, utilities monitoring, lighting management, and maintenance management.
- Assessments for building condition inspections, condition reporting, security vulnerability, and risk assessments.

A CAFM with an integrated BIM database and location based services provides benefits such as visualization for space planning and forecasting, compilation of information and viewing assets in the context of the space. It establishes a more robust system by synchronizing with design information available from a BIM.

Building Automation Systems (BAS)

BAS are computerized distributed control systems for intelligent buildings, which monitor and control certain parameters for heating, ventilation and air-conditioning (HVAC), mechanical, electrical and plumbing (MEP), fire protection and lighting systems. Core functionalities include controlling building temperatures and lighting based on occupancy and monitoring system performances and device failures. The primary objective is to reduce building energy and maintenance costs

as compared to a non-controlled building and increase sustainability through better performance of systems. BAS linked to BIM provides owners and facility managers the visualization to simulate performance, track energy efficiency by comparison with the design data. This also allows opportunity for controlling the BAS through the model using third party software.

Energy Management System (EMS)

EMS refers to a computer system which provides metering, sub-metering, and monitoring functions that allow facility and building managers to gather data and insight. This allows them to make more informed decisions about energy activities across their sites. The scope may span from a single building to a group of buildings. Most of EMSs also provide ability for the monitoring of electricity, gas, and water metering systems. They can be used to centrally control devices like HVAC units and lighting systems across multiple locations. The data obtained from these can then be used to perform self-diagnostic and optimization routines frequently and to produce trend analysis and annual consumption forecasts. Connecting the BIM data and the facility life cycle data to the EMS will ensure that proper energy management is maintained through the life cycle of the building.

Ideally, a productive workflow can be achieved if the CMMS, CAFM, BAS and EMS systems are able to smoothly exchange data with the BIM authoring tools. However, due to the fact that these programs are developed by multiple software developers on a variety of platforms, there is a constant roadblock when it comes to information exchange. The following section will discuss the concept of information exchange from a technology perspective.

INFORMATION EXCHANGE

Information exchange to a Facility Manager connotes the semantics of the information being communicated to answer the question: *what is the data being exchanged in the FM process?* For a technology expert and software vendor, it connotes the ability to seamlessly exchange data over several disparate platforms or: *how and in what form is the data being exchanged?* According to Redmond et al. (2012), from a computer science perspective, in general there are three methods for data exchange:

- Direct links that incorporate Application Programming Interfaces (API) to extract and exchange data,
- Proprietary file exchange developed by an organization to interface solely with its own proprietary software applications and,
- Public product data model exchange such as IFC and ifcXML which are open and publicly managed data and schema.

The industry at present is in a transition period, making the change from closed proprietary standards to open source or common standards. Several

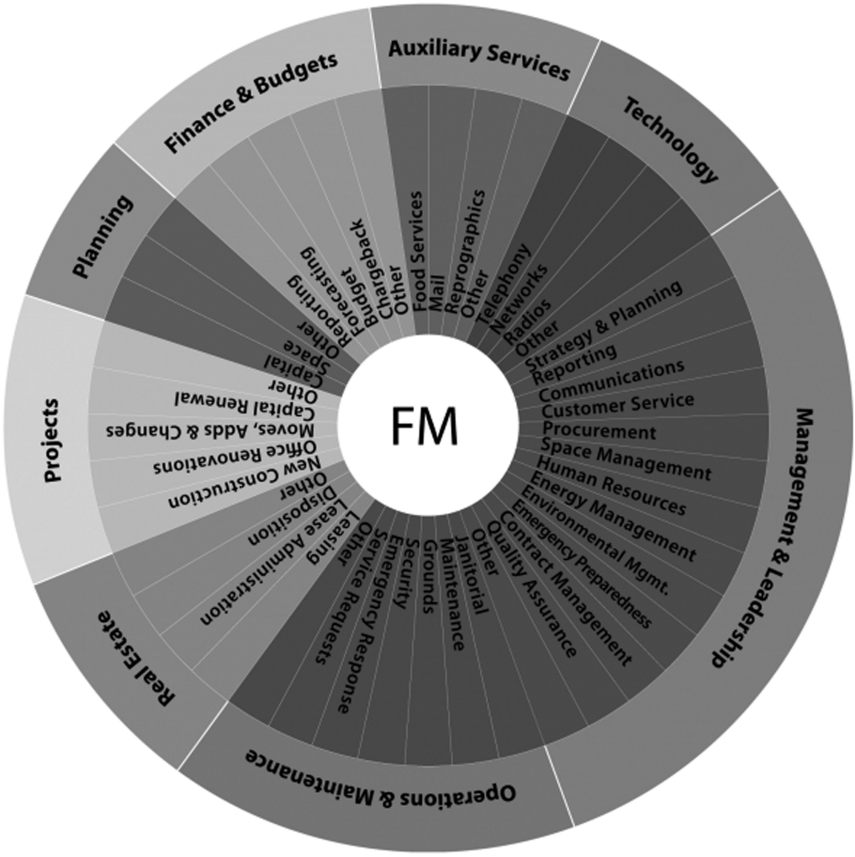


Figure 9-2. FM data needs and functions (Theriault 2010).

questions are being researched at organizational, technological, operational and strategic levels. The research for interoperability and seamless technology integration is being led by the efforts of non-governmental organizations such as buildingSMART alliance (bSa), research projects in universities and several other private organizations across the United States. The need for interoperability is paramount for the fluid transition of BIM to BIM-FM.

From the perspective of the Facility Manager, the most important challenge is understanding what data is included in BIM and its effective use for daily work processes. The organizational structure and the projects lifecycle together create various points of data origin that collectively inform the facility manager's decision-making process (see Figure 9-2). The types and points of information generation can be classified as:

- Design, construction and equipment information flowing horizontally through the projects lifecycle, produced by architects, engineers, contractors and vendors,
- Current operations and usability information from end users and staff,

- Condition and current performance information from CMMS, EMS or BAS systems,
- Core-process information flowing vertically through an organizational structure,
- Non-core process information from different facility departments.

As mentioned earlier, generation of disparate formats of data from these various sources is inevitable. Coupled with numerous way of communication, this is often a reason for problems arising from interoperability, redundancy of data and inefficiencies in decision-making because of either too much, too less or inconsistent information. Consolidating the critical data to provide the FM with the correct information at the perfect decision moment is important for bridging the efficiency hurdles omnipresent in most FM organizations. This section discusses the cost of interoperability borne by owners and the open standards being developed for architecture-engineering-construction (AEC) data.

NIST study: Cost Analysis of Inadequate Interoperability in the US Capital Facilities Industry

In 2004, the National Institute of Standards and Technology (NIST) commissioned a study to identify and estimate the efficiency losses in the US capital facilities industry resulting from inadequate interoperability among CAD, engineering, and software systems. The study concluded that interoperability problems in the capital facilities industry stem from "the highly fragmented nature of the industry, the continued paper based business practices, a lack of standardization, and inconsistent technology adoption among stakeholders" (Gallaher et al. 2004). The study showed that in 2002, the industry as a whole spent $15.8 billion on interoperability, 67% of which was borne by owners (see Figure 9-3). Of the $10.6 billion spent by owners and operators in a year, $9.03 billion (or 85%) was spent in the O&M phase itself, of which $4.8 billion or 53.1% was the cost of information verification and validation (see Figure 9-4).

In the decade after this report was first published, several advances have been made to mitigate the challenges faced due to interoperability of software applications by the adoption of neutral format standards such as Industry Foundation Classes (IFC) and Construction Operations Building Information Exchange (COBie). Flow of information has been streamlined with the establishment of standards and execution plans and also the inclusion of O&M needs in the contractual language.

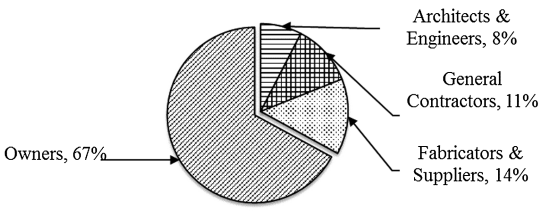


Figure 9-3. Costs of inadequate interoperability borne by stakeholder group.

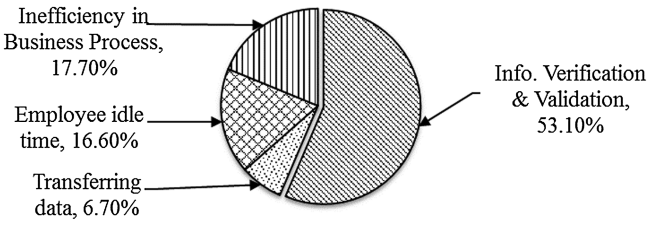


Figure 9-4. Costs of inadequate interoperability borne by owners.

Open Standards – IFC and COBie

Industry Foundation Class (IFC) is an ISO Standard (ISO 26739) vendor neutral data format used to describe, exchange and share information. It is a data schema based on class definitions representing objects such as building elements, spaces, properties etc. It is able to link alphanumeric information such as properties to the physical geometry of an object such as a door or a wall while preserving their semantic relationships. IFC model information is typically exchanged through an information exchange format called STEP (ISO 10303). Most BIM authoring tools now provide an export function for converting the model geometry to an. ifc format that can be read by any other non-compatible software application.

Construction Operations Building Information Exchange (COBie) is an information exchange model that helps capture information at the point of origin and assures a smooth transfer of information through the stages of the facility lifecycle without losing its context. It contains three types of information; information created by designers, information created by contractors and supporting information created by both (see Figure 9-5). This process is based on the

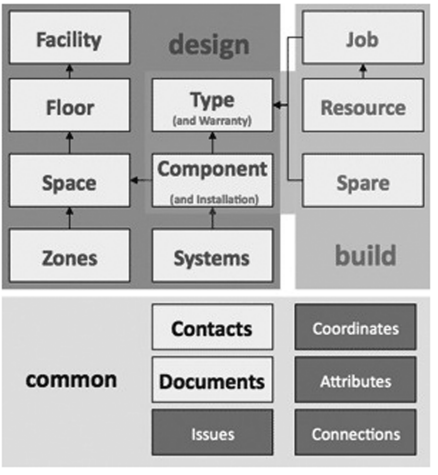


Figure 9-5. COBie organization (East 2014, March 3).

assumption that the data will be provided by the party contractually required to create the information. It is then translated to an Excel spreadsheet format, which enables the capture of the data in its simplest format. COBie attributes can be added to a BIM authoring tool and can be exported as a function of the BIM.

"COBie organizes all task based actions that need to be documented at construction handover into one common format of 'jobs', identified by the type of work, preventative maintenance, startup and emergency procedures etc." (East 2013). This is useful for the maintenance staff as it enables them to understand the design intent of the architects, the relationship between different spaces and systems, plan their expected personnel requirements, provides an accurate as-built information model and eliminates the waste associated with interoperability and manual data re-entry.

PLANNING FOR FM DATA ACQUISITION

This section looks at the importance of acquiring accurate and appropriate information throughout the projects lifecycle for a successful BIM use for FM. Subsequent to which it will discuss the current practices and standards in the industry that help us in planning that effort.

Information Handover

A facilities life cycle passes through a series of identifiable phases; planning and programming, design, construction, project closeout and commissioning, operations and maintenance (O&M) and finally disposal. For alternative project delivery methods, such as design-build (DB), construction management at risk (CMAR) and integrated project delivery (IPD), these phases overlap, but the information flow still remains horizontal and successive. In reality, the transfer of information is such that its quantitative and qualitative value is dependent on the previous phase and also has an effect on the next. By streamlining information flow and communication between these aforementioned phases, life cycle costs can be reduced and services to the owner can be improved (Guo et al. 2010). Thus, managing the accuracy, appropriateness and quality of this information flow becomes critical for the knowledge needed to make optimal decisions during O&M. According to Lucas et al. (2012), the information needed for facility management (FM) comes from two directions, "horizontally, across the lifecycle and vertically, from within the concurrent operations". In many cases, attributing to the ad-hoc nature of the FM industry, a third source of information is often from the memory of the facility technicians and engineers.

Typically the information handed over to owners is in the form of paper based as-built 2D construction documents including drawings, specifications, equipment lists and O&M manuals from various vendors. Since they are organized by the constructors in a format to align with their needs, the information is marginally useful for the facility manager (Goedert and Meadati 2008). Even

when the information is available digitally, lack of interoperability of the software platforms reduces the usefulness of the data. Rework and manual data entry is usually required to update the FM systems, leading to duplication of efforts and high chances of error. Unavailability of specific task-centric FM information, in a format that is useful and at the time that it is needed, leads to uninformed decisions, patchy solutions, lack of predictability, poor performance of building systems and increased energy consumption. This ultimately affects the environmental and financial health of the facility, the owner organization and the end users.

With BIM as the deliverable, it becomes a central repository of information collected throughout the projects life cycle and also blurs the lines between the phases of the life cycle. Now, even though the handover remains successive, the data added to the model is iterative. This increases the need for accuracy of the data earlier in the lifecycle. The owner benefits by receiving a complete model with a full range of project information (Goedert and Meadati 2008). However, for an accurate building information model and its successful use for FM, rather than waiting till project closeout to receive information, it is imperative that the owner proactively specifies the information requirements at the front end of the life cycle, so that the data is structured as per the FM's needs. This calls for a revision of the data handover standards, contracts and owners project requirements (OPR), as discussed below.

NIST Study: General Building's Information Handover Guide

After the 2004 NIST report about costs of inadequate interoperability (described in the previous section), in 2007 NIST published a guide providing a framework for the successful use of advanced technology and avoiding the pitfalls encountered in information handovers between phases. The guide outlines four steps for a successful information handover emphasizing on an owner defined information strategy (Fallon and Palmer 2007):

1. Information Strategy: A strategic information package developed in alignment with the organizations goals and data security policies.
2. Information Handover requirements: The definition of the form and format of each information package considering the associated metadata.
3. Project Information Handover Plan: The authors of the information packages.
4. Implementation: Technical implementation as well as establishment of project procedures, contractual responsibilities and training programs.

National BIM Standard – United States – Version 2 (NBIM-US™V2)

The National BIM Standard (NBIMS) is an ongoing effort of the bSa. The NBIMS-US™ project defines certain standards for efficiently accessing the information needed to create and operate optimized facilities (NIBS 2012). Supporting and

promoting the use of IFC as the data schema, encouraging transparency and automating the information exchange process are some of the features of this standard. The target audiences for this document are software developers, vendors and industry implementers. There are three sections that form the framework for the application of the standards:

1. Reference Standards includes model and dictionary standards, exchange standards and data structure and identifier standards. They include:
   - ISO16739 Industry Foundation Class (IFC)
   - World Wide Web Extensible Markup Language (XML)
   - OmniClass™ Tables 13(Spaces by Function), 21(Elements), 22(Work Results), 23(Products), 32(Services), 36(Information)
   - International Framework for Dictionaries (IFD) Library based on ISO 120006-3: Framework for Object Oriented Data Exchange.
2. *Information Exchange Standards* include "documents that outline information exchange standards through process modeling, information delivery manuals, and their correlating model view definitions developed to guide information exchange protocols" (NIBS 2012).
   - Construction Operations Building information exchange (COBie)
   - General Services Administration (GSA) defined BIM guides for information exchanges relating to spatial program validation, building energy analysis and quantity takeoff for cost estimating.
3. *Practice documents* for implementing BIM requirements include:
   - Minimum BIM as defined by the Capability Maturity Model
   - BIM Project Execution Planning Guide (developed by Pennsylvania State Universities Computer Integrated Construction research program)
   - Mechanical, electrical, plumbing and fire protection systems' spatial coordination requirements for construction installation models and deliverables
   - Chapter 5: Planning, Executing and Managing Information Handovers (updated in June 2011) from the 2007 NIST study titled General Building's Information Handover Guide (Fallon and Palmer, 2007).

Contract Documents

Traditional contract processes and legal language must be revised to incorporate the BIM-FM deliverable. Several different thought processes, standards and guidelines prescribe what needs to be included in the contract. The key is to determine what information aligns best with the philosophies of the organization and the facility to avoid wasting precious time, effort and capital. Answering some key questions early in process may help develop a contract with a defined scope.

These questions can also be inferred from the BIM Planning Guide for Facility Owners described in the next section.

- How will your facility implement the BIM-FM deliverable into the FM process?
- What is the cost for implementing BIM-FM and FM for your facility?
- What is the purpose of the BIM-FM deliverable?
- What is the level of detail within the BIM-FM deliverable?
- What information should your facility track from the BIM-FM deliverable?
- What asset data does your facility want to manage in the BIM-FM deliverable?
- Does your facility want to extract life cycle cost analysis from the model and BIM-FM process?
- Does your facility want to track trending history?
- Does your facility want to own and control their BIM content for release to the design team?
- Does your facility want access to model numbers, warranty information and O&M manuals from the BIM authoring tool or a FM tool?

Once these questions have been answered we can begin to define the scope and set the expectations for a BIM-FM deliverable. When writing a contract for a BIM project the following items will need to be clearly defined in the contract:

- The BIM-FM objectives should be defined as per contract language
- Set BIM-FM standards for the deliverable in the contract
- Define the architects, engineers, consultants and contractors obligations for the BIM-FM deliverable in the contract
- Determine who will be responsible for ownership of the BIM-FM deliverable
- Clarify who will manage the BIM-FM deliverable from concept through construction
- Define the BIM-FM deliverable clearly in the contract
- Determine the software package in which the BIM-FM deliverable will be delivered
- Define model sharing for collaboration among the design team
- Define fee structure since BIM-FM deliverables require more design time during the schematic design and design development stage.

The AIA E203-2012 (BIM protocol exhibit) document, offers some guidelines to help with setting modeling guidelines and expected levels of model development. This document also outlines responsibility and guidelines for the model development during each phase of a project.

Owners Project Requirements (OPR)

As defined in the ASHRAE-NIBS Guideline 0-2005: The Commissioning Process, Owners Project Requirements (OPR), "forms the basis for evaluating all activities and products during pre-design, design, construction, acceptance, and operational decisions", addressing function, form, economy and time (Enck 2009). According to Enck (2009), the OPR details the high level functional requirements or end goals of a project at the beginning, with an approach of blending operational and user needs for optimal performance results and user satisfaction. It is in theory, different from an architectural program, which is the designer's definition of the project addressing heuristic goals for facility needs.

BIM Planning Guide for Facility Owners Version 1.01

The team at the Computer Integrated Construction Research Program (CICR) at Pennsylvania State University; the authors of the BIM Project Execution Planning Guide, released the first version of the BIM Planning Guide for Facility Owners in May 2012. This guide is based on the hypothesis that "through effective BIM planning, owners can develop a clear business case to maximize the value of BIM implementation for the lifecycle" (CICR 2012). It is recommended that owners establish a clear strategic plan at the organizational level for BIM implementation, by following three steps:

1. Assessment and evaluation of the organizations internal and external BIM status
2. Aligning the organizations BIM objectives by identifying the desired level of maturity
3. Advancing the BIM maturity by defining a process to transition its use into organizational business practices

The guide lists some of the critical tasks as; data commissioning, performance monitoring, systems control, space tracking, asset management, maintenance management, condition documentation and scenario forecasting (see Figure 9-6).

GSA BIM Guide Series 08: GSA BIM Guide for Facility Management

The US General Services Administration (GSA) released their BIM Guide for Facility Management as a part of their GSA BIM Guides with the primary objective of using and maintaining facility data throughout the lifecycle. Their goals were to have accurate as-builts during renovations, optimize O&M of building systems to reduce energy usage and increase customer satisfaction. These are definitely one of the more advanced guidelines for businesses processes and technical requirements set forth by an owner (GSA 2011). The guide consists of five sections:

1. *BIM and FM*: A central facility repository is envisioned that integrates FM data from various sources; real-time sensor data, parametric information

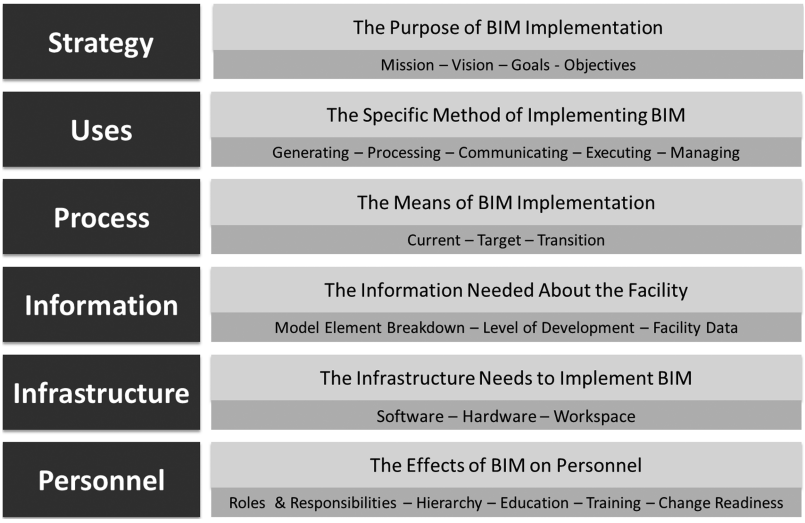


Figure 9-6. BIM implementation by owners (CICR 2012).

from BIM, CMMS and CAFM data, laser scanning data in one place. The software tools 'sit on top' to provide security, version control, notifications on updates, analysis and reporting (See Figure 9-7). GSA has developed three tiers of data requirements that are necessary to support the FM needs for the wide range of facilities they manage (362 million square feet in 9624 buildings located in 50 states).

- Tier 1: Accurate as-built geometry for equipments and spatial program BIM - Mandated to address the significant benefits of an accurate 3D geometric model to downstream users (Teicholz 2013).
- Tier 2: Equipment inventory and O&M management - Used in larger facilities to track equipments for assessing equipment conditions, energy management, warranties, manpower calculations etc.
- Tier 3: As-designed BIM with energy analysis - This is an optional requirement and applicable if the as-designed BIM with energy analysis is captured.

2. *Implementation Guidance*: This section provides guidance to the GSA project teams by recommending a workflow, which includes the following steps:
   - Identify project requirements,
   - Define an implementation strategy,
   - Identify phase of the lifecycle and status of existing systems and data,
   - Identify impact of project delivery approach on implementation,
   - Develop a BIM execution plan with format requirements (GSA recommends information exchange using the vendor neutral IFC format supported by COBie),

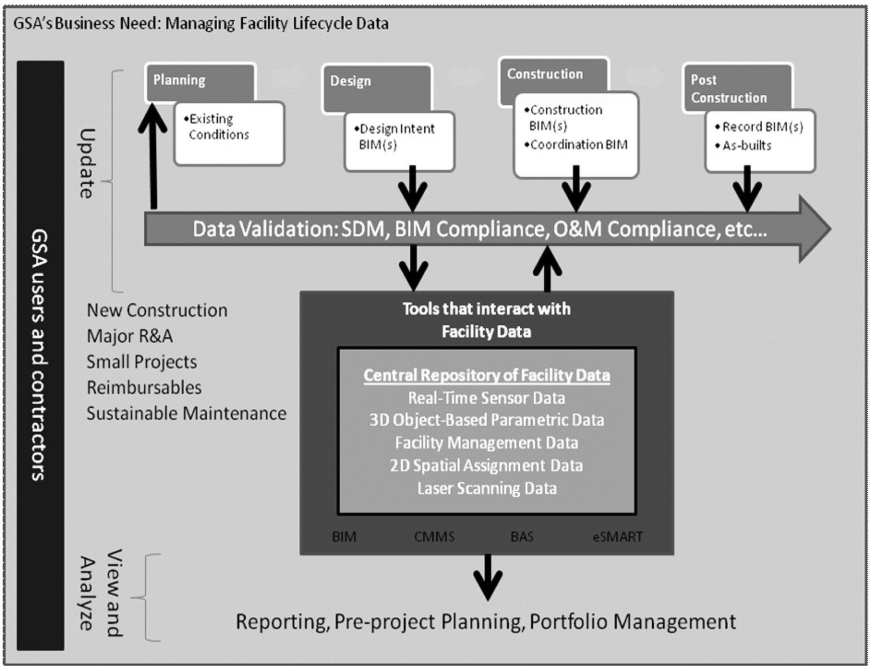


Figure 9-7. BIM vision for facility lifecycle information (GSA 2011).

- Determine when and by whom information is created,
- A/E requirements – BIM and COBie deliverables,
- Contractor requirements,
- Monitoring compliance and submittals for quality assurance.

3. *Modeling Requirements*: This section specifies the minimum 3d modeling requirements and information in a COBie format specified by GSA. The recommendations include:
   - High-level modeling requirements:
     - Use of IFC compliant BIM authoring applications,
     - Model containment hierarchy defined by the BIM authoring tool,
     - An asset identification number in addition to a GUID.
   - Design, construction and record BIMs: At the end of construction, multiple building-system specific construction BIMs are produced. GSA recommends certain modeling best practices that will be useful for comparing at project checkpoints the progress on the constructed building versus the virtual building. These recommendations include:
     - Specified list of required BIM objects and their properties,
     - National equipment standard (under development),

    - Organization of the model by floors and systems,
    - System of measure for new projects and renovations,
    - Prior to submittal check for list of BIM objects and properties specified by GSA, a record BIM for each floor saved in the native format and as IFC's,
    - Maintaining and updating as-built BIMs: GSA has established internal workflows to identify what information needs to be maintained in a BIM versus an external database and how they must be updated to present an accurate snapshot of the facility at any given time.
  - COBie Submittals: According to this document, not all attribute information is necessary to be captured in a BIM. But the required information must be transferred via COBie compliant files. GSA has prescribed the use of COBie because it maximizes the chances of getting accurate and relevant information since it is being created by its author. Project teams are asked to mention in their BIM execution plans how they will comply with the COBie requirements.
4. Technology Requirements:
   - Concept of a central repository of facility information,
   - Infrastructure to support technology and data,
   - Security of data,
   - Functionality at every phase,
   - Multi user updates, management of updates, multi user access and viewing and vendor neutral options. These are also the current challenges,
   - Use of 'model servers' in future to mitigate the above mentioned challenges and improve functionality.
5. *Pilot projects:* The pilot projects documented were in their early stages when the Guide was published. The book 'BIM for Facility Managers', published in May 2013 provides an updated review and status of the projects, summarized here in Table 9-1. This feedback was received through a structured interview and provides some useful first-hand experience about using BIM and COBie for FM.

The responses validate the hypothesis that while technology is crucial, it is the definition, accuracy and appropriateness of the information, which is the guiding factor for a successful BIM-FM integration.

COMMISSIONING (Cx)

Building commissioning is defined as the process of documenting and verifying that the project's energy-related systems are planned, designed, installed, tested, operated, and maintained to meet the Owners Project Requirements (OPR). The BIM-Cx process acts as the bridge for transferring the gains of BIM in the

Table 9-1. Feedback from GSA implemented pilot projects reproduced from 'BIM for Facility Managers' (Adapted from Teicholz 2013).

	Federal building modernization, NJ	*Federal building replacement of HVAC & MEP systems, MN*	*Integration of BIM, CMMS & BAS into a single system, NASA*
Type of data collected	COBie	COBie	Spatial programming, facility, construction & commissioning phase
Data requirement specification	Added by modification to original Design-Build contract	Contract language generic and vague	Specified in the contract
BIM use for FM data	BIM not used by designer, BIM-FM requirement added by modification	BIM used as a supplement to AutoCAD	BIM used for documenting existing conditions
FM staff involvement	During design & while creating BIM-FM specifications	During design but found no benefits and lost interest	During project planning
Data (COBie) collection method during projects lifecycle	Vela Systems (now BIM360 glue) for construction field data, customized spreadsheet for subcontractor information and Onuma Planning System for data verification	General Contractor coordinated with subcontractor for data collection	CMMS system and inventory spreadsheet
Challenges faced	• Determining what data was truly important to the building maintenance staff. • Data collection was labor intensive	• Unfamiliarity of AEC firms with COBie caused confusion, misdirection and incorrect interpretation • Need of a clear definition of what the FM data entails at each phase	• Lack of understanding of BIM use by FM • Lack of understanding of FM standard practices and workflows • Lack of trust in unproven technologies

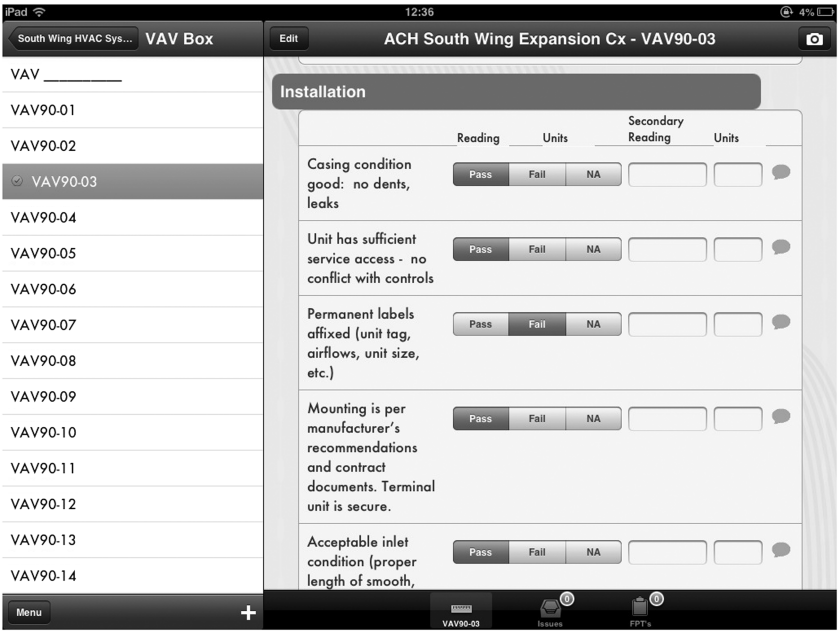


Figure 9-8. Commissioning on mobile tablets (TME 2013, unpublished).

AEC industry to the FM industry. The BIM-Cx-FM process works to ensure that the OPR and the design teams Basis of Design are updated throughout the design process. Onsite field verification using BIM and commissioning (Figure 9-8) principles complement the accrual of accurate data that is needed for FM and energy conservation and generate tremendous savings over the life cycle. Most commissioning projects apply the LEED-Cx standards. Ensuring design and construction team's awareness and compliance with indoor air quality requirements, comfort assurance standards, energy measurement-verification standards and controllability of systems standards helps accomplish the project goals.

Coordinating the BIM-Cx-FM process establishes a communication flow helping manage the project in an efficient manner. This communication flow should be part of the BIM-FM database so that work is not duplicated. The use of early and effective communication of the scheduling requirements for commissioning activities is critical to project success. The approach is summarized below:

1. The early development and review of the following detailed documents is critical in communicating the BIM process for the project schedule requirements. Completing this effort early, along with conducting an early commissioning kickoff meeting, helps integrate commissioning into the overall BIM-FM project delivery. These include:

  - Detailed commissioning specifications that outline the roles and responsibilities of each team member,
  - Detailed testing and balancing specifications that outline the role of the contractor in the commissioning process,
  - Detailed commissioning plan to enhance the team member assignments.
  - Commissioning issue logs are published throughout the project to track the level of completion of all commissioning activities. The issue logs serve as an on-going reminder of all outstanding commissioning items that need to be completed and the dates by which they need to be completed.
2. The commissioning agent must ensure that commissioning activities do not impact the critical path of the project.
3. The commissioning agent should use the BIM-FM process to frequently attend project meetings in an effort to communicate commissioning scheduling activities, outstanding commissioning issues, and to develop team dynamics.
4. Certain commissioning activities are completed post-occupancy. The mindset that all commissioning activities have to be completed prior to owner occupancy, can be avoided through proper communication.

The best practices published by National Environmental Balancing Bureau (NEBB) include detailed requirements for on-site commissioning:

- *On-site commissioning team*: The level of involvement during construction and familiarity with building equipment, systems and BIM deliverable, provides the team with the best opportunity to obtain owner buy-in regarding facility operations, contractor buy-in regarding commissioning value and design team buy-in regarding appropriate application of design concepts.
- *Detailed documentation focusing on life cycle management*: The BIM-FM commissioning process should set the tone for project documentation by documenting all meeting notes, project observation reports, testing results, review comments, issue logs, schedule requirements, action items, etc. Further, the commissioning agent must work ensure proper documentation of owner training, operations and maintenance manuals, and as-built BIM deliverable data.
- *Transparency*: The BIM-FM commissioning process achieves transparency by immediately reviewing the work that has been completed to date, providing the commissioning work products in a timely manner.
- *The Commissioning Plan*: Only after an initial review of design documents and the BIM deliverable, development of the detailed project-commissioning plan must be initiated. The plan developed will include significant details on the commissioning process, specific commissioning project assignments, sample pre-functional checklists for review, sample functional performance testing procedures for review, typical project

observation reports, typical issues logs, typical meeting notes, as well as a detailed list of activities to be performed by all commissioning team members beyond building occupancy.

- *Meetings*: Upon selection, the commissioning agent should immediately schedule a meeting with the owner, design team, and contractors to review activities included in the current design documents. These meetings will also focus on any potential issues that could have an impact on the BIM-FM commissioning process.

The BIM-FM commissioning process should key on achieving transparency and focus on team building with all project team members. Team building success is predicated on trust and common vision. The relationship between BIM-FM commissioning process and the construction process should be focused on the accrual of accurate data so that the owner can begin maintaining a building before it is occupied.

IMPLEMENTATION OF ADVANCED TECHNOLOGIES WITH BIM

BIM is an evolving technology. While BIM provides the data repository, a broader integration of technology supports field applications of FM functions. This section will describe some of the applications of emerging technologies for FM using BIM as the information backbone.

Cloud Hosting and Computing

Cloud-Computing is a solution for binding all heterogeneous applications through a central repository platform. In computer science it refers to any distributed computing over a network. It essentially works as a virtual server with the hardware and software hosted at a remote datacenter. Other than providing an enormous amount of space for storing data, a shared platform also reduces the investment in infrastructure that would have normally accrued in response to the fast changing technology and the increasing use of multiple applications. Privacy and security of data are concerns with the cloud that are being actively researched by various organizations in computer science. From a BIM perspective, the cloud platform lets the non-programmer easily access and exchange information using a BIM authoring tool (Redmond et al. 2012).

FM Dashboards

FM-Dashboards are decision making tools that provide a consolidated view of all the information regarding a facilities current condition in a single location (see Figure 9-9). It can display real-time updates about the health of the facility by reading sensor information from the BAS and EMS systems. Depending on the complexity of the database that it feeds into, varied information including

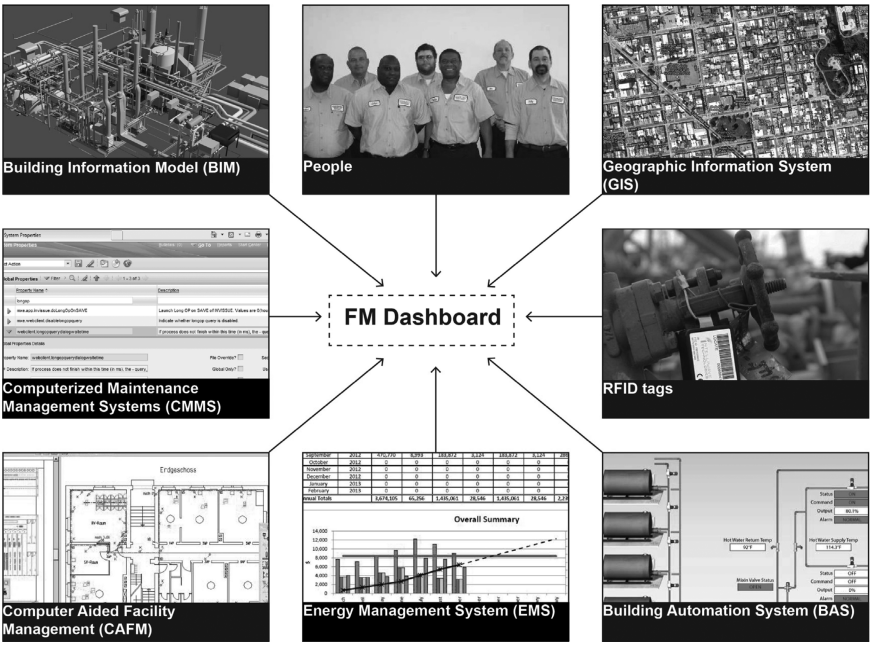


Figure 9-9. Information feeding in to a FM Dashboard.

performance data, historical data and operating parameters can be displayed. Dashboards simplify the operations of complex systems by keeping the programming at the back end. What is seen is the data. It is an effective tool for communicating the facilities condition to staff and upper management. It also improves the productivity of maintenance staff by giving them access to complete and continuous information, aiding in the process of decision-making. Some dashboards are also programmed to provide maintenance staff with suggested modifications based on historical trends and decision support.

RFID Technologies

Radio Frequency Identification (RFID) is a "wireless non-contact sensor technology based on detection of electromagnetic signals" (Domdouzis et al. 2007). The system consists of three parts; antenna for transmitting signals, a transceiver for data acquisition and a transponder or a tag. The antenna produces radio signals to establish communication between the transceiver (scanning device) and transponder (tagged object). The antenna is packaged with the transceiver and together they can be attached to a mobile device. The transponder must be attached to the equipment or material. The user is able to access information about the tagged object from a database via the internet in real time (see Figure 9-10) (Ko 2009). RFID tags can be Read-Only i.e. no data

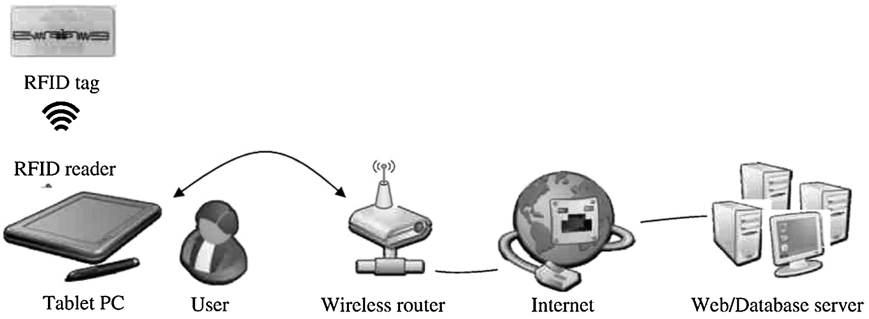


Figure 9-10. System application architecture (Ko 2009).

storage capability or Read/Write i.e. data storage capacity from 256KB to 3MB. The difference between RFID and Bar Codes, apart from their size, is that "RFID can dynamically transmit and receive information to help identify objects without line-of-sight whereas for a bar-code, labels must be positioned so that they can be detected and identified by a laser scanner" (Ko 2009). Hence, RFID tags tend to be more rugged, reusable and can be read dynamically from larger distances.

Most apparent use of this technology is for asset tracking; hidden or otherwise. BIM data can be accessed and displayed on a mobile hand held device automatically when the person with the transceiver is in range. The benefits of this technology for maintenance are far reaching, because of its high utility value. Some of it advantages include (Ko 2009):

- Operational time is saved as the automatic identification of equipment ID eliminates human error,
- Non-contact and non-line-of-sight RFID technology enhances maintenance convenience behind walls, ceilings, floors and objects,
- RFID technology cooperates extensively with other information technologies.

Hyperlinking Information

The importance of the 'I' in BIM has been repeatedly stressed upon. Easy access to information is the essence of a successful BIM-FM integration. Data rich parametric 3d models often lead to large file sizes and have either too much, too less or irrelevant information for a technicians daily use. Moreover, pertinent information such as equipment cut-sheets, previous work orders, submittals, warranty information etc. may not be included as an attribute in the original handover model and in some cases the required information may not even exist at the time of handover. Also, for a technician to access a model in a BIM authoring environment requires proper training to use the program and a sophisticated hardware system to support its use. Such a workflow is not only time consuming but unnecessary, as the objective is not to edit the file but to

access the information embedded in it within the context of the 3d visual capabilities of the model.

The popular method is the use of location based FM documents in PDF format hyperlinked from a facility information database to a lighter version of the 3D model. This is generally capable of being viewed on a hand held device such as an iPad®. Converting the parametric model to a surface geometry for easy viewing reduces the file sizes. The embedded metadata is nevertheless preserved and is available to view when the object is selected. Web browsers and PDF documents can also be linked to the geometry of the model. Combined with interior GPS and RFID tags, the model can be opened in its exact location and subsequently provide the additional functions of link to ancillary maintenance information. Such solutions are popular for providing field access to valuable enterprise information; work order data, training videos, and parts information. They also include enhanced features that support annotation and markup features and RFI and task creation (Sabol 2013).

Augmented Reality

Augmented Reality (AR) is a technology that creates an enhanced environment by superimposing computer-generated information onto the users real-life view. Several AR apps are available to download for most Android and iOS devices. Some of the AR apps include; *Yelp Monocole*, which superimposes customer ratings over a live view of the establishments; *Wikitude World Browser* pulls up a Wikipedia entry for a building on a smartphone when the phone camera is aimed at it; *Google SkyMap* uses GPS and compass data to display names of celestial bodies just by pointing the phone to the sky. These are very few amongst the many applications of AR in education, gaming, social networking, design, manufacturing and entertainment (Chi et al. 2013). More recently ubiquitous computing has been further exemplified with Google's Project Glass that utilizes an AR Head Mounted Display (HMD) to create an immersive environment layering information from a smartphone on the user's field of vision. Integration with location-based technologies like RFID, GPS and sensors enables AR technology to be localized and 'context-aware' substantiating their use in the field for construction and maintenance (Chi et al. 2013).

According to Lee and Akin (2011) AR technology promises to be one of the most suitable interfaces for O&M, as it is able to resolve the challenges posed in interpreting 2D drawings by superimposing the 3D geometry and information on real life objects. This reduces the time taken by the user in locating and identifying an object such as a piece of equipment and also provides access to information from a database, while in the field. To reduce inefficiencies in the detection and diagnosis of problems in the field, Lee and Akin conducted a research that makes use of an AR-based Fieldwork Facilitator. They found that it took the same personnel 51% less time when locating information using their AR prototype than the conventional process.

CHALLENGES

The potential value of BIM has grown significantly in the last 40 years with 71% of the AEC industry adopting some form of BIM, a growth from 28% in 2007 and 49% in 2009. According to the 2012 SmartMarket Report by Mcgraw-Hill, 47% of contractors using BIM saw a moderately positive (up to 25%) Return on Investment (McGraw-Hill 2012). They experienced added value through reduced rework, marketing new business and maintaining them, early detection of coordination errors and reduced project duration. It was also theorized that the adoption rate of BIM would increase further and faster if owners demand it. For an owner, the challenge is in bringing together the pieces of a fragmented industry and convincingly investing in a technology with a future benefit over established and tested traditional processes. While contractors have evidenced a reciprocal benefit of BIM use with its rapid adoption in the AEC community, the FM industry has yet to experience any significant benefits. BIM-FM integration has been marred by the absence of validation aligning with organizational objectives, fear for change and a slow adaptation to technology and interoperability issues characteristic of the fragmented industry. This section discusses the challenges faced under the three broad categories of – Organizational Goals, People and Technology.

Organizational Goals

Organization level goals, philosophies and practices are deciding factors that influence the workflows and styles of management within the departments. Adapting BIM to the existing work methods requires investment in software, hardware, new talent and training. Even after this initial expense, there is a steep learning curve for those comfortable using their traditional methods. The successful integration of BIM-FM is a lot dependent on proving its value to the organization and its subsequent adoption in the culture of the workplace.

ROI for BIM-FM

There are not enough metrics to support a definite calculation of the Return on Investment in BIM-FM integration. However, some conservative estimates can be made based on the identified benefits. In the book 'BIM for Facility Managers', it is estimated that the ROI in BIM-FM integration for a 400,000 SF Office building with useful life of 25 years is 64% with a payback period of 1.56 years (Teicholz 2013). This is based on rough calculations with data obtained from a 2009 IFMA Survey of maintenance data. Some of the assumptions made in the calculations are:

- Calculations are for a new construction with FM data captured during design and construction,
- 1 FTE will spend 25% of time to maintain and update the integrated system,

- Initial investment to create an integrated system including systems investment, data collection and verification will be roughly $100,000,
- Better access to accurate information will save 30 minutes per work order, (A separate research by Sandia National Labs estimates 2 hours saved per work order when information is easily accessible)
- Improved maintenance and performance of equipment will reduce energy costs by at least 3%.

For existing facilities, the calculations to estimate the ROI will change significantly. It will have to include initial costs for surveying, as-built modeling, updated changes to the model, legacy data integration and installation of RFID tags. In that case, the critical variables would be the current condition of the existing facility and its relative age compared to the total lifecycle.

Culture of the Workplace

According to Bryson and Yetmen (2010), "construction is the only trillion-dollar industry in the history of the world in which clients routinely demand the most inefficient processes creating the least value". The fragmented culture of the AEC industry is well known. The situation is exaggerated in the FM domain because of the wide array of functions involving professionals and trades from many different specialty fields. Hence, FM professionals are usually a diverse group, coming from different industries with various levels of education and cutting across all levels of management (IFMA 2013). To bring efficiency in this diversity requires a leadership structure, led by the owner that can create an environment for collaboration, innovation and knowledge building (Bryson and Yetmen 2010). The BIM process poses a different challenge of retraining existing skills and cultures to think outside of their own specialty field and consider the actions and functions of other fields as well. A culture of collaboration is essential for the successful adaptation of BIM.

People

The changing technology requires people to be well versed with computers along with possessing a good knowledge of building systems, equipment's and business processes. Some computer applications have a steep learning curve, which can be daunting for those who are not proficient with computers. Regular workforce training thus becomes necessary for every organization. To keep up with this flux, academic institutions are now starting to provide dedicated degree programs in FM and related fields to train the future workforce.

Technology

Interoperability and a central information system; are the two pertinent technological requirements and also the biggest challenges at the moment. The reason for using BIM as a vehicle is to support "synchronization of information across applications to speed up workflows and enable decision support" (Redmond et al.

2012). The BIM to IFC conversion has allowed interoperability across many commercially used authoring tools, but the workflow is still not defined. The traditional BIM workflow requires information to be exported from one application and imported into another application, adding redundancy to the data. The envisioned solution is in the form of a Service Oriented Architecture, which enables data to remain in one application, and allowed access by another application allowing model views to be shared in small data chunks (Onuma 2010). A few other areas that require attention are:

Legacy Systems

As of 2010, US had a total building stock of approximately 275 billion square feet, with statistics showing an addition of 5 billion square feet per year of new construction and an equal amount of renovations per year. Renovations pose a challenge for BIM integration as it is often found that current condition is far from the as-built since the drawings were never updated during that time. Equipments are replaced, entire wings are renovated but the information is not updated. Such situations are seen even more in facilities transitioning from paper to digital. Laser Scanning is required in such cases to identify current conditions and to update drawings. While modeling is achievable, the integration of facility information is a painstaking manual task as most legacy systems are not compatible with new systems.

Bi-directional Flow of Information

Facility Managers not only require access to information, they also need to update the information. Web based FM servers provide easy access to a light version of the model allowing technicians to find their way around the 3D geometry with ease. They also allow updating the information to the database. However, technology at present does not support parametrically updating the geometry in the model without routing through the original authoring tool.

CONCLUSION

"There is no universal approach to managing facilities. Each organization even within the same sector will have different needs. Understanding those needs is the key to effective facilities management measured in terms of providing best value" (Atkin 2009).

The day-to-day management of the facility, including the operations and maintenance, are guided in part by the philosophies of the owner organization and by the contextual relationship of its physical setting. The job of the Facility Management team is to operate the building for its lifecycle, making sure it is performing to its designed intent, saving energy and creating value for the owner. Over the lifecycle of the project, a variety of facility information is created and developed. Even after occupancy, information is continually updated and new information is created that affects future developments. To

do their jobs effectively, the FM team requires easy access to up to date and accurate facility information for making informed decisions. Thus, information which is accumulated and transformed through the projects lifecycle, from design through construction; whether physical, computational, social or cognitive; are important factors affecting the decisions made during operation, maintenance and management of a facility. The pre-occupancy facility data is compounded with the information created during occupancy, creating a vast body of knowledge. This when used to its advantage can provide valuable information to the FM team, contributing to their overall performance while providing cost savings.

As shown in this chapter, a Building Information Model serves as a robust database for facility information, which when used in conjunction with advanced technologies provides a promising platform for FM. BIM has the potential of significantly impacting the owners ROI by simulating activities during the design and construction phases; predicting operations, reducing risk and providing the ability for financial forecasting (McGraw-Hill 2012). Being a relatively new field, there are several unanswered questions, hurdles and unexplored avenues in the BIM-FM domain. The primary objective of this chapter was to familiarize the reader with the established standards and current technologies being used in the industry. A few other research areas to add to the current body of knowledge are outlined here:

- BIM Execution Plans for facilities management, maintenance and operations
- Incorporating legacy data into the future BIM-FM system
- Revised contractual requirements and delivery processes, specifically the legal aspects of BIM-FM
- Remotely controlling building systems or Virtual FM
- Bi-directional flow of information including parametrically updating the geometric data in BIM with changes reflected in FM or the Living BIM
- Increased interoperability between BIM authoring tools and FM systems
- The vision for a self-repairing self-maintaining intelligent building

References

Anderson, A., Marsters, A., Dossick, C., and Neff, G. (2012). "Construction to Operations Exchange: Challenges of Implementing COBie and BIM in a Large Owner Organization." *Proc., Construction Research Congress*, 688–697.

Akcamete, A., Akinci, B., and Garrett, J. H., Jr. (2010). "Potential utilization of building information models for planning maintenance activities." *Proceedings of the International Conference on Computing in Building and Civil Engineering*, Tizani, W. (Ed.), Nottingham University Press, University of Nottingham, UK.

Atkin, B. (2009). *Total facilities management* (3rd ed.). United Kingdom: Wiley-Blackwell.

Becerik-Gerber, B., Jazizadeh, F., Li, N., and Calis, G. (2012). "Application areas and data requirements for BIM-enabled facilities management." *Journal of Construction Engineering and Management*, 138, 431–442.

Bryson, B. W. and Yetmen, C. (2010). The Owner's Dilemma: Driving Success and Innovation in the Design and Construction Industry. Greenway Communications, 1st ed..

Chi, H. L., Kang, S. C., and Wang, X. (2013). "Research trends and opportunities of augmented reality applications in architecture, engineering, and construction." *J. Automation in Construction*, 33, 116–122.

Computer Integrated Construction Research Program. (2012). *BIM Planning Guide for Facility Owners. Version 1.01, May*, The Pennsylvania State University, University Park, PA, USA.

Cotts, D. G., Roper, K. O., and Payant, R. (2009). *The Facility Management Handbook*, (3rd ed.) New York, AMACOM Publishing.

De Toni, A. F., Fornasier, A., and Nonino, F. (2012). "Organizational Models for Non-Core Processes Management: A Classification Framework." *International Journal of Engineering Business Management*, 4, 1. doi:10.5772/55182.

Domdouzis, K., Kumar, B., and Anumba, C. (2007). "Radio-Frequency Identification (RFID) applications: A brief introduction." *J. Advanced Engineering Informatics*, 21 (4), 350–355.

East, E. W. (2014, March 3). *Construction Operations Building Information Exchange (COBie)*. Retrieved from http://www.wbdg.org/resources/cobie.php#

East, E. W. (2013). "Using COBie." In P. Teicholz (Ed.), *BIM for Facility Managers* (1st ed.). Hoboken, New Jersey: IFMA Foundation, John Wiley & Sons, Inc.

Enck, H. J. (2009). "The Owners Project Requirements and where it fits in the Design Process." *17th National Conference on Building Commissioning*, Seattle, 1–10.

Fallon, K. K. and Palmer, M. E. (2007). *General Buildings Information Handover Guide: Principles, Methodology and Case Studies (NISTIR 7417)*. National Institute of Standards and Technology, US Department of Commerce, Gaithersburg, Maryland.

Foster, B. (2012). "Using Real-Time CMMS Asset Data Capture during Construction to Improve Facility Management." *Journal of Building Information Modeling Fall 2012*, 16–17.

Gallaher, M. P., Connor, A. C., Dettbarn, J. L., and Gilday, L. T. (2004). *Cost Analysis of Inadequate Interoperability in the US Capital Facilities Industry*. National Institute of Standards and Technology, US Department of Commerce, Gaithersburg, Maryland.

General Services Administration. (2011). *GSA BIM Guide for Facility Management*. Washington DC. Retrieved from http://www.gsa.gov/bim.

Goedert, J. D. and Meadati, P. (2008). "Integrating Construction Process Documentation into Building Information Modeling." *Journal of Construction Engineering and Management*, 134(7), 509–516.

Guo, H. L., Li, Heng, and Skitmore, Martin (2010). "Life-cycle management of construction projects based on virtual prototyping technology." *Journal of Management in Engineering*, 26(1), 41–47.

IFMA. (2013). "What is Facility Management?" *IFMA International Facility Management Association*. Retrieved from http://ifma.org/about/about-ifma.

Ko, C. H. (2009). "RFID-based Building Maintenance System." *J. Automation in Construction*, 18, 275–284.

Lee, S. and Akin, O. (2011). "Augmented reality-based computational fieldwork support for equipment operations and maintenance." *J. Automation in Construction*, 20, 338-352, doi:10.1016/j.autcon.2010.11.004.

Lewis, B. T. and Payant, R. P. (2007). *Facility Managers Maintenance Handbook*, McGraw Hill Professional Publishing.

Lucas, J., Bulbul, T., and Thabet, W. (2012). "A Pilot model for a Proof of Concept Healthcare Facility Information Management Prototype." *Journal of Information Technology in Construction (ITcon)*, 18, 76–98.

McGraw-Hill. (2012). SmartMarket Report: The Business Value of BIM in North America SmartMarket Report.

NIBS. (2012). National BIM standard-united states Version2, an initiative of the national institute of building sciences buildingSMART alliance. Retrieved from http://www.nationalbimstandard.org/.

Onuma, K. (2010). "Location, location, location, BIM, BIM, BIM." *Journal of Building Information modeling*, Fall 2010, 21–22.

Redmond, A., Hore, A., Alshawi, M., and West, R. (2012). "Exploring how information exchanges can be enhanced through Cloud BIM." *J. Automation in Construction*, 24, 175–183.

Sabol, L. (2013). "BIM technology for FM." In P. Teicholz (Ed.), *BIM for Facility Managers* (1st ed.). Hoboken, New Jersey: IFMA Foundation, John Wiley & Sons, Inc.

Shear, M. A. (1983). *Handbook of Building Maintenance Management*, Virginia, Reston Publishing Company, Inc.

Teicholz, P. (2013). "Owner BIM for FM guidelines." In P. Teicholz (Ed.), *BIM for Facility Managers* (1st ed.). Hoboken, New Jersey: IFMA Foundation, John Wiley & Sons, Inc.

Theriault, M., (2010). *Managing Facilities and Real Estate: 50 strategies, approaches and leading practices*, Woodstone Press, Toronto, Canada.

Watson, J. R. and Watson, R. (2011). "Computer-Aided Facilities Management (CAFM)." Whole Building Design Guide, <http://www.wbdg.org/om/cafm.php> (March 15 2013).

Bibliography

Clayton, M. J., Johnson, R. E., and Song, Y. (1999). "Operations Documents : Addressing The Information Needs Of Facility Managers." *Durability of Building Materials and Components*, 8, 2441–2451.

Hao, Q., Xue, Y., Shen, W., Jones, B., and Zhu, J. (2010). "A Decision Support System for Integrating Corrective Maintenance, Preventive Maintenance and Condition-based Maintenance." *Proc., Construction Research Congress 2010, 470–479.*

Krukowski, A. and Arsenijevic, D. (2010). "RFID-Based positioning for building management systems." *Proceedings in the 2010 IEEE International Symposium on Circuits and Systems (ISCAS), IEEE*, Piscataway, NJ.

Shohet, I. M. and Lavy, S. (2004). "Healthcare facilities management: state of the art review" *Facilities, 22(7/8), 210-220*. Emerald Group Publishing Limited,

Whyte, J., Lindkvist, C., and Hassan Ibrahim, N. (2010). *Value to Clients through Data Hand-Over: A Pilot Study*, Summary Report to Institution of Civil Engineers (ICE) Information Systems (IS) Panel, [v1.1].

This page intentionally left blank

CHAPTER 10

BIM Use and Requirements Among Building Owners

Brittany K. Giel*
Glenda Mayo†
Raja R. A. Issa, F.ASCE‡

Abstract: *The belief that Building Information Modeling (BIM) results in fewer conflicts and improved coordination has led many owners to mandate its utilization on new construction projects. However, owners are often unsure of what BIM deliverables and processes to demand and how proficient the entities they choose to contract with are in using such technologies. Furthermore, though owners are working to operationalize BIM for Facilities Management (FM) to obtain the full life cycle benefits, they may still lack the technical resources and core competencies to utilize models post-construction.*

The state of BIM deployment and execution among building owner organizations within the US is in its infancy. Using a survey consisting of primarily higher education building owners conducted at the end of 2012, this study looks at the state of BIM execution among facility owners. It aims to determine what requirements are being set forth for BIM deliverables and how those deliverables are being used post-construction for Operations and Maintenance (O&M) in the current market.

INTRODUCTION

Motivated by the perception that Building Information Modeling (BIM) may result in more successful project outcomes, many facility owners are now requiring that BIM be utilized on their construction projects. However, utilizing

*Virtual Design and Construction Engineer at the Whiting-Turner Contracting Company, 300 E. Joppa Rd Baltimore, MD 21204; email: brittany.giel@whiting-turner.com

†Ph.D. Candidate, M.E. Rinker School of Building Construction, Univ. of Florida, Gainesville, FL 32611-5703; email: gmayo9703@ufl.edu

‡UF Research Foundation and Holland Professor and Director of Center for Advanced Construction Information Modeling, M.E. Rinker, Sr. School of Building Construction, Univ. of Florida, Gainesville, FL 32611-5703; e-mail: raymond-issa@ufl.edu

BIM post-construction has posed many challenges which include a lack of understanding of the potential benefits as well as how to balance multiple resources, options and stakeholders in BIM planning efforts. BIM implementation by owners appears to be in its early stages. However, similar to users in the design and construction areas, it may take some time for owners to fully explore the operational changes and improvements needed to encourage the life-cycle use of models. Furthermore, benchmarking with other owners has been proven to be problematic, as these organizations are diverse in terms of size, support and operational functions. Hence, the purpose of this research is to determine the obstacles to owners operationalizing building information models and their attribute data post-construction.

BACKGROUND

BIM Adoption by Building Owners

The publication of several industry surveys since 2005 (FMI Corporation 2007; McGraw-Hill Construction 2008, 2009, and 2012; Forns-Samso 2010; Becerik-Gerber et al. 2012; I²SL et al. 2013) have indicated that the adoption of BIM by building owner organizations is gaining momentum. In a Smart Market survey conducted by McGraw-Hill Construction (2012), 30% of owners surveyed indicated that they were using BIM on more than 60% of their projects. It was also predicted that by 2014 the proportion of BIM use by owners would increase by 14%. The term "use" however should be delineated by phase when attempting to categorize it. More than 50% of those owners surveyed indicated their BIM expertise level to be that of beginners; viewing their role to be consumers of end products of BIM processes rather than users (McGraw-Hill Construction 2012).

These results reinforce earlier survey findings. For example, in the 2009 Smart Market Survey, when asked which phases of a project's life reaped the greatest value from utilizing BIM, industry respondents indicated closeout/commissioning and Operations and Maintenance (O&M) to be of the least value; suggesting that owners had yet to realize the potential benefits of using models post-construction at that time (McGraw-Hill Construction 2009).

Forns-Samso (2010) studied the perceived value of using BIM in O&M by FM personnel through a national survey as well. Using the Chi-Square test for independence, he found a significant relationship between whether BIM was being used by owner organizations for design and construction and the respondents' predicted future use of BIM for O&M ($p = 0.013 < \alpha = 0.05$). There was also an association found between the size of facilities being managed and whether BIM was being utilized ($p = 0.029 < \alpha = 0.05$).

Also in 2010, Becerik-Gerber et al. (2012) conducted an online survey of facility owners and managers to determine the extent of BIM implementation

within Facilities Management (FM). At that time, the highest response rates were from educational institutions and government agencies representing 53% and 13% of their sample respectively. Thirty-two percent of the 77 respondents indicated that their organizations used BIM. When asked in which project phases BIM was used, 83% indicated using it for design, 79% indicated using it for construction and 42% were implementing BIM in the O&M stage (Becerik-Gerber et al. 2012).

Finally, in 2012, the International Institute for Sustainable Laboratories (I^2SL), the building Smart Alliance (bSa), and the International Facility Management Association (IFMA) Research and Development Council (2013) piloted a national survey on BIM for FM as well. In this survey, the highest response rates were from architects, representing 35% (63) of the respondents. Owners and facility managers followed with 29 and 28 respondents respectively. Similar to the Becerik-Gerber et al. (2012) and the McGraw Hill Construction (2012) findings, 34.8% (56) of the respondents indicated that they were using BIM on all new projects. In that study, 13.3% (18) of the respondents indicated that their organizations used BIM for FM. Additionally, 69.9% (94) of the respondents felt the further pursuit of BIM use in O&M and FM to be of value.

Although there has been increased BIM adoption by building owners, the utilization of models during O&M is falling behind design and construction applications; despite the fact that there may be more to gain from the outcome (Akcamete et al. 2010). More specifically, in the university facility segment of owners, the adoption of BIM is currently dependent upon efforts to understand not only the software applications, but also the contract and what to outline in terms of deliverables. A portion of the difficulties experienced by owners is a qualitative issue, requiring a cultural change to make an effective improvement in the way that industry has been providing deliverables. This change requires a combination of technology and strategy. Although owners understand that they are driving this request, many lack expertise and knowledge of BIM applications and must rely somewhat on consulting partners (Reilly 2010). Consultants may help where technology expertise is required, but the strategic planning must be a contribution of the owner since owners have their own specific needs.

Potential Benefits of BIM to Owners

The top rated benefits of utilizing BIM as expressed by the building owners surveyed in the 2012 Smart Market report included a reduction in document errors and omissions, reduced rework, reduced construction cost, reduced construction duration and fewer claims and litigation. Additionally, owners surveyed also indicated that more clearly defined BIM deliverables between partners, was the single most important factor contributing to the increase in the benefits derived from BIM (McGraw-Hill Construction 2012). However, relatively few owners are engaged in BIM use during operations at high levels, specifically for the purposes of FM (Becerick and Rice 2010; McGraw-Hill Construction 2012). Table 10-1 shows the proportion of owners who responded to frequently using BIM for O&M and FM processes as indicated by the 2012 Smart Market Survey.

Table 10-1. Percentage of owners using BIM for FM processes (n = 36) [Adapted from McGraw-Hill Construction 2012]

FM Use	*Percentage of Owners*
Building System Operating Analysis	32%
Maintenance Scheduling	24%
Asset Management	24%
Space Management and Tracking	24%
Building Performance Against Specified Design	18%

These results were based on a sample of 36 owners (6.2% of all responses) who completed the survey.

Several researchers have explored the specific applications of BIM for FM. Kreider (2012) outlined a categorical view of 25 specific BIM uses and then conducted a survey to identify the frequency of use and perceived level of benefit. A low response rate was received from owners (4% from the sample of those downloading the BIM Project Execution Planning Guide); thus, possibly representing the segment of users just beginning the BIM process (CIC Research Program 2009). As an indication of the possibilities for BIM in FM, Kreider (2012), Autodesk (2012), FM: Systems (2012) and Becerik-Gerber et al. (2012) have listed possible uses for the technology and information, as summarized in Table 10-2. The consistent uses include record modelling, space management, asset management, preventative maintenance scheduling, and energy management.

Owners will potentially benefit the most from using BIM out of all stakeholders through the use of the facility model and its embedded knowledge of the facility's life cycle (GSA 2006). Often, the same information is viewed at the time of specification, purchase, installation, and lastly when creating a handover file.

The digital collection of important information throughout the process has already shown potential savings and has become much easier as project delivery has migrated from hard bid to a more collaborative process. Newer delivery methods are allowing for the information to be captured and documented in the model. This reduces the redundant manual data entry effort required after the handover process for facilities personnel, especially since it allows for the automatic creation of equipment inventory lists which can populate the owner's computerized maintenance management system (CMMS). The reduction in effort is extremely beneficial at handover in reducing the requirement for manual entry of the documentation into another platform for facilities use (GSA 2011).

The Construction Operations Building information exchange (COBie) protocol, specified as part of the National BIM Standard, was created to facilitate electronic data transfer from BIM to FM systems in order to discourage the continued use of paper-based information at construction handover. The standard allows almost all BIM authoring tools to export data in an open standard format (IFC) to FM systems platforms. From 2008-2011, the COBie

Table 10-2. Research comparison of post-construction use of BIM

Kreider (2012)	*Autodesk Education Community (2012)*	*FM: Systems (2012)*	*Becerik-Gerber et al. (2012)**
Asset Management	Asset Management		Creating Digital Assets
Space Management & Tracking	Space Management & Tracking	Improved Space Management	Space Management
Building Maintenance Scheduling	Preventative Maintenance Scheduling	Streamlined Maintenance	
Disaster Planning	Disaster Planning & Response		Emergency Management
		Monitoring Energy Use	Controlling & Monitoring Energy
Record Modeling	Building Systems Analysis	Economical Retrofits & Renovations	Real-time Data Access
		Lifecycle Management	Checking Maintainability
			Personal training and development
			Locating Building Components

*Uses listed for design and construction have been removed in this table

Challenge event established benchmarks for software vendors to test the COBie importing capabilities of a variety of BIM authoring and CMMS software packages. Although there are still improvements to be made with commercial software packages, COBie has been incorporated into more than 20 different products (East 2013). The capability to utilize the COBie standard (and in multiple formats) gives owners a specific first step to operationalize the attribute information collected in the design and construction phases, especially if importing directly to a computer-aided facility management system (CAFM). Though the benefits have been well publicized, industry has been slow to adopt COBie. In fact, I^{2}SL et al. (2013) indicated that just over half of their survey respondents had even heard about COBie in 2012. This may also help explain the response that 65 (61%) of the 106 respondents indicated that they do not plan to require COBie on their projects.

The model also provides an improved means of space asset management and equipment maintenance to owners and FM personnel post construction. This is a significant improvement since space designations establish the platform for all information in energy management and CMMS systems. For space managers, BIM provides increased precision in terms of existing condition information. Now room designations and net assignable square footages (areas of a room assigned to an occupant or specific use) are automatically calculated in BIM authoring tools as opposed to the need in AutoCAD to create manual polylines for each space (GSA 2011). Sixty-one owners (43%) surveyed by I²SL et al. (2013) indicated using the model to extract area data for space management; signifying a promising use for BIM by space managers.

BIM Resource Trends Among Building Owners

To ensure that BIM deliverables are useful to facility managers post-construction, a number of owners have begun dictating specific requirements for BIM implementation. Many government agencies as well as private owners have developed BIM requirement guidelines, contractual addendums and standards to improve the quality of information handover.

Perhaps the most noteworthy has been the work of the General Services Administration (GSA). In 2003, the GSA's Public Building Services (PBS) office of chief architect established its "National 3D-4D BIM program", setting a goal to require BIM on all new projects undertaken in the 2006 fiscal year as a means for improving design and construction quality and delivery (Hagan et al. 2009). What followed in later years was the publication of eight BIM Guide Series covering a vast array of topics specific to GSA's detailed requirements on BIM-assisted projects (Yee et al. 2010).

Similarly, in 2006, the Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) published its own BIM roadmap outlining BIM implementation strategies for military construction and civil works projects with a primary goal to reduce project delivery time and costs and improve overall project quality (Brucker et al. 2006). The program was presented in a phased approach, designed to allow the strategic plan to be revised incrementally with time. The USACE later released its Minimum Modeling Matrix (M3) in September of 2012 to supplement these guidelines and outline the level of development required of models delivered on MILCON projects (McGraw-Hill Construction 2012).

The department of Veterans Affairs followed suite, publishing its VA BIM Guide in April of 2010. The guide includes 45 pages of the organization's life-cycle vision, implementation strategies, roles and responsibilities of different stakeholders, model sharing practices and requirements for using BIM as well as an in depth set of standards for model applications and paper deliverables (Department of Veterans Affairs 2010). Concurrently, the U.S. Air Force also began mandating BIM in 2009 with a requirement for BIM based designs on all future vertical construction projects. In 2011, they issued "Attachment F" which outlines the BIM requirements for Design-Build and Design-Bid-Build projects. Not only does the

document require that designs be produced in an IFC compatible BIM-authoring platform, but also that an execution/implementation plan be utilized which addresses BIM management procedures and how facility data will be captured in the as-built model (NIBS 2013).

In June of 2008, the AGC and ConsensusDOCS consortium drafted the *Consensus Docs 301: BIM addendum* to help aid in contract language and legal ramifications that may result from sharing the model between different stakeholders and the liability related to the model's completeness or accuracy. Shortly after, the AIA released its own *E202 BIM Protocols exhibit* to be used with design or construction contracts in which BIM is employed. One major difference between the two contractual addendums is that the AIA E202 references an extensive model element table which defines the level of development required for each modeling object; whereas, CD301 references an *external BIM execution plan* allowing project members to customize their contractual requirements to their own specific level of depth (Haynes 2009).

Amidst the increased publication of these master BIM guides, standards and contracts by larger building owner organizations, there have also been two major emerging trends. One has been the increased requirement for the informed use of a *project-specific* BIM execution plan (BEP) as referenced in CD301. The other has been the supplemental distribution of model progression specifications designed to establish the level of development (LOD) and responsible modeling party required for each object in the model during each life cycle phase of the building project. While some organizations have defined their own requirements for level of development, most BEPs reference definitions for LOD 100-500 from what is established in AIA E202, as shown in Table 10-3.

The AGC BIMForum (2013) released a proposed set of standards establishing a level of model completion for model elements at different stages during design and construction. The *Level of Development Specification's* intent is to outline specific expectations of the model from different disciplines. Thus, the ambiguity of the AIA's broad definitions may soon be alleviated (McGraw-Hill Construction 2012).

Also on the forefront of developing these BIM execution plans have been many higher education institutions. Indiana University published an organizational BIM Guidelines and Standards document in 2009 which was supplemented by three project-specific templates including an execution plan, an IPD methodology plan and a BIM proficiency matrix (Indiana University 2009). Shortly after IU issued these documents, Pennsylvania State University's Computer Integrated Construction (CIC) Research Program published its Project Execution Planning Guide in October of 2009. The guide outlines procedures for developing a detailed BIM execution plan to be customized by any project team wishing to implement BIM. It was the first of several references published in 2009 to synthesize the different categories of information suggested to be integrated in a BEP (CIC Research Group 2009). The BIM Project Execution Planning template and guide were so well received that they were formally included in chapter five of the NBIMs v2 publication in 2012. The documents have since been an adopted

Table 10-3. Model LOD descriptions [Adapted from CIC Research Program 2012]

Level of Development	*Description*
LOD 100: Schematic Design	Overall building massing indicative of area, height, volume, location, and orientation may be modeled in three dimensions or represented by other data.
LOD 200: Design Development	Model elements are modeled, as generalized systems or assemblies with approximate quantities, size, shape, location, and orientation. Non-geometric information may also be attached to Model elements.
LOD 300: Construction Documentation	Model elements are modeled as specific assemblies accurate in terms of quantity, size shape, location, and orientation. Non-geometric information may also be attached to model elements.
LOD 400: Construction	Model elements are modeled as specific assemblies that are accurate in terms of size, shape, location, quantity, and orientation with complete fabrication, assembly, and detailed information. Non-geometric information may be attached to model elements.
LOD 500: Record	Model elements are modeled as constructed assemblies actual and accurate in terms of size, shape, location, quantity, and orientation. Non-geometric information may also be attached to modeled elements.

requirement of owners like the USACE, the US Air Force, Penn States' own Physical Plant office and the Division of Capital Asset Management Commonwealth of Massachusetts (NIBS 2012).

The CIC Research Program also published a BIM planning guide specific to facility owners in 2012 with the intent to facilitate a standardized approach for the planning and execution of BIM by construction clients. The document outlines procedures for developing: an organizational strategic plan, an organizational BIM execution plan, and project procurement language which may determine and change traditional contracts (CIC Research Program 2012).

Perceived Difficulties for Operationalizing BIM by Owners

Despite the aforementioned and increased adoption, there are still many obstacles to owners operationalizing BIM. Most commonly, they may fall into one of the

common pitfalls outlined by Cotts et al. (2010), which includes the failure to define the needed documentation or deliverables required at handover. The failure in defining deliverables partly stems from obstacles of multiple stakeholders (thus multiple needs) and numerous options from the recommendations from guides and templates. According to the International Facility Management Association (IFMA), Facility Management is "a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, places, processes and technology" (Cotts et al. 2010, p.4). Therefore, the building owner cannot be defined as one person within the organization. When the term building owner is used, unfortunately, the tendency is to associate the term with one segment of the profession; however, the reality is that the owner can consist of a multitude of individuals, all of whom have a specialized interest in specific job duties as well as different needs from the information provided at handover. At minimum, owner organizations often encompass both the team of individuals acting as owners' representatives and project managers during project delivery on new facility projects *and* the many individuals acting as operators or facility managers for existing facilities. In many organizations, these two roles may be completely segregated in nature, which complicates the required collaboration to define deliverables.

The handover process has always been difficult for owners, in terms of the distribution of information. The transition from hard copies to electronic version was a marked improvement; however, the owner is still left with a substantial amount of information to be distributed to multiple stakeholders within their organization. Standardization is beginning to occur through the execution of COBie and IFC; however, owners continue to maintain information in many different formats including CAD, MS Word, MS Excel, PDF and additionally in GIS and BIM. This illustrates the struggles that they experience when beginning to utilize a new application, because integration and interoperability must flow from the files received to the format of those that need the information. Although the use of BIM as a repository for information is possible, owners are still in transition and continue to struggle with numerous file formats.

To operationalize BIM, the transfer of information from BIM to CMMS offers an advantage in the fact that the information needed by the owner, in many cases, can be provided in a non-graphical format which eliminates the need for the owner to immediately become proficient in BIM tools and obtain its useful benefits. For example, a spreadsheet identifying the building and room number of a pump to be maintained does not necessarily need to be in graphic format (East 2009). Owners, with just the need to define space continue to utilize additional steps through third party tools to enable all of the stakeholders to have access to the space files. The transfer of information to CMMS systems creates a challenge as well. There are many different FM applications so it is difficult for owners to benchmark with other organizations. Ahamed et al. (2010) identified 15 different FM/CMMS software applications. Not only is this problematic for user groups who wish to discuss solutions, data import is not yet a seamless effort. The US Army Corps of Engineers, in 2008, developed a 44 page document on the transfer of COBie data into Maximo (Nisbet 2008). The abilities to transfer information are improving; however, unlike

the GSA, many owners are at the point of beginning to request models as part of their contract and have not yet identified a trained staff member within their organization to champion this fundamental change in data transfer.

The intent for most implementation plans includes the collection of information in a central repository, the model. Most stakeholders see the model as a "container" and transporter for information. BIM users have adopted the theory of a "central core model" and ideally, this model will be utilized for facilities throughout the life cycle. Several authors, including Becerik-Gerber et al. (2012), discuss the development of a "functional" model for the operations stage. Unlike the design and construction phases, the O&M phase has a need to delineate between the geometric and non-geometric information stored in the model for the purpose of distribution to facility stakeholders.

Handover begins the "unpacking" process for distribution of the information contained in the model. One example of the types of information distributed is space information, which is at the core of managing the facility. Owners rely heavily on space management for the organizational uses of almost every aspect of the handover files. To provide this information to facility users, a space manager must often perform some action on the deliverable before disbursement. For universities, difficulties are compounded by the fact that space must be reported based on specific space standards such as BOMA or the Facilities Inventory Classification Manual (FICM).

Keith Beck, Director of the Bureau of Facilities Management for Wisconsin's Department of Administration, worked with several organizations to develop a Digital Facility Management Information Handover document. Having recognized that simply delivering an as-built model to an owner provided only a partial solution, Beck began to initiate forward movement for the state of Wisconsin regarding the transfer of important information. The agency now accepts many different types of deliverables. In an attempt to better understand trends in handover documentation, Beck, and the Department of State Facilities (DSF) conducted their own interview process with 12 large contracting firms. At that time, none of the contractors were handing over information beyond the typical closeout documents; however, they were not opposed to the change. Some contractors reported the volume of handover information to be so large that it had to be transferred via a large external drive. The central thread in the survey responses included the fact that when FM data is required, the DSF just needed to specify what kind of information was needed and in what format (Beck 2012). Thus, the perceived difficulties for owners exist as a planning need, along with an interrelated mixture of issues which relate to the multiple resources, options and stakeholders involved.

Summary

Researchers and owners are beginning to explore all uses of BIM for FM and many of the benefits remain to be quantified. Owners typically adopt technologies and management strategies based on a proven record of benefits. This type of data which has surfaced from larger owners who have started to operationalize the

model for FM is slowing becoming available. The literature indicates that owners are taking steps to utilize BIM for FM, the first of which is to mandate the model as a deliverable and it appears that A/E firms and contractors are willing to assist with this step. However, owners must still define the needed deliverables in order for this approach to be successful. Developing a consensus on the post-construction uses and benefits, as well as the obstacles to executing BIM for FM will assist in providing the foundation for the resolutions required to operationalize the model for facilities management use.

RESEARCH METHODOLOGY

In 2012, an online questionnaire consisting of 29 questions in a variety of formats was made available to representatives from several leading facility owner organizations with the intent to assess the state of BIM execution among owners in the U.S. The survey was distributed via email to members of the Florida Chapter of the Construction Owner's Association of America (COAA) in January and later distributed to the building SMART alliance list serve and the "BIM for building owners" group on LinkedIn in November of 2012. Questions were organized into four distinct parts including: 1) a section on demographics; 2) a section on BIM Execution requirements; 3) a section on BIM uses and required format of deliverables; and 4) a final section on the quality assurance procedures for those deliverables.

RESULTS

Demographics

A total of 62 responses were received, of which 42 were fully completed. The low response rate on some of the questions towards the end of the survey may have been an indicator of the respondents' lack of detailed knowledge related to BIM execution planning. Though many of their organizations had begun implementing BIM in some form, they may not yet have been knowledgeable about certain aspects of the process. As shown in Figure 10-1, the survey sample consisted of mostly College/University organizations, representing 56% (35) of all respondents. This may be attributed to the COAA sample that was available to the authors and their current connections within the state of Florida university system. The authors acknowledge this as a limitation of the study and would caution readers in making any generalizations about the findings of this research based on the sample population that the survey was distributed to.

Although the organization types represented by the sample are somewhat skewed towards educational institutions, the different roles played by the survey

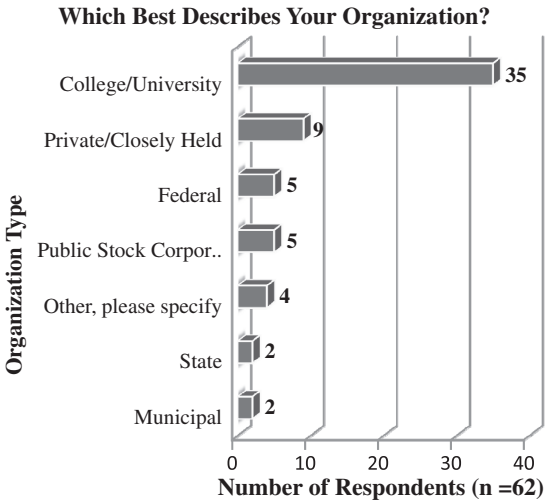


Figure 10-1. Organization type of respondents.

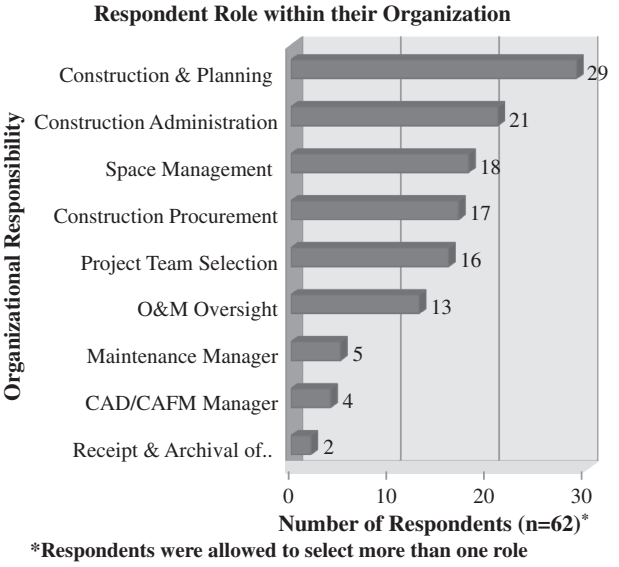


Figure 10-2. Organizational role of respondents.

respondents within their organizations were more evenly distributed. Most respondents indicated having multiple responsibilities within their various organizations. As shown in Figure 10-2, the most common roles indicated by respondents included oversight of construction and planning operations and construction administration.

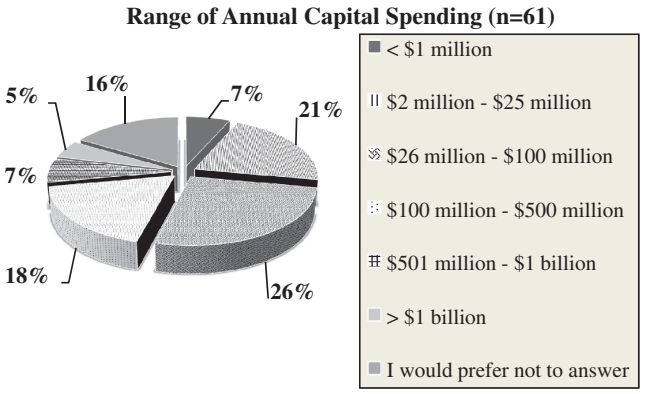


Figure 10-3. Annual construction spending.

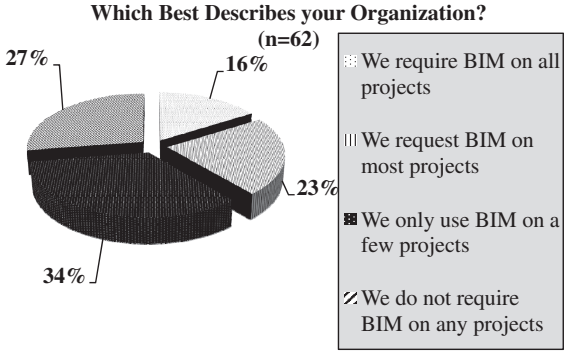


Figure 10-4. BIM use by respondent organizations.

Figure 10-3 shows the range of annual construction capital spending reported by the sample respondents. A majority (72%) of the organizations indicated budgetary spending under $500 million. These results are again reflective of the predominant education market sector represented by the sample.

When asked whether BIM was currently a requirement of their organization, 27% (17) of respondents indicated that they had no existing requirements for it and 34% (21) indicated using BIM on only a few projects up to that point. Sixteen percent of the respondents (10) indicated that BIM was a requirement for ALL their projects. Similar to the existing literature (Becerik-Gerber et al. 2012; McGraw Hill Construction 2012; I^{2}SL et al. 2013), these findings suggest that the implementation of BIM processes by owners, at least at the University level, has not yet been fully developed. A breakdown of the proportion of respondents among each BIM use category is shown in Figure 10-4.

Table 10-4 shows the different perceived obstacles to adopting BIM as noted by survey respondents in a free-response question. The largest proportion of

Table 10-4. Perceived obstacles to owners adopting BIM

Obstacles	*Number*	*% of Total*
Lack of trained in house personnel	10	33%
High initial cost/budgetary restrictions	8	26%
Lack of experience from design and construction side. They are still unable to provide BIM deliverable at this time.	4	13%
Project size	4	13%
Lack of standardization and open usability	2	7%
Existing delivery methods (Design/Bid/Build)	1	3%
Lack of market understanding	1	3%
Total	**30**	**100%**

respondents (33%, 10) indicated a lack of training for in-house personnel to be the greatest impediment preventing their implementation of BIM thus far. Although they may be requiring BIM in some way, many respondents indicated that their existing staff lacked the technical capabilities to utilize the as-built model. Additionally, the high initial cost of training and software was another recurrent obstacle noted by respondents. Many of the university organizations surveyed were faced with great budgetary restrictions during the 2012 fiscal year, which may have contributed to these responses as well.

When asked what construction delivery method seemed most conducive for using BIM, the most common response was CM at Risk and Design-Build, representing 22% (10) and 16% (7) respectively in each category. However, 13% (6) of the respondents still indicated using Design-Bid-Build as a primary delivery method.

BIM Execution Requirements

Despite the lack of formal BIM mandates among many of the responding owner organizations, the respondents still indicated having made certain strides in their organization toward BIM execution. Table 10-5 shows the frequency of BIM contractual provisions being used by building owner organizations in the survey sample. The greatest proportion of respondents (39%, 14) indicated having implemented revised contractual agreements to address BIM processes. Additionally, 36% (13) noted the presence of a BIM execution guide.

In addition to the executable provisions being made, they were also asked what types of contractual changes had been implemented as a result of requiring BIM processes. Approximately 28% (11) of the respondents indicated that they did not yet have contracts which addressed BIM. However, 36% (14) also indicated that their contracts referenced either supplemental BIM documentation or that a new contract had been developed to meet their needs. Interestingly, few respondents within the survey population indicated having used the AIA E202 or CD301 documents.

*Table 10-5. BIM provisions made by survey respondents**

BIM Provision	*# of Respondents (n = 36)*	*Percent of Respondents*
Revised contracts	14	39%
Presence of a BIM execution guide	13	36%
No BIM provisions	12	33%
Education and Training	10	28%
A trained staff member to manage BIM procedures	10	28%

*Respondents were able to select more than one BIM provision

*Table 10-6. Required BIM leadership roles indicated by respondents**

Common job roles	*# of respondents (n = 40)*	*Percent of respondents*
No specific provisions have been made regarding leadership roles and responsibilities related to BIM	15	37.5%
A construction BIM manager	10	25.0%
A project BIM manager to assist in construction administration within your organization	8	20.0%
A design BIM manager	8	20.0%
BIM coordinators for each technical trade and discipline	6	15.0%

*Respondents were able to select more than one job role

A common clause found within most BIM Execution Plans designates all lead BIM personnel on the project team and defines their roles and responsibilities related to BIM procedures. Table 10-6 illustrates the frequency of certain leadership roles required on BIM assisted projects as indicated by the survey respondents. Fifteen respondents indicated having no provisions related to BIM leadership on projects thus far. The next most commonly selected answer choice was a construction BIM manager. Additionally, the least selected category was a requirement for BIM coordinators within each technical trade (6 responses); suggesting that BIM management on the owner's side is mainly required of the primary leaders in a project team. Eight respondents indicated having a BIM manager within their internal organization. This perhaps relates back to the many roles and responsibilities which employees of owner organizations have assigned to them. Some respondents noted that this role was often taken on by a project

manager from within their organization, rather than being a dedicated job assigned to one individual within their organization.

Quality Assurance/Quality Control (QA/QC) Procedures

The section of the survey regarding Quality Assurance and Control (QA/QC) procedures was dedicated to determining which methods respondent organizations used to assess the BIM proficiency of the parties that the respondents contracted with as well as how the quality of the BIM deliverables received were evaluated. When asked if any formal method was used to evaluate the BIM proficiency of stakeholders when selecting a project team, five respondents noted the existence of a formalized procedure. Four of those five responses specified that team selection was conducted using a formal Request for Qualifications (RFQ) and interview session used to gauge the BIM experience of a project team. Only one university respondent indicated having a formalized procedure for measuring the BIM proficiency of the parties used on capital projects of contract value greater than $5 million.

When asked if any formalized method was used to assess the accuracy or completeness of model deliverables, few respondents indicated having any formal QA/QC process. Table 10-7 shows the frequency of responses in each category related to QC procedures for model deliverables. Eighteen respondents to that question indicated that they had no formal process for checking the models. If an assessment was conducted, it usually was related to visual checks of geometry and

*Table 10-7. Procedures used to assess accuracy and completeness of BIM deliverables**

Model quality assessment procedure	*# of responses (n = 33)*	*Percent of responses*
We do not have any formal QA/QC process for the models	18	54.5%
We have designated staff member(s) responsible for model management and QC	8	24.2%
Visual checks are performed through navigation	5	15.2%
Interference checks are performed to coordinate different stakeholders' models	5	15.2%
Element validation is performed ensuring all model objects are defined accurately and consistently through all phases	3	9.1%
We send deliverables to an external auditor/ consultant to check the model	2	6.1%

*Respondents were able to select more than one QC procedure

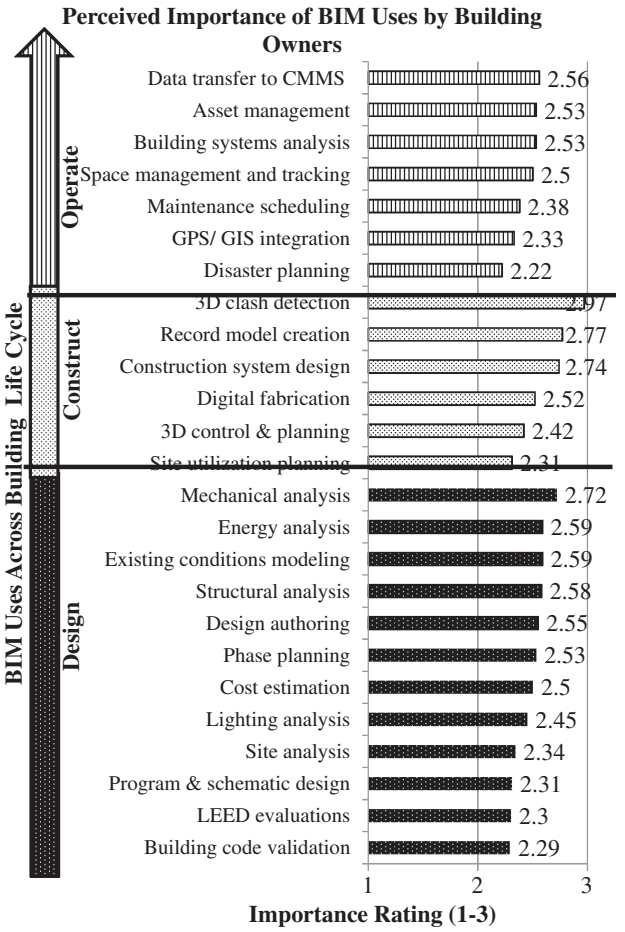


Figure 10-5. Perceived importance of BIM uses.

coordination between trades. Two respondents indicated utilizing an external third party or auditing method to check the quality of *information* in the model.

Operational Uses of BIM and their Perceived Importance

In order to gauge owners' perceptions of BIM's value across the building life cycle, respondents were asked to rate the importance of several leading uses for BIM on a scale from 1 to 3; 1 indicating "Irrelevant", 2 indicating "Somewhat Important" and 3 indicating "Very Important". The average importance rating of each BIM use along the building lifecycle is shown in Figure 10-5. As shown, the respondents generally perceived the importance of BIM use for *planning and design* to be in the areas of mechanical analysis, energy modeling and existing conditions documentation. During the *construction* phase, consistent with the literature,

Table 10-8. Perceived importance of BIM uses in the operations phase of building projects

Perceived Importance in Operations Phase	*Somewhat Important*	*VeryImportant*	*% of Total (n = 38)*
Building systems analysis	10	21	82%
Asset management	7	24	82%
GPS/GIS integration	16	14	79%
Ease of transfer to CMMS	7	23	79%
Maintenance Scheduling	14	15	76%
Space management and tracking	7	22	76%
Disaster planning	15	12	71%

3D coordination and clash detection were rated highest; however, the creation of record models was also rated highly.

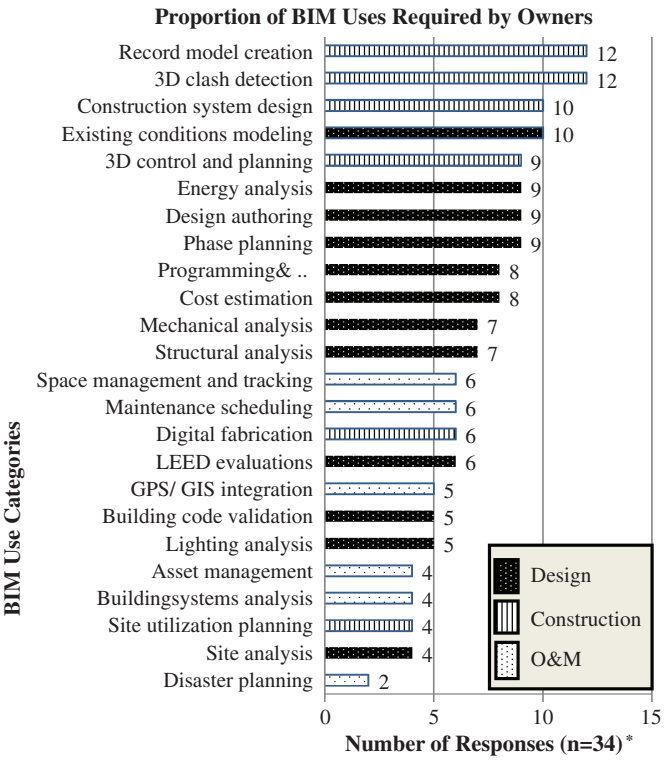
Table 10-8 shows the responses which relate to the Operate phase in Figure 10-5 and provides a closer look at the *O&M* phase importance ratings for each BIM use listed. Applications of BIM for asset management and building systems analysis proved to be the highest rated areas indicated by survey respondents.

The survey also asked which of the common BIM uses had been addressed in a BIM execution guide by respondent organizations thus far. Almost half of the respondents (47%, 16) indicated that they did not have BIM requirements in place. However, Figure 10-6 shows the remaining proportion of the respondents actually requiring each BIM use, as outlined in the organization's execution guide.

The BIM uses addressed by requirements which comprised more than 25% of responses for that question were predominantly applications required during *design* and *construction* as shown in Figure 10-6. Space management/tracking and maintenance scheduling were the most frequently noted *O&M* Phase uses and comprised roughly 17% (6) of responses. All other BIM uses from the operations phases which were noted to be addressed in the owner's BIM Execution Guides were among the lowest responses of the survey respondents. Therefore, although more than 70% of respondents recognized the importance of BIM uses for O&M, these results indicate that few respondent organizations had fully implemented plans to begin requesting the information for operationalizing the model yet.

Deliverable Requirements

Finally, survey respondents were asked additional questions regarding the format of the deliverables requested and how they were utilized post construction. In a free response question, they were asked to indicate which Level of Development



*Respondents were allowed to select multiple BIM uses

Figure 10-6. Required BIM uses.

(LOD) they required for most BIM deliverables. Of the 13 respondents who answered that question, an equal proportion indicated requiring LOD 300, 400 and 500. If a model progression specification was utilized, they indicated requiring LOD 100-500 in each life cycle phase.

Although six respondents did indicate that they would accept an IFC or COBie compliant model as part of their as-built deliverable, the majority (65%) of the respondents indicated mandating a federated model in Autodesk's 2011 or 2012 Revit building suite. Thus, many of the organizations who have invested the time and money are software-specific in their standards suggesting that the idea of "Open BIM" has yet to materialize among the educational owner population. Another trend indicated by the survey respondents was a request for the native file format of the BIM authoring tool used as well as the PDF, DWG, Navisworks files associated with the as-built deliverable. Additionally, 60% of the respondent organizations indicated that they continue to request hard copy and CAD files on compact disc as part of the as-built deliverable. This may also suggest that despite their requirement for BIM use, many organizations are not using the model during O&M.

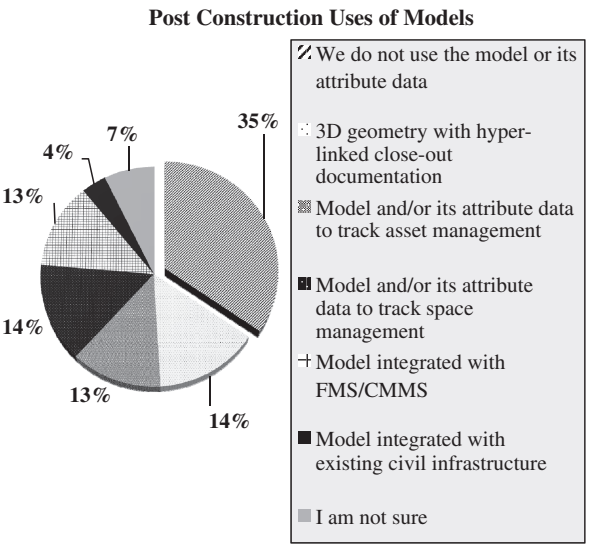


Figure 10-7. Utilization of the model post construction.

Finally, when asked how their organization planned to utilize the final BIM deliverable, 35% of the respondents indicated no utilization of the model or its information after construction handover. Figure 10-7 shows the distributions of responses regarding post-construction. A common pattern found in the data shows, that if BIM was utilized during O&M, it was also utilized for space and asset management as well as being integrated with CMMS. Therefore, if O& M use was attempted, it was often attempted in multiple applications.

Analysis and Limitations

Due to the small sample size and the method in which respondents were solicited in this study, generalizations cannot be made regarding the true state of BIM execution among US building owners. Consistent with many of the other studies published in this domain thus far, the results of this survey do indicate that owners who have adopted BIM are still working internally to operationalize the model and/or the data it encompasses. In fact, 35% of the respondents were not using the model or the attribute data post construction. However, the perceptions of the model's value during post-construction provide several areas of interest and direction for owners and may offer a possible focus for more specific areas of study.

The reality is that an owner organization comprises multiple stakeholders and numerous positions within the organization. Each position can have vastly different goals for not only their overall mission, but also for the use of the model post-construction. The respondents' included a cross-section of duties; therefore, these results represent the average perceptions of many different roles within an owner organization.

CONCLUSIONS

The post-construction uses outlined in Tables 10-1 and 10-2 are all applications of BIM requiring internal planning for implementation; a time consuming process with multiple stakeholders. Clear evidence of a single or a select few obstacles for owners would provide at a minimum, a focus and direction for both owners and researchers. However, this study assists to solidify the complex issue: Owners are beginning to understand the possible value in operationalizing the model for FM but are in various stages of both understanding and implementing internal procedures. It is clear that their adoption of BIM continues to increase and though many resources are now available regarding possible methodologies for requiring BIM, the literature review found great variability in the level of detail found in owner's requirements specifications.

Despite a small sample size, the survey findings, in support of similar literature, suggest that the maturity of building owners in terms of BIM execution is still in its infancy. The research results, though limited, indicated that even owners with BIM experience were not utilizing their models post-construction for facilities management as of 2012. The respondents indicated similar obstacles to those found in the literature including: lack of interoperability, misunderstanding of information handover requirements, and a general lack of technical skills and software knowledge required to utilize the BIM deliverables.

This research provides a benchmark for owners in terms of strategic planning for the advancement of BIM for FM. Unlike the design and construction phases of the project, the owner's considerations for operationalizing the model has multiple stakeholders and uses within the organization. Similar to the A/E's need to establish earlier decisions, the owner is also forced to provide earlier contributions to the project to obtain a record model for post-construction uses and benefits. The proposed considerations provide areas for future research, recognition of obstacles for the industry, and the establishment of prioritized considerations for the framework of an owner's approach to solutions.

References

Associated General Contractors [AGC] BIMForum. (2013). "Level of development specification." [Draft].www.bimforum.org/lod (April 19, 2013).

Ahamed, S. S., Neelamkavil, J., and Canas, R. (2010). "Impact of Building Information Modeling on facility maintenance management." *Proc., the E-SIM 2010 Conference*, Winnipeg, Canada, May 19-20, 2010.

Akcamete, A., Akinci, B., and Garrett, J. H., Jr (2010). "Potential utilization of Building Information Models for planning maintenance activities." *Proc., the International Conference on Computing in Civil and Building Engineering*, ASCE, Nottingham, UK, June 30-July 2, 2010.

Autodesk Education Community (2012) "Lesson 5: using BIM for operations and facilities management." http://bimcurriculum.autodesk.com/lesson/lesson-5-using-bim-operations-and-facilities-management (May 17, 2013).

Becerik-Gerber, B., Jazizadeh, F., Li, N., and Clis, G. (2012). "Application areas and data requirements for BIM-enabled facilities management." *Journal of Construction Engineering and Management*, 138(3), 431–442. Doi: http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000433

Becerik-Gerber, B. and Rice, S. (2010). "The perceived value of Building Information Modeling in the U.S. building industry." *Journal of Information Technology in Construction* [ITcon], 15, 185–201.

Beck, K. (2012). "The state of Wisconsin: BIM – digital FM handover pilot projects." *Journal of Building Information Modeling*, Spring 2012, 22–23.

Brucker, B. and Nachtighal, S. (2006). "Initiating the Building Information Model from owner and operator criteria and requirements." *Proc., Computing in Civil Engineering* 2005, 1-12, doi: 10.1061/40794(179)20

Computer Integrated Construction (CIC) Research Program. (2009). "BIM project execution planning guide." Pennsylvania State University: University Park, PA. <http://bim.psu.edu> (April 16, 2013)

Computer Integrated Construction (CIC) Research Program (2012). "BIM planning guide for facility owners." Pennsylvania State University: University Park, PA. <http://bim.psu.edu> (April 20, 2013)

Cotts, D., Roper, K., and Payant, R. (2010). "The facility management handbook." (3rd ed.) American Management Association, New York, N.Y.

Department of Veterans Affairs [VA]. (2010). "The VA BIM guide." Washington, DC. <http://www.cfm.va.gov/til/bim/BIMGuide/modreq.htm> (February 2, 2013).

East, B. (2009). "Performance specifications for building information exchange." *Journal of Building Information Modeling*, Fall 2010, 18–20.

East, B. (2013). "BIM for facility managers." *Using COBi*, P. Teicholz, ed., John Wiley & Sons, Inc. and International Facility Management Association, Hoboken, New Jersey, 107–143.

Forns-Samso, F. (2010). "Perceived value of Building Information Modeling in facilitites operations and maintenance." M.S. thesis, University of New Mexico: Albuquerque, New Mexico.

FM: Systems (2012). "Benefits of BIM for facilitymanagement." BIM & Owners, <http://www.fmbim.com/bim_facility_management.htm> (May 18, 2013)

FMI Corporation (2007). "FMI/CMAA eigth annual survey of owners – the perfect storm construction style." FMI Corporation: North Carolina.

General Services Administration (GSA) Public Buildings Service Office of the Chief Architect (2006). "GSA building information modeling guide series 01- GSA BIM guide overview."

General Services Administration (GSA) Public Buildings Service Office of the Chief Architect (2011). "GSA building information modeling guide series 08- GSA BIM guide for facilities management."

Haynes, D. (2009). "A tale of two exhibits – a comparision of the CD301 and E3202 BIM exhibits." *PEPE&HAZAED LLP Construction Watch*, No. 3–09.

Hagan, S., Ho, P., and Matta, H. (2009). "BIM: the GSA story." *Journal of Building Information Modeling*, Spring 2009, 27–29.

Indiana University. (2009). "Building Information Modeling (BIM) guidelines and standards for architects, engineers, and contractors." <http://www.indiana.edu/~uao/iubim.html>.

International Institute for Sustainable Laboratories (I²SL), buildingSmart Alliance (bSa) and International Facility Management Association (IFMA) Research and Development

Council (2013). "BIM for facility management survey." *Proc., the building Smart Alliance Conference -Integrating BIM: Moving the Industry Forward*, Washington, D.C., January 7-11 2012.

Kreider, R., Messner, J., and Dubler, C. (2012). "Determining the frequency and impact of applying bim for different purposes on projects." *Innovation in AEC Conference*, Pennsylvania State University, University Park, PA, July 9–11. <http://www.documbase.com/BIM-Use.pdf> (December 5, 2013).

McGraw-Hill Construction (2008). *Building Information Modeling (BIM) transforming design and construction to achieve greater industry productivity*, McGraw-Hill Construction SmartMarket Report, McGraw-Hill: New York.

McGraw-Hill Construction (2009). *The business value of BIM: getting Building Information Modeling to the bottom line*, McGraw-Hill Construction SmartMarket Report, McGraw-Hill: New York.

McGraw-Hill Construction (2012). The business value of BIM in North America: multi-year trend analysis and user ratings (2007–2012), McGraw-Hill Construction SmartMarket Report, McGraw-Hill: New York.

National Institute of Building (NIBS). (2012). National Building Information Modeling Standard - version 2.0: "Chapter 5.2 Minimum BIM": National Institute of Building Sciences."

National Institute of Building (NIBS). (2013). "USAF attachment F for BIM-based design-build and design-bid-build projects." *Air Force building information modeling for MILCON transformation – Guidelines*. Retrieved from: http://www.wbdg.org/references/afbim_guidelines.php

Nisbet, N. (2008). "COBIE data import/export interoperability with the MAXIMO computerized maintenance management system." US Army Corps of Engineers ERDC/CERL CR-08-1[Draft]. http://www.wbdg.org/pdfs/use_cobie_maximo.pdf (December 5, 2012).

Reilly, M. (2010). 'The business of BIM' reviews business challenges, benefits of bim adoption."<http://www.architects.org/news/business-bim-reviews-business-challenges-benefits-bim-adoption> (November 2, 2012).

Yee, P., Matta, C., Kam, C., Hagan, S., and Valdimarsson, O. (2010). "The GSA BIM story." *Journal of Building Information Modeling*, Spring 2012, 20–21.

This page intentionally left blank

CHAPTER 11

Integrating Augmented Reality into Building Information Modeling for Facility Management Case Studies

Jun Wang[*,†]
Lei Hou[‡]
Ying Wang[§]
Xiangyu Wang[¶,**]
Ian Simpson[††]

Abstract: *The management of complex information flow can be a crucial aspect of Facility Management (FM). Because of the increasing complexity of the present-day building projects, FM activities, for example, maintaining a building facility or a system, normally involve enormous human multitasking across different knowledge domains. Lessons learned from the present successful FM instances manifest that the FM teams are increasingly interested in applying more viable technologies to achieve*

*Australasian Joint Research Centre for BIM, Curtin University, GPO Box U1987 Perth, WA 6845, Australia; PH (+61) 8 9266 9059; email: jun.wang1@curtin.edu.au

†School of Construction Management and Real Estate, Chongqing University, Chongqing, 400044, China; PH (+86) 23-65123204; email: wangjun19891224@126.com

‡Australasian Joint Research Centre for BIM, Curtin University, GPO Box U1987 Perth, WA 6845, Australia; PH (+61) 8 9266 9059; email: lei.hou@curtin.edu.au

§Australasian Joint Research Centre for BIM, Curtin University, GPO Box U1987 Perth, WA 6845, Australia; PH (+61) 8 9266 9059; email: ying.wang13@postgrad.curtin.edu.au

¶Australasian Joint Research Centre for BIM, Curtin University, GPO Box U1987 Perth, WA 6845, Australia; PH (+61) 8 9266 9059; email: xiangyu.wang@curtin.edu.au

**Department of Housing and Interior Design, Kyung Hee University, South Korea; email: xiangyu.wang@curtin.edu.au

††CSI Global Services, Level 1, 87 Wickham Terrace, Brisbane QLD 4000, Australia; PH (+61) 7 3837 0605; FAX 1300 362 140; email: ian.simpson@aecsystems.com.au

the effective management of massive information. Building Information Modelling (BIM) technology is one of the promising approaches, as it forms a platform for the users to manage the information of a facility and leverages virtual digital representations as a reliable basis for decisions during its life-cycle. Nevertheless, the fully immersive environments produced by BIM still lack the capability of mapping a virtual world into a real world, or vice versa. Augmented Reality (AR) is emerging as an advanced visualization which is possible to bridge the gap. It enables the demonstration of BIM context into the real world, and is envisaged to effectively improve the way of how information is displayed. Meanwhile, the virtuality-to-reality changeover from BIM to AR is conductive to a better understanding of information about a facility from the human perception perspective. The objective of the study is to explore that the merging of AR with BIM is a way for improving the information search and management in FM applications. This chapter firstly brief what is FM and how it is generally implemented. Followed by the state-of-the-art review of BIM/AR aided FM research, the chapter then proposes the viability of integrating BIM and AR and demonstrates its efficacy of processing complex onsite information based on four BIM+AR case studies. Finally, the chapter discusses the technological transferability issues in terms of deploying more and more BIM+AR scenarios in the prospective FM process.

INTRODUCTION

Facility Management (FM) is based on a series of technical, economic and organizational measures, and to carry out scientific management to the equipment. In order to fulfill the functionality associated with the building assets, the facilities management department has responsibilities for the day to day administering of various building systems and facilities, for example, piping and cabling, lighting and energy, audio and visual system, etc, The operation and maintenance to these facilities normally take up a large proposition of the lifespan of the building. Meanwhile, the process also has a huge impact on costs (take equipment shutdown as an example), work efficiency (productivity), occupational safety and health and environment. A poor implementation of the process is typically associated with incomplete, incorrect or not immediately usable engineering information. As reported by Rasys et al. (2014), the effective integration and delivery of such information are primarily challenged by the technical and procedural processing such as recognizing the facility location, optimizing the FM workflow, and so on. This study accordingly aims at addressing the information accessibility issue which widely exists in the traditional manner of conducting FM, such as, how to quickly and accurately acquire the information. The chapter is organized as follows: the literature review section presents the state-of-the-art FM research works that applies the advanced technologies such as Building Information Modelling (BIM) and Augmented Reality (AR). The following section proposes the concept of integrating BIM and AR in FM implementation as well as its technological merits in facilitating context awareness, comparing 'as-built'

and 'as-planned' information, linking digital data to physical environments, and visualizing maintenance guidance. Followed by the elaboration of four practical BIM+AR scenarios, the chapter finally concludes that the conjunct use of BIM and AR is promising in processing complex onsite information in FM instances.

LITERATURE REVIEW

BIM is emerging as a method of creating, sharing, exchanging and managing the information throughout lifecycle between all stakeholders (Becerik-Gerber et al. 2012; Sun and Che 2012; Wang et al. 2012; Motawa and Almarshad 2013). AR, on the other hand, is regarded as the manner of representing information generated in FM. AR allows a user to work in a real-world environment while visually receiving additional computer-generated or modelled information to support the task at hand (Wang et al. 2012). The applications of BIM and AR into the operation and maintenance of facility have received a significant consideration from academics and practitioners.

BIM and FM Review

Considerable research works have looked into FM in the last ten years, which are mainly concentrated on the following aspects: Innovation process for FM (Mudrak et al. 2005; Sharma et al. 2007; Lavy 2008; Madritsch and May 2009), measurement system for FM (De Toni et al. 2007; Meng and Minogue 2011), End-user requirements for green FM (Nousiainen and Junnila 2008), and improvement for FM (Lennerts et al. 2005; Leung et al. 2005; Pennanen et al. 2005; Lavy 2008). From the literature review, three main disadvantages have been identified in the state-of-the-art FM:

1. FM software interface is not intuitive (Cotts 2009; Park et al. 2011). The typical FM system focuses either on flow chart, schematic diagram, and equipment number and type, whereas the location of equipment and the actual pipe routes tend to be ignored;
2. FM data is scattered and difficult to be searched in a timely manner (Cardellino 2006; Stack 2012). It highly demands the domain knowledge and project technology from design to construction (Cotts 2009). FM would work properly if all the materials and data are collected and integrated along with project design and construction stages. However, facility managers normally do not have a useful standard to structure the information in a relevant way for a better management; and
3. FM software platforms are not compatible (Cardellino 2006; Liao et al. 2012). The traditional FM system is either provided by equipment suppliers or developed by FM parties. All of the software platforms are independent, such as Central Air Conditioning System, Access Control System and Monitoring System which all contain their own hardware and software

platforms. Different equipment suppliers provide different platforms so that there are not any interaction and sharing between these platforms. Therefore, the FM stakeholders are facing more difficulties in operation.

BIM is emerging as a new approach to address these disadvantages. A range of studies identified that there were numerous potential applications and benefits when implementing 3D/4D CAD/BIM in FM (Asli Akcamete 2010; Chen et al. 2011; Park et al. 2011; Becerik-Gerber et al. 2012; Sun and Che 2012; Liu and Issa 2012; Liao et al. 2012; Yu et al. 2012; Motawa and Almarshad 2013). Wang et al. (2013) had engaged FM in design stage through BIM so as to improve FM performance. Yu et al. (2012) identified 13 factors that have direct or indirect effects on BIM acceptance, and proposed the foundation of research underlying the BIM potential benefits for FM practice in future. Becerik-Gerber et al. (2012) presented a non-geometric data structure, introduced life-cycle continuum of data requirements, and discussed roles and responsibilities of stakeholders for data provision. In order to better apply BIM in FM, some development work has been done to improve BIM application. Liu and Issa (2012) focused on automatic bidirectional communications between Computerized Maintenance Management Systems (CMMS) and BIM models on a database level. Motamedi and Hammad (2009) attached the permanent RFID tags to facility components, where the memory of the tags was populated with accumulated lifecycle information of the components taken from a standard BIM database. They also developed a conceptual RFID-based system structure and data storage/retrieval design. Given the complexity of property management during the operational period where enormous information could be lost during the several periods before operation, it is very difficult to manage equipment all through the way (Sun and Che 2012). Some authors (Sun and Che 2012; Liao et al. 2012; Motawa and Almarshad 2013) built a visualized FM platform based on BIM which integrated all the equipment information and operation method to solve this problem. Sun and Che (2012) further realized the real-time monitoring of the update of equipment information, equipment maintenance and fault handling is very critical during the operation stage. Aaron Costin (2012) have developed and evaluated a framework that utilizes the integration of commercially-available Radio Frequency Identification (RFID) and a BIM model for real-time resource location tracking within an indoor environment.

BIM has been considered as an important technology for current FM performance improvement. However, the previous research mainly focused on supporting facility managers to make sound decisions and real-time control using BIM data. Rare research was concerned about guiding operators and repairmen to work efficiently and letting them obtain relevant in-situ information concerning BIM database. Some commercial software has enhanced BIM application in FM. *Ecodomus (http://www.ecodomus.com/index.php/ecodomus-fm/)* is a software application that provides for real-time integration of BIM with Building Automation Systems, ARCHIBUS, and GIS. EcoDomus FM can serve as a part of Central Facility Repository (CFR) helping owners keep data always up-to-date across the applications and databases. *YOUBIM (http://www.youbim.com/)* is a Cloud-based

solution which extends all the value of BIM through to Facilities Management, by integrating information and making it instantly available in the form of data-rich online Models. *BIM anywhere (http://bimanywhere.com/features.php)* is field tested and proven lean workflows make accessing and sharing 3D model information easy and intuitive for every single person on the jobsite to use for planning, tracking, and verification. *ArtrA (http://www.artra.co.uk/asset-lifecycle-management-3d-facilities-management)* uses 3D as-built coordination models and BIMs for asset management by linking all relevant documentation and information to the model and to a SQL database where it can be searched and retrieved. Design information and intelligence, contained in model's attributes, is augmented with installation, operation and maintenance information and documentation that is added to ArtrA's database. This in its entirety is made accessible on-site through tablet PCs. These commercial systems are all only based on BIM, this book chapter aim at developing a BIM+AR system which not only can realize field BIM function but enhance the combination of virtual reality and physical environment with AR technology.

AR Review

AR creates an environment where digital information is superimposed into a real-world view. Considerable efforts have been made to promote AR in different application scenarios during last decade, such as such as design collaboration (Shin et al. 2005; Wang et al. 2008; Wang and Schnabel 2008; Wang 2009; Chi et al. 2013), construction management (Wang 2007, Dong et al. 2009; Park et al. 2013) and training (Wang and Dunston 2007). Hincapie et al. (2011) presented an example of AR application in aeronautical maintenance. The principal flaws of AR were commented while the possible lines of investigation were suggested. S. Benbelkacem (2010) developed an AR maintenance design platform and applied it to a case of solar system, and the result showed AR was an optimum option for operators to work efficiently, safely and flexibly. Henderson and Feiner (2009) evaluated the benefits of AR for task localization in maintenance of an armored personnel carrier turret, and a qualitative survey showed the AR condition was intuitive and satisfied for the tested sequence of tasks.

However, rare research has been done with regard to the AR-enabled operation and maintenance in building environment. Lee and Akin (2011) developed an AR-based equipment Operations and Maintenance (O&M) fieldwork support application to improve efficiency at the site and the experimental evaluation of the application. The application consisted of an AR-based interface for intuitive GUI and an O&M information model developed with various types of O&M specific information obtained through observing trades people's fieldwork activities, and those from Computerized Maintenance Management System (CMMS) and Building Automation System (BAS). Zhu et al. (2013) developed an authorable context-aware AR system to assist the maintenance technicians. Wang and Dunston (2006a) have selected some scenarios where AR can be potentially applied, such as working distantly and hazardously, construction and assembly, maintenance

and renovation, inspection, safety and training. They further used AR as an assistant viewer for computer-aided drawing (Wang and Dunston 2006b). Wang et al. (2013) provided a state-of-the-art review of the mainstream study undertaken between 2005 and 2011 within the normative literature. They identified: 1) wide variety of built environment applications for which AR systems are now being developed and tested; and 2) the most part of the published papers still consist of lab-based controlled studies without industrial practitioner-based control groups, geared toward feasibility or proof of concept testing.

Summary

The preceding literature review addresses the underlying integration between BIM and AR to improve current FM performance. It also helps draw the following conclusions:

- Current FM platforms and practices are mainly paper-based and insufficient in supporting field maintenance people to work correctly and efficiently.
- There exists a strong interest among industrial circles and academics in how emerging technologies can be used to improve current FM practice.
- BIM has been considered as an important technology in achieving high-level performance of building operation and maintenance, such as visualized equipment tracking, real-time system control and accurate decision-making.
- Current BIM-based FM systems are mostly useful for maintenance managers instead of field works. Tools for repairmen are insufficient in performing maintenance work with high productivity.
- Functionality of current AR tools is not perfect, but sufficient in super-imposing digital maintenance information into a real-world view.

Nevertheless, the immersive environment created in BIM still lacks an ability of matching a real world into a virtual world. AR, featured as a 'walking-through' technology, enables the demonstration of BIM context into the real world, and is envisaged to be effectively used to improve the way of how information is displayed. Meanwhile, the virtuality-to-reality changeover is conductive to a better understanding of information about a facility from the human perception perspective. Therefore, the objective of the study is to explore that the merging of AR with BIM is a way for improving the information search and management in FM applications.

IMPLEMENTATION AND BENEFITS OF INTEGRATING BIM AND AR IN FM

Dunston and Wang (2011) revealed that the composite task and primitive task were the underlying blocks for FM fieldwork. Activities associated with composite tasks include measure, connect, navigate, organize, obtain, select, align, connect,

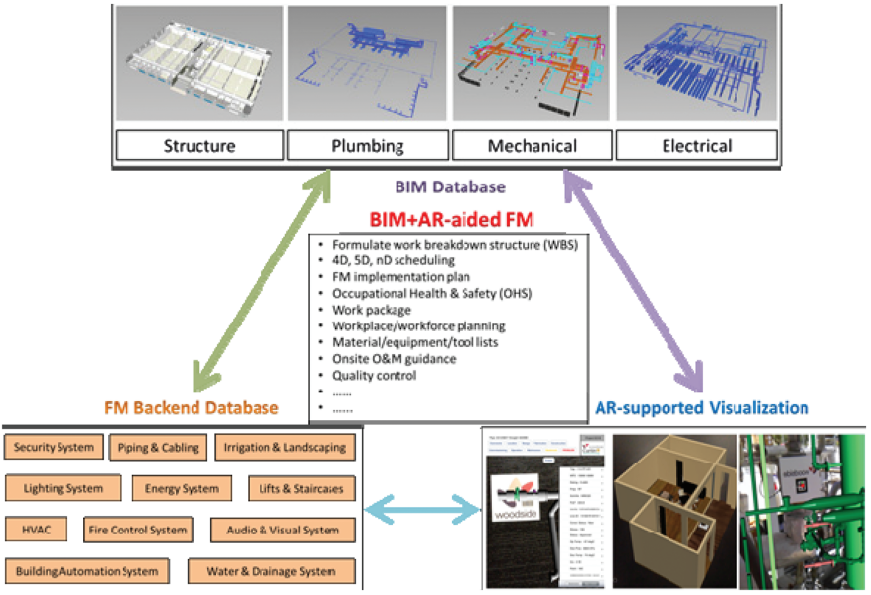


Figure 11-1. Implementation of BIM+AR in FM.

record, and report. To acquire an object, for example, a user must move their arm and hand into position before grasping it. Primitive Tasks refer to elemental motion and include reaching, grasping, moving, and eye travel. From the perspective of mental tasks involved at these levels, it is believed that the primitive and composite tasks could be readily applied within a BIM+AR environment. With this in mind, a concept of BIM+AR is of significance that can facilitate cognitive perception and learning of FM tasks. As suggested by Dunston and Wang (2011), there are three major mental aspects that need to be addressed when assessing the feasibility of using BIM+AR for FM related work processes: how information is obtained, attention distraction from disturbance, and memorial processing (visual representation, short-term and long-term memory), as referred to Figure 11-1. The BIM database creates an environment for project participants to collaborate on a shared information platform of project knowledge. FM engineers from different disciplines/teams can remotely and efficiently access the information of the building elements, such as security system, piping, cabling, lighting system, HAVC, etc. With AR, the information derived from BIM can be visually presented in real space, in real scale, and in real time, which bridges the gap of the virtual context and the real world from the human perception perspective. This is the step in how BIM integrated AR will continue to help us across the spectrum of design, construction, commissioning, and operation and maintenance.

A considerable amount of time and effort may be undertaken to determine the location as well as reading procedural and related information. According to Hou and Wang (2011), AR can be used to expedite tasks more efficiently and effectively, as information can be made readily available in real-time and real context. Enabling salient information to be available on demand, particularly during operation and maintenance phases, can improve decision-making. Towne (1985) revealed that cognitive time (i.e. time not engaged with devices or tools) accounted for about 50% of total task time. The use of AR should lower the frequency of switching between information resource (paper drawings or computer) and work piece tasks by integrating the required information into activities and therefore reduce the time and energy associated with repetitive switching (Wang et al. 2012). The memory system is composed of three distinct memory stores (Proctor and Van Zandt 1984): (1) sensory store, (2) short-term store, and (3) long-term store. For many tasks, accurate performance requires not only that pertinent information be retained in the short-term store, but also that the information be acted on quickly (Proctor and Van Zandt 1984). Therefore, the limited capacity of the short-term store has implications for any task or situation in which successful achievement of a task/operation requires a subcontractor to encode and retain information accurately for brief periods of time (Wang et al. 2012). Proctor and Van Zandt (1984) indicated that the accuracy of retention can be increased by minimizing the activities that intervene between the presentation of information and the actions required. In the case of AR, information is directly inserted into the subcontractor's real world view of the task, releasing part of the short memory occupied by those items and therefore facilitating efficient retrieval of information from memory.

In Figure 11-2, BIM models contain as-built building information, operation information and maintenance information, which include for example, the formats of 1D text, 2D image/drawing, 3D wireframe, 3D model, and animation. AR can be used to display the above formats information in real world. There are five basic technological components of AR: media representation, interaction device, feedback display, trackers, and the computing unit (Wang et al. 2012). When integrating BIM with AR, there are five benefits for FM: intelligent fault diagnosis, visualized operation guidance, situation awareness, building performance monitoring and mobile route guidance. These benefits are elaborated in the following sub-sections.

Intelligent Fault Diagnosis

Take the state-of-the-art facility maintenance process as an example, when a fault occurs, the duty officer will normally assign the related workers to inspect and address. To the workers, they will start from searching the relevant materials, formulating potential solutions, and finally troubleshooting the problems. This process is time-consuming and unsafe. AR can be used to expedite tasks more efficiently and effectively, as information can be made readily available in the real-time context. For example, when leakage occurs, the sensor can detect it and report to the server (as shown in figure 11-3). BIM model and AR model are stored

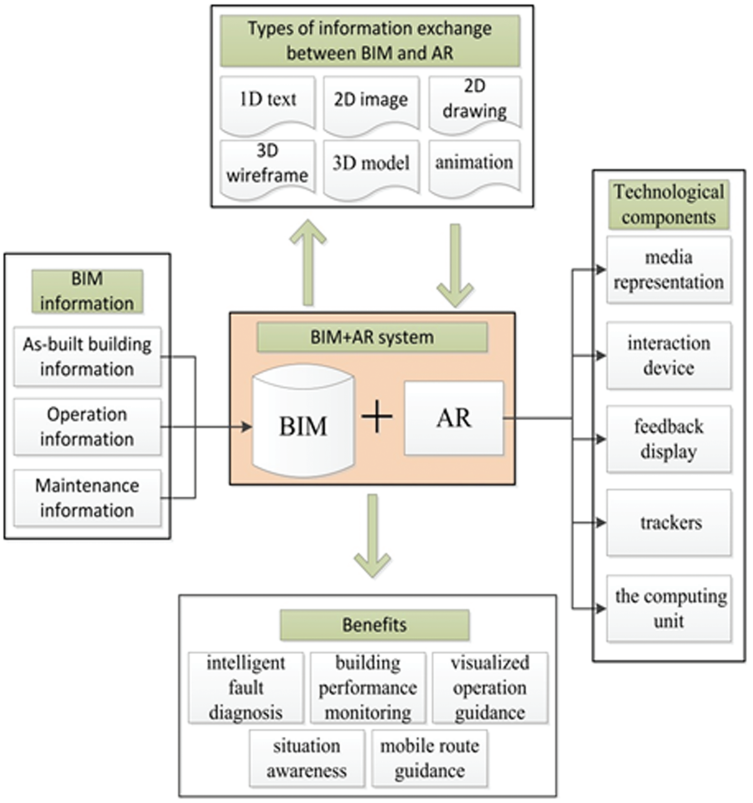


Figure 11-2. Application areas and benefits of BIM+AR in FM.

in the server. After obtaining the position of leaking part, the leaking pipe will be highlighted in the BIM model. AR model of the whole pipe will then be generated automatically with the specific leaking part highlighted. After this process, request of fixing the pipe will be pushed to the mobile devices of FM personnel. They can scan the specific marker to view the leaking parts highlighted in the hidden pipe behind the wall.

Visualized Operation Guidance

Equipment maintenance includes the installation or removal of a component from an facility or facility subassembly, the current practice utilizes 2D drawings and manual as the main visualization means to guide repair (Wang et al. 2013). Other visualization means such as video and virtual reality have also been applied to assist in operation (Boessenkool et al. 2013). According to Hou and Wang (2013), the insertion of digitalized information into the real-world workspace using AR can provide workers with the means to implement correct operation procedures with improved accuracy and reduced errors.

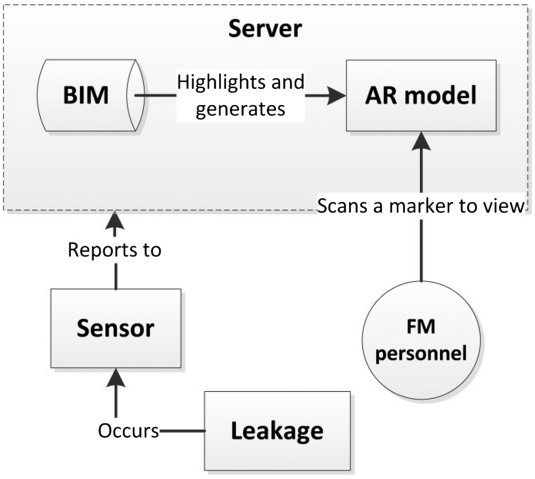


Figure 11-3. Intelligent detection of the leakage.

Situational Awareness

AR can naturally complement pervasive computing by providing an intuitive and interactive interface to a 3D information space embedded within physical reality. According to Lee et al. (2008), AR can be used to afford a situation-aware and adaptable service which considers user preferences, device profiles, and security. Therefore the action list associated with a particular job can be viewed by different user profiles (cleaner, security guard, technician, etc.) via AR. BIM stores all this information that can be used to generate action lists in a single data repository. Information can be extracted from a BIM model using Industry Foundation Classes (IFC) and gbXML to support the operation and maintenance processes. For example, facility manager designs and distributes work order based on BIM firstly, and then a cleaner can see what his/her to-be-cleaned area is in a building via AR; a service man can see the sensor values or other damaged components in this room, etc. Finally the real-time feedback of maintenance information can be sent to BIM database.

Building Performance Monitoring

The current practice of real-time building performance typically visualizes the information collected from sensors distributed throughout a building (Costa et al. 2013). The visualization shows the raw data values as simple text labels on top of 2D floor plans (Costa et al. 2013). This requires large amount of unordered and non-geo-tagged 2D imageries to be manually analyzed at a later stage, which makes the analysis time-consuming and labor-intensive. Due to the absence of a benchmark for energy performance, identification of performance problems also heavily relies on the auditor's knowledge and experience, and consequently may lead to subjective and error-prone inspections (Golparvar-Fard and Ham 2013).

BIM can better visualize the same data in 3D in the context of the specific zone configuration of the building under consideration. However, quick and reliable identification of energy performance problems in buildings is a critical step in improving audits' efficiency. According to Golparvar-Fard and Ham (2013), AR can be used to automate the analysis and visualization of deviations between buildings' actual and simulated energy performances. In addition, actual and expected 3D spatio-thermal models are generated and superimposed in a common 3D virtual environment (Golparvar-Fard and Ham 2013). The visualization of deviations in 3D enables auditors to easily identify potential performance problems, and in turn enable auditors to focus more on other important tasks of analyzing retrofit alternatives. For instance, a service man using tablet can see from the outside of the building and assess the temperature distribution of its various parts.

Mobile Route Guidance

Mobile route guidance is significant for operators in the maintenance process when a building is complex and has restricted areas (Frankenstein et al. 2012). Traditionally, workers rely on memory, signs and building plan maps to find a route to destination step-by-step. However, most signs are not arranged in a proper way. Workers might get lost in moving from one sign to the next due to faulty memory and unclear signs. AR appears to create a promising platform if equipped with BIM technology which can facilitate the mobile route guidance. Wang (2012) have developed an in-door wayfinding prototype based on AR technology and Longitude, Latitude and Altitude (LLA) marker. Lin et al. (2013) introduced a new method to cope with path planning for 3D indoor space through an IFC file as input, and developed a navigation system which automatically extracted and managed geometric and semantic information on building components and spaces from the IFC file. The experimental results demonstrated that the presented method was able to cope with the properties of building components and was more accurate and efficient than some previous work used for path planning. With indoor route guidance, auditors can reach destination quickly, easily and securely. Moreover, auditors are able to do the auditing comments/marks (utilizing indoor positioning) when walking in the building.

THE APPROACH OF LINKING AR WITH BIM

The conventional AR environments are based on ARToolkit where virtual objects are usually drawn using pure drawing functions of Open Graphical Language (OpenGL), a multi-platform high-level 3D graphics Application Programming Interface (API) (Piekarski and Thomas 2002). However, if users want to build their own AR applications, they must acquire the knowledge of OpenGL. Most of the AR applications could only show the 3D model and animation such as ARmedia, D'fusion by total immersion and Build AR. They are mostly used for

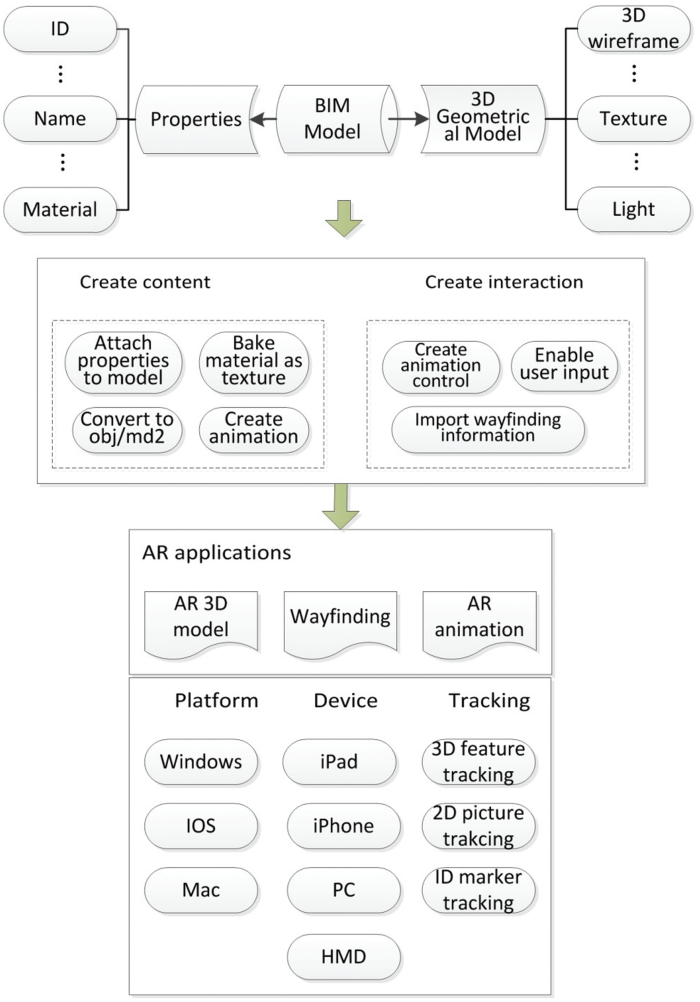


Figure 11-4. Framework of linking AR with BIM for FM.

advertisements or demonstration. However, in FM process, animation and 3D model are not sufficient to provide instructions for facility managers. They need to refer to the properties for the specific id and other attributes of equipment. For the purpose of facilitating the development cycle, the framework is developed as depicted in Figure 11-4.

BIM model includes 3D geometry wireframe and properties. They are converted and processed into AR supported formats in specific modelling software. In this process, contents and interactions need to be created by modelling and scripts. AR model and relevant information are retrieved and

converted from BIM model. Obj and md2 are the supported formats of the AR system. For example, the procedure below describes baking texture in blender:

1. Export model to obj format in blender
2. Create UV Maps and activate it
3. Enter edit mode and do Smart UV project
4. Create new image for the texture baking process
5. Select all models and bake the material into texture image
6. Save the texture image
7. Add new material and click "assign all"
8. Add texture to this material and then select the texture and mapping coordinates
9. Delete the other material

Properties are imported into AR system via attached xml. After attaching the AR models to specific markers, the AR system is ready to be applied. Animations can be imported into the AR interface via the attached exporter of 3D modelling software, and recognized by the pre-defined markers without using more sophisticated exporter such as OSGExp (de Bérigny Wall and Wang 2008). The standard materials and rendering effects can be securely conserved after been exported. For the step-by-step guidance in operation, pause, resume and other interactions, objective C is chosen as the language to enable the user-input and the control of animation in IOS platform.

The gesture of panning, rotation, clicking and pinching is activated by importing relevant framework. Each of this gesture is linked to specific the control of 3D model or animation, e.g., panning moves the position of virtual model, pinching zooms in/out the virtual model and clicking makes the animation pause or continue, etc. Wayfinding information is retrieved from BIM model and inserted into AR system in php script. The hardware required for the AR system is as simple as one iPad or iPhone. In order to create an immersive working environment, the system could be transferred to a normal windows operational system with PC and Head-Mounted Display (HMD) or OS system. Tracking patterns such as ID marker, picture marker and 3D feature could be chosen in different situation. By scanning a marker, the user could see the 3D model of equipment overlaying on top of real environment. If AR animation is loaded into the system, the user can do interactions with animation. Properties of equipment can be visualized beside the model for the purpose of guidance. Additionally, navigational information retrieved from BIM model helps the user find the shortest and safest path to the specific equipment in maintenance work.

The final outputs are in three types: AR 3D model, AR animation and AR-enabled wayfinding. The three types of AR contents can be viewed in both desktop, mobile computers and tablets such as iPad, iPhone, Windows or

Mac based PC and Android based tablets. Applications of this animated AR system in FM can be classified into five areas as aligned with the five FM benefits aforementioned in the last section: intelligent fault diagnosis, visualized operation guidance, situation awareness, building performance monitoring and mobile route guidance.For example, for intelligent diagnosis, AR can be used to identify the invisible component behind the wall. With AR's context-aware characteristics facility manager can view the affected zone of the damaged component in real environment efficiently and effectively. Working status, navigation and maintenance can be retrieved from BIM model in order to monitor building performance, guide the facility manager to find specific equipment and provide instructions of operation.

CASE STUDY

This approach has been applied into a chosen scenario in this case study. The target healthcare project is located in Perth. The layout of equipment in healthcare project is reasonably complicated and has the strong need for an effective method to increase its maintenance efficiency. As stated in the introduction section, the traditional FM software is not intuitive and the data is scattered. The BIM+AR solution can improve the efficiency of FM by providing the right information in the right place efficiently and intelligently. A Magnetic Resonance Imaging (MRI) room of the healthcare project is modelled in Revit Architecture and exported into fbx format, serving as the BIM model. Figure 11-5 shows the BIM model of the MRI room.

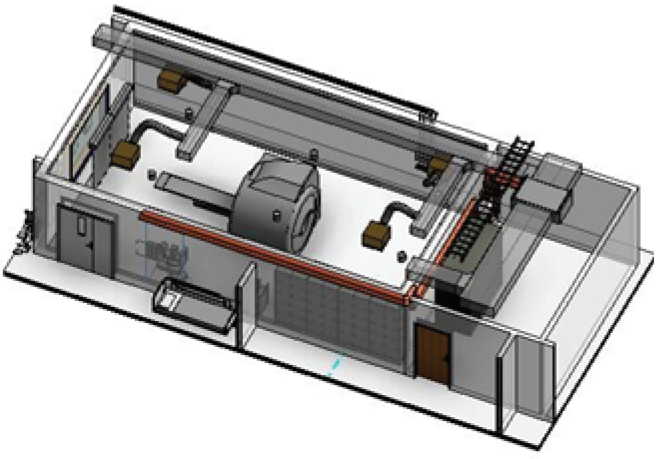


Figure 11-5. BIM model of the MRI room.

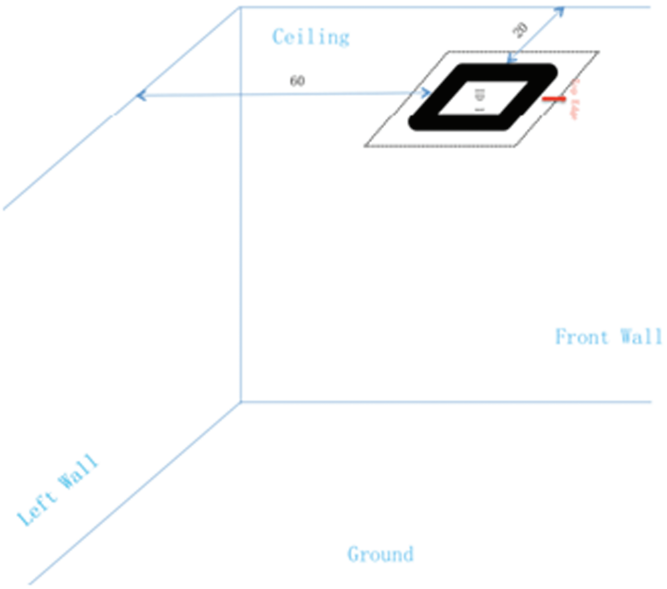


Figure 11-6. Marker (ID1) on the ceiling.

Four equipment facilities are chosen for AR visualization (depicted in Figure 11-8, 11-9 and 11-10), each of which was positioned on the ground, ceiling, and the two walls respectively, as shown in Figure 11-6 and Figure 11-7. All of the BIM models are created in Revit Architecture and exported into fbx format. Figure 11-6 and Figure 11-7 depict the way the markers are positioned, e.g., markers are set vertically on the walls, and horizontally on the ground and the ceiling to have the AR context superimposed onto different patches of the room. Figure 11-6 shows that the marker (ID 1) was immobilized onto the roof. The distance from the border of the marker was designed to be 20 cm to the Front wall and 60 cm to the left wall separately. The distance from the marker to the ground may vary from the height of user. Figure 11-7 depicts the position of marker ID2, ID3 and ID4 in the same way.

The positions of each marker can be prescribed in the BIM model. In the predesign of AR scenario, the size and position of each marker can be marked in the BIM model. Preferable observing distance can be marked in the BIM model as well for a better experience of the virtual model. These markers are arranged according to the predefined positions and sizes, thus the user can have a sense of standing in the real MRI room. All of these models are shown in real scales. In order to ensure the rendering quality and speed, the shadows of models are baked as the adhering textures in jpg format in 3ds Max. Scanning the marker ID1, ID2, ID3 and ID4 with a mobile device will bring out the specific model. The model of the hidden pipes (Figure 11-8), AR animation (Figure 11-10), Air-Conditioning

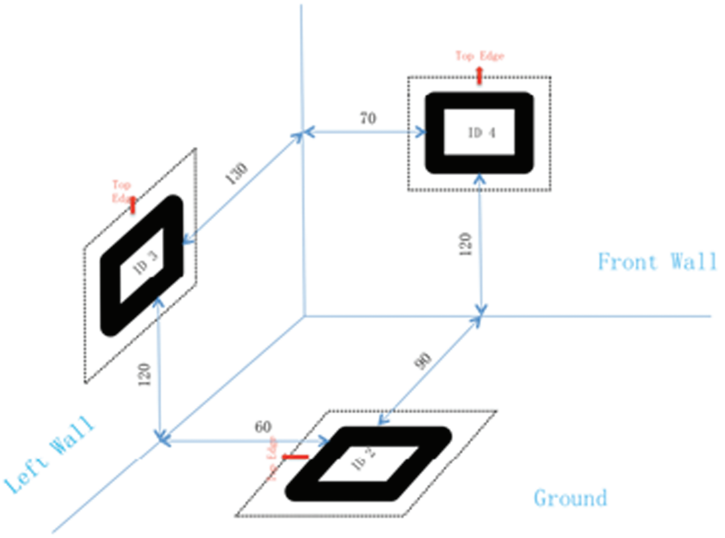


Figure 11-7. Markers (ID2, ID3 and ID4) on the ground, left and front wall.

(AC) units and MRI equipment will be superimposed on top of the real environment.The AR system is used to identify the location of the invisible pipes behind the wall, provide a step-by-step guidance of operation, design and update the layout of equipment facilities, and facilitate in finding the specific equipment.

This case study highlights four application scenarios of the integrated approach of BIM and AR:

1. Identifying the location of hidden components
2. AR-enabled step-by-step guidance for maintenance procedure
3. Layout arrangement of equipment
4. Mobile Route Guidance for maintenance

As stated in the introduction, data integration in traditional FM is poor. Massive time is wasted in looking for information in FM. The context-aware characteristics of AR can help the FM personnel get the right information efficiently. In this case, maintenance is the main task. Thus efficient identification of the location of hidden components can improve the productivity. Time of looking for specific manuals is saved because AR-enabled step-by-step guidance can show the relevant maintenance procedure clearly and intelligently. Layout arrangement of equipment enables the view of as-planned and as-updated layout prior to putting them in space. Last but not least, mobile route guidance provides a preferable way of navigation which saves the time of searching for the location of specific components. BIM model stores both the geometry and properties. Since most of these information is predefined in BIM, these four applications could be scaled up easily for BIM enabled FM projects.

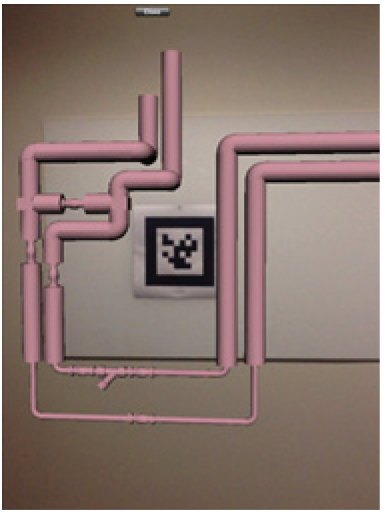


Figure 11-8. Virtual piping system behind the wall.

Identifying the Location of Hidden Components

In the FM process, the hidden components' positions are difficult to be identified efficiently and precisely. For example, traditionally, when the FM personnel are requested to fix the leaking pipeline behind the wall, they refer to the as-built drawing to identify the location of the pipe. This may lead to the imprecision in punching on the wall. In this case study, the pipeline system on the wall consists of several components extracted from BIM. Figure 11-8 shows that AR can provide a view of the hidden pipes behind the wall. With this function, the facility manager can efficiently locate the right position of a specific pipe when leakage occurs. The process indicates the following four steps:

1. The facility manager is requested to fix a leaking pipe
2. From what has been requested, the facility manager understands the rough position of the leaking point of the pipe, which, as stated in Figure 11-6, is on the right hand side of wall
3. He decides to start with the left-most pipe
4. He scans the pre-arranged marker on this wall to view the virtual pipe in the AR system and points the component's position on the wall

Information retrieval capacity typically differs between individuals since it depends on personal expertise obtained from training or practicing, as well as the difficulty of the task itself. Effective retrieval capacity refers to a series of fast mental behaviours, i.e., searching, analysing and interpreting information. A low level of individual retrieval capacity on the other hand, generally hampers the transition from informational novice to expert. From the perspective of searching

for and accessing information, operating information is detached from equipment, tools, and materials. Nevertheless, control panels and lighting which are used frequently allow physical labels or tags to be attached. The worker needs to search some types of medium for information, often in the form of an annotated drawing or manual print. A great deal of time is typically spent on finding and reading procedural and related information. It seems obvious therefore, that accelerating the search for information would benefit task performance. Animated AR visualisation can save the worker a time-consuming search by triggering information with little user effort. It provides a more effective method that aids information retrieval compared with conventional assembly guidance, where unilateral information retrieval behaviour is supplanted by the interaction between multimedia and the human.

AR-Enabled Step-by-Step Guidance

In the conventional FM process, FM personnel need to refer to massive manuals, certificates and other relevant information to find the right information effectively. It is difficult to look for the right information in the right place. Efficient identification of hidden components' locations can improve the productivity. Time wasted in looking for specific manuals is saved because AR-enabled step-by-step guidance can show the relevant maintenance procedure clearly and intelligently. The guidance of operational procedure can be shown in the AR system step-by-step to give the facility manager clear instructions. In this case study, the procedure of unscrewing a shut-off valve access panel is animated in the AR system. Firstly, the fbx models of the pipes, screws, valves and the screw driver are imported into 3ds Max. Then the step-by-step animations are created and exported into the AR system. By scanning the marker (ID3) in Figure 11-7 with an iPad, the facility manager can observe this animation in real environment (depicted in Figure 11-9). The procedure animated to guide the operation follows these steps:

1. Unscrew the shut-off valve access panel (Figure 11-10a)
2. Rotate the handle anti-clockwise 180 degrees starting from the left hand air pipe (Figure 11-10b)
3. Repeat this process for other four pipes
4. Re-screw shut-off valve access panel
5. Add "OUT OF ORDER" tags to the front of the pipes (Figure 11-10c)

The user can play, pause and replay the animation, as well as move the virtual images in the augmented scene. Another characteristic feature of animated AR visualisation means are in lending collaborative guidance to the user. Within each assembly step, augmented animation dynamically and sequentially ushers the position changes of spatial components in a way that the user triggers each animation segment. When completing each animation segment, AR turns into a visual tool for presenting the statically augmented images of the component, as

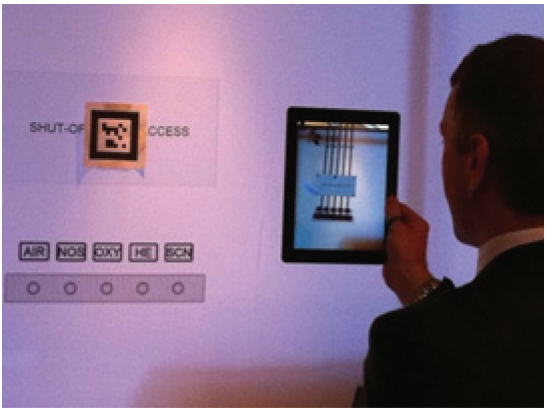


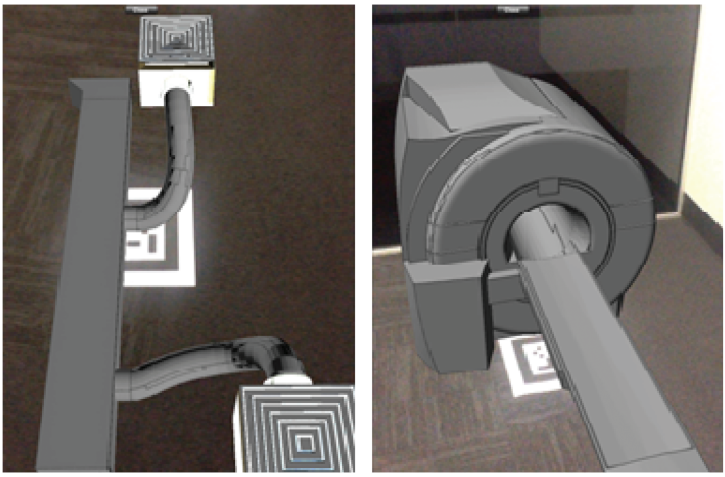
Figure 11-9. AR animation in iPad.



(a) (b) (c)

Figure 11-10. Guided process of example scenario in the AR system.

well as the attached information. In parallel, this pattern is temporarily suspended for the next triggering by users. At each suspended interval (after the preceding section of guiding animation), users have sufficient time to inspect the problems to date and to process the information for the repair of the next component. Through this method, implementing the repair and retrieving the augmented guidance can be conducted collaboratively and simultaneously. Following this step by step collaboration, the visualisation means is also able to improve the performance of the repair men. By seeing the animated repair process, plus the sequence information being built into the AR visualization, this made it possible for the inexperienced novice repairmen to develop problem solving skills after the AR training.



(a) (b)

Figure 11-11. Virtual equipment visualized in AR.

Layout Arrangement of Equipment

In the FM process, layout of equipment needs to be updated in some circumstance. It is difficult to move the equipment into the space and arrange them in a proper location. Both time and cost are wasted in this process. Layout arrangement of equipment in each room could be predesigned in BIM and then visualized in real context via the AR system prior to putting them in place. This enables the FM personnel arrange the layout of equipment in an easier way. Simply by rotating and moving the marker, the virtual model will rotate and move in the same way. On the ceiling, AR shows an AC unit (see Figure 11-11a). The virtual AC units attached to a real roof are in a real scale. On the floor, AR shows the MRI equipment (see Figure 11-11b). The virtual model's position and angle will be changed in the AR scene when the user moves or rotates the marker. Thus the user can efficiently arrange the position of equipment where they prefer to. Displaying these real-scale models in AR scene provides the user an immersive environment.

Mobile Route Guidance

Last but not least, the facility manager regularly finds the way to the target equipment based on his or her familiarity with the hospital. This may not be the shortest path. Additionally, there is a probability of running into potential hazards for lack of relevant knowledge. Since some equipment may injure the facility manager, travelling path needs to be identified in a striking way. The AR system can offer navigation for facility managers' travelling in the maintenance process. With the navigation function of this AR system, travelling time can be reduced. Potential hazards can be also avoided with warning in the AR scene. The AR

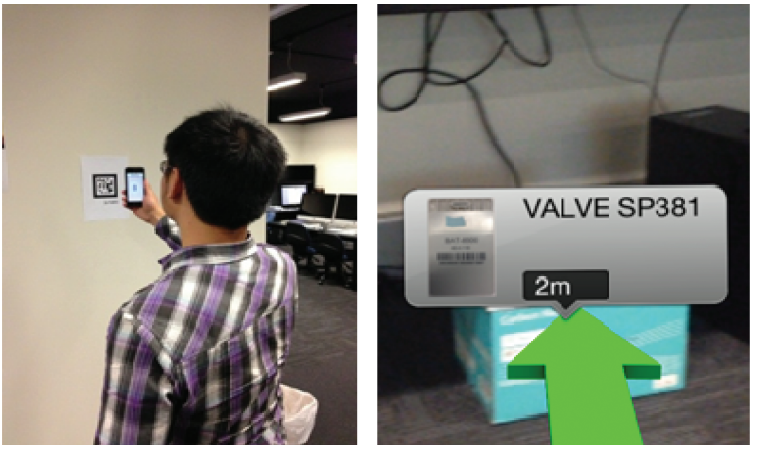


Figure 11-12. Navigational information in the AR system.

system can show the shortest path and warning information predefined in BIM. This could reduce facility managers' time cost in looking for equipment and ensure their safety. Figure 11-12 shows that the user scans the marker with an iPhone. Then a green arrow indicates the direction of the box containing the target valve. The real time navigational information in the AR system helps the FM personnel find the specific component in an efficient way. Additionally, this ensures the safety of FM personnel by highlighting the potential hazards.

CONCLUSIONS

Operation and maintenance normally involve a large number of collaborative tasks across different geographical locations and domain expertise. The preliminary case study reveals that FM personnel making use of AR and BIM can cope with enormous information flow more effectively and efficiently, compared with using the traditional index sheets with a mass of drawings. AR enables the "walking-through" functionality, which can particularly facilitate the review process right on the site, as AR, by nature, involves the human sensations with both real and virtual information sources. Due to the lack of investigations or insights of how BIM can be integrated with AR to support the onsite FM work, the previous research has not fully addressed the issues such as, how to up-scale and fully apply the BIM context in the real space via AR, how to effectively visualize the maintenance instruction in step-by-step animations, and how to dynamically generate the route within a building using a AR-supported visual system and the BIM models. To address these issues, this chapter demonstrates the viability of implementing BIM and AR as a context-aware visualization platform in four FM cases, from which a series of technological deployments are presented.

The demonstration also reinforces the evidences that the BIM+AR context-aware platform is conductive to reasoning the interdependences of tasks, designing the spatial site layout of the to-be-positioned, linking digital context to physical environments, visualizing maintenance instruction and so on.

FUTURE WORK

In future, in order to realize ubiquitous and accurate AR, more technologies such as laser pointing can be considered to introduce which can. Moreover, the currently applied marker-based tracking systems within AR can be replaced by markerless-based tracking or feature-based 3D tracking to improve the flexibility of deploying AR devices.

ACKNOWLEDGMENT

Acknowledgement goes to CSI, which provided the BIM models, project information presented in this book chapter, and the contributed time of their experts to the research and developmental work that have been described and presented in this book chapter.

References

Aaron Costin, N. P., Teizer, J., and Marks, E. (2012). "Real-time resource location tracking in Building Information Models (BIM)." *In Cooperative Design*, Visualization, and Engineering, pp. 41–48. Springer Berlin Heidelberg, 2012.

Akcamete, A., Akinci, B., and Garrett, J. H. (2010). "Potential utilization of building information models for planning maintenance activities." *Proceedings of the International Conference on Computing in Civil and Building Engineering*.

Becerik-Gerber, B., Jazizadeh, F., Li, N., and Calis, G. (2012). "Application areas and data requirements for bim-enabled facilities management." *Journal of Construction Engineering and Management*, 138(3): 431–442.

Benbelkacem, S., Zenati-Henda, N., Belhocine, M., Bellarbi, A., Tadjine, M., and Malek, S. (2010). "Augmented reality platform for solar systems maintenance assistance." *EFEEA'10 International Symposium on Environment Friendly Energies in Electrical Applications*.

Boessenkool, H., Abbink, D., Heemskerk, C., Steinbuch, C., de Baar, M., Wildenbeest, J., Ronden, D., and Koning, J. (2013). "Analysis of human-in-the-loop tele-operated maintenance inspection tasks using VR." *Fusion Engineering and Design* 88(9): 2164–2167.

Cardellino, P. and Finch, E. (2006). "Evidence of systematic approaches to innovation in facilities management." *Journal of Facilities Management*, 4(3): 150–166.

Chen, C., Dib, H. Y., and Lasker, G. C. (2011). "Benefits of implementing building information modeling for healthcare facility commissioning." *Computing in Civil Engineering*: 578–585.

Chi, H.-L., Kang, S.-C., and Wang, X. (2013). "Research trends and opportunities of augmented reality applications in architecture, engineering, and construction." *Automation in Construction*, 33: 116–122.

Cotts, D., Roper, K. O., and Payant, R. P. (2009). *The facility management handbook*. New York, NY: AMACOM.

Costa, A., Keane, M. M., Torrens, J. I., and Corry, E. (2013). "Building operation and energy performance: Monitoring, analysis and optimisation toolkit." *Applied Energy*, 101, 310–316.

de Bérigny Wall, C. and Wang, X. (2008). "Interactive Antarctica: a museum installation based on an augmented reality system." *Proceedings of the 3rd international conference on Digital Interactive Media in Entertainment and Arts*, pp. 319–325. ACM, 2008.

De Toni, A. F., Fornasier, A., Montagner, M., and Nonino, F. (2007). "A performance measurement system for facility management: the case study of a medical service authority." *International Journal of Productivity and Performance Management* 56(5/6): 417–435.

Dong, A., Maher, M. L., Kim, M. J., Gu, N., and Wang, X. (2009). "Construction defect management using a telematic digital workbench." *Automation in Construction*, 18(6): 814–824.

Dunston, P. S. and Wang, X. (2011). "A hierarchical taxonomy of aec operations for mixed reality applications." *Journal of Information Technology in Construction*, 16: 433–444.

Frankenstein, J., Brüssow, S., Ruzzoli, F., and Hölscher, C. (2012). "The language of landmarks: the role of background knowledge in indoor wayfinding." *Cognitive processing*, 13(1): 165–170.

Golparvar-Fard, M. and Ham, Y. (2013). "Automated diagnostics and visualization of potential energy performance problems in existing buildings using EPAR-Energy Performance Augmented Reality-Models." *Journal of Computing in Civil Engineering*, 28(1), 17–29

Henderson, S. J. and Feiner, S. (2009). "Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret." *Mixed and Augmented Reality, ISMAR 2009. 8th IEEE International Symposium on*, pp. 135–144. IEEE.

Hincapie, M., Caponio, A., Rios, H., and Mendivil, E. G. (2011). "An introduction to Augmented Reality with applications in aeronautical maintenance." *13th International Conference on Transparent Optical Networks (ICTON)*, pp. 1–4. IEEE.

Hou, L. and Wang, X. (2011). "Experimental framework for evaluating cognitive workload of using ar system for general assembly task." *Proceedings of the 28th International Symposium on Automation and Robotics in Construction*.

Hou, L. and Wang, X. (2013). "A study on the benefits of augmented reality in retaining working memory in assembly tasks: A focus on differences in gender." *Automation in Construction*, 32: 38–45.

Lavy, S. (2008). "Facility management practices in higher education buildings: A case study." *Journal of Facilities Management*, 6(4): 303–315.

Lee, J. Y., Seo, D. W., and Rhee, G. (2008). "Visualization and interaction of pervasive services using context-aware augmented reality." *Expert Systems with Applications*, 35(4): 1873–1882.

Lee, S. and Akin, Ö. (2011). "Augmented reality-based computational fieldwork support for equipment operations and maintenance." *Automation in Construction*, 20(4): 338–352.

Lennerts, K., Abel, J., Pfründer, U., and Sharma, V. (2005). "Step-by-step process analysis for hospital facility management: An insight into the OPIK research project." *Facilities*, 23(3/4): 164–175.

Leung, M. Y., Lu, X., and Ip, H. Y. (2005). "Investigating key components of the facility management of secondary schools in Hong Kong. Facilities," 23(5/6), 226–238.

Liao, C., Tan, D., and Li, Y. (2012). "Research on the application of BIM in the operation stage of green building." *Applied Mechanics and Materials*," 174–177: 2111–2114.

Lin, Y.-H., Liu, Y.-S., Gao, G., Han, X.-G., Lai, C.-Y., and Gu, M. (2013). "The IFC-based path planning for 3D indoor spaces." *Advanced Engineering Informatics*, 27(2): 189–205.

Liu, R. and Issa, R. R. A. (2012). "Automatically updating maintenance information from a bim database." *Computing in Civil Engineering*: 373–380.

Madritsch, T. and May, M. (2009). "Successful IT implementation in facility management." *Facilities*, 27(11/12): 429–444.

Meng, X. and Minogue, M. (2011). "Performance measurement models in facility management: a comparative study." *Facilities*, 29(11/12): 472–484.

Motamedi, A. and Hammad, A. (2009). "Lifecycle management of facilities components using radio frequency identification and building information model." *Information Technology in Construction*, 14 (Special Issue "Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning"): 238–262.

Motawa, I. and Almarshad, A. (2013). "A knowledge-based BIM system for building maintenance." *Automation in Construction*, 29: 173–182.

Mudrak, T., van Wagenberg, A., and Wubben, E. (2005). "Innovation process and innovativeness of facility management organizations." *Facilities*, 23(3/4): 103–118.

Nousiainen, M. and Junnila, S. (2008). "End-user requirements for green facility management." *Journal of Facilities Management*, 6(4): 266–278.

Park, J., Kim, B., Kim, C., and Kim, H. (2011). "3D/4D CAD applicability for life-cycle facility management." *Journal of Computing in Civil Engineering*, 25(2): 129–138.

Park, C.-S., Lee, D.-Y., Kwon, O.-S., and Wang, X. (2013). "A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template." *Automation in Construction*, 33: 61–71.

Pennanen, A., Whelton, M., and Ballard, G. (2005). "Managing stakeholder expectations in facility management using workplace planning and commitment making techniques." *Facilities*, 23(13/14): 542–557.

Piekarski, W. and Thomas, B. H. (2002). "Using ARToolKit for 3D hand position tracking in mobile outdoor environments." *Augmented Reality Toolkit, The First IEEE International Workshop, pp. 2–3. IEEE.* doi: 10.1109/ART.2002.1107003

Proctor, R. W. and Van Zandt, T. (1984). *Human factors in simple and complex systems*, Needham Heights, MA: Allyn & Bacon.

Rasys, E., Hodds, M., Dawood, N., and Kassem, M. (2014). "A web3D enabled information integration framework for facility management." *In Australasian Journal of Construction Economics and Building-Conference Series*, 2(1), 1–12.

Sharma, V., Abel, J., Al-Hussein, M., Lennerts, K., and Pfründer, U. (2007). "Simulation application for resource allocation in facility management processes in hospitals." *Facilities*, 25(13/14): 493–506.

Shin, D. H., Dunston, P. S., and Wang, X. (2005). "View changes in mixed reality-based collaborative virtual environments." *ACM Transactions on Applied Perception, Association for Computing Machinery (ACM)*, 2(1), 1–14.

Stack, P. (2012). "Development of a mobile platform to support building maintenance engineering." *Computer Software and Applications Conference Workshops (COMPSACW), 2012 IEEE 36th Annual (pp. 482–487).* IEEE.

Sun, C. S. and Che, Q. (2012). "BIM-based real-time monitoring of the equipment maintenance of property." *Applied Mechanics and Materials* (Vibration, Structural Engineering and Measurement II): 2217–2221.

Towne, D. M. (1985). *Cognitive Workload in Fault Diagnosis* (No. TR-107). University Of Southern California Los Angeles Behavioral Technology Labs.

Wang, X. and Dunston, P. S. (2006a). "Compatibility issues in augmented reality systems for AEC: An experimental prototype study." *Automation in Construction*, 15(3): 314–326.

Wang, X. and Dunston, P. (2006b). "Potential of augmented reality as an assistant viewer for computer-aided drawing." *Journal of Computing in Civil Engineering*, 20(6): 437–441.

Wang, X. (2007). "Using augmented reality to plan virtual construction worksite." *International Journal of Advanced Robotic Systems*, 4(4): 501–512.

Wang, X. and Dunston, P. (2007). "Design, strategies, and issues towards an augmented reality-based construction training platform." *Journal of Information Technology in Construction (ITcon)*, International Council for Research and Innovation in Building and Construction (CIB), Rotterdam, Netherlands, 12, 363–380.

Wang, X., Gu, N., and Marchant, D. (2008). "An empirical case study on designer's perceptions of augmented reality within an architectural firm." *Journal of Information Technology in Construction (ITcon)*, International Council for Research and Innovation in Building and Construction (CIB), Rotterdam, Netherlands, 13, 536–552.

Wang, X. and Schnabel, M. A. (2008). *Mixed reality in architecture, design, and construction*, ISBN: 978-1-4020-9087-5, Springer-Verlag.

Wang, X. (2009). "Augmented reality in architecture and design: potentials and challenges for application." *International Journal of Architectural Computing*, 7(2): 309–326.

Wang, Y., Wang, X., and Davis, P. (2012). "Augmented reality-based wayfinding: improving human's navigational efficiency in complex buildings." *Proceedings of Australasian Conference on Innovative Technologies in Construction-"From Building Information Modeling to Beyond,"* 125–130.

Wang, X., Love, P. E. D., Kim, M. J., Park, C.-S., Sing, C.-P., and Hou, L. (2012). "A conceptual framework for integrating building information modeling with augmented reality." *Automation in Construction*, 34: 37–44.

Wang, X., Kim, M. J., Love, P. E. D., and Kang, S.-C. (2013). "Augmented reality in built environment: Classification and implications for future research." *Automation in Construction*, 32: 1–13.

Wang, J., Li, S., Wang, X., Mao, C., and Guo, J. (2013). "The application of bim-enabled facility management system in complex building." *International Journal of 3-D Information Modeling (IJ3DIM)*, 2(3): 16–33.

Wang, Y., Wang, X., Wang, J., Yung, P., and Jun, G. (2013). "Engagement of facilities management in design stage through BIM: framework and a case study." *Advances in Civil Engineering*, 2013, 1–8.

Wu, W. and Issa, R. R. A. (2012). "BIM-enabled building commissioning and handover." *Computing in Civil Engineering*, 2012, 237–244.

Yu, J.-H., Lee, S.-K., and An, H.-K. (2012). "An extension of the technology acceptance model for BIM-based FM." *Construction Research Congress 2012*: 602–611.

Zhu, J., Ong, S., and Nee, A. (2013). "An authorable context-aware augmented reality system to assist the maintenance technicians." *The International Journal of Advanced Manufacturing Technology*, 66(9-12), 1699–1714.

Further Reading

Augmented Reality in Architecture, Engineering, and Construction, *Automation in Construction*, Volume 33, Pages 1-136 (August 2013), http://www.sciencedirect.com/science/journal/09265805/33

CHAPTER 12

A Domain-Independent Facility Control Framework

E. William East*
Chris Bogen†

Abstract: *The purpose of our built environment is to provide spaces in which human-designed activities may comfortably occur. An ever-increasing set of technical disciplines, economics, and societal norms place dynamic requirements on those who plan, design, construct, maintain, operate and manage our built environment. In this paper, a domain-independent framework to capture design requirements and then compare those requirements to the actual performance of a facility is presented. The foundations of this framework are five related Industry Foundation Class Model View Definitions that are partially implemented within commercial software and are contained in the United States National Building Information Model Standard (NBIMS-US V3). The application of this framework was tested using an algorithm that compares expected data with as-operated sensor telemetry. This algorithm was verified against simulated data and validated against sensor data. The sample models and tool kit developed for this project's experimental test bed has been adopted by industry and academia to support their missions of streamlining design and construction processes and educating future design and construction professionals. In addition, the initial application of this framework to support wider sustainability, engineering economics, and business process analysis goals is introduced. These applications demonstrate how small additions to structured building information deliverables may quantitatively address current and future requirements placed on our engineered environment.*

*Owner, Prairie Sky Consulting, 1104 Parkview Drive, Mahomet, IL 61853 (corresponding author). E-mail: bill.east@prairieskyconsulting.com.

†Senior Cyber Security Engineer, Fluor Federal Petroleum Operations, 850 S. Clearview Pkwy., New Orleans, LA 70123. E-mail: chris.bogen@spr.doe.

INTRODUCTION

United States Department of Commerce information has for decades shown flat productivity in the construction sector, compared with more than 250% productivity increase in other business sectors (Teicholz 2004). Another widely cited study points to waste amounting to $15.8B per year USD resulting from failure to streamline work and information flows (Fallon 2006). Such findings were not, however, news to the research community. In 1983, a blue-ribbon panel identified potential productivity gains achieved through the application of "Personal Computers" by capturing life cycle building information (BRB 1985). Despite 30 years of using computers in the design office and construction trailer, the production of paper (or e-paper) documents and use of databases for exception reporting remains the common level of use of these amazing machines with their now ubiquitous computer networks. Digitizing one small part of this process, the construction handover data, would have saved the United States over $2B USD per annum (Fallon 2007).

The design and construction industry's ability to implement new approaches and technologies comes at a time when owners and society are making increasing demands of our engineered environment. Examples of such criteria on U.S. Army Corps of Engineers' projects include the Americans' with Disability Act (starting in 1990), life cycle costing (starting in 2004), sustainability (starting in 2010), force protection (starting in 2011) and net-zero energy requirements (starting in 2012). In each case, practitioners have followed the well-worn path of waiting for guidance from technical experts who form organizations supporting each of these individual sets of requirements.

The necessary self-promotion of interest-group organizations has led each group to maximize its individual value, even when such behavior may actually decrease the groups' ability to meet the needs for which it was created. The most egregious of these efforts has focused on a domain currently receiving a high level of attention - energy modeling and sustainability. Leading researchers in the field of energy simulation have stated unequivocally that the results provided by energy simulation models are not reproducible and cannot be trusted due to "arbitrary decisions" made by the energy modeler and incorrect assumptions made by simulation tools (Bazjanac 2008). Other authors have also shown a pattern of deviation between predicted energy use and actual performance of the constructed facility (Polly 2011). Practitioners have argued for years that complex energy models are too difficult to use, but more simplified methods, such as the Leadership in Energy and Environmental Design (LEED) design-by-checklist system, have also proven ineffective. Although tools such as LEED may have raised consciousness, their widespread application has created sufficient problems to generate lawsuits from owners claiming non-performance of highly rated facilities (McLellan 2011). Recognizing these problems, owners are beginning to pull back from LEED requirements. For example, in 2012 the United States Congress prohibited the Department of Defense to provide any funds for LEED certifications above Silver (USC 2012).

Lack of standardized performance measures to evaluate projects, and lack of strategic research direction, have been identified as essential causes of low construction industry productivity (NRC 2009). One reason for the inability to improve different aspects of building performance is the need for a common framework for building information modeling. Sacks (2010) outlines many potential benefits stemming from building information but indicates that, unless a holistic view of these disparate parts can be achieved, it will be difficult for building information technology to have a major impact. Forgues (2012) states that a unified framework is needed to guide the building industry to a more sustainable future. Jung (2011) argues that any such framework must consider both the technology to be used and the business activity being accomplished.

Regardless of the form of a framework, that framework must be clearly specified (London 2011). The lack of specificity in contract clauses that require building information deliverables demonstrates that unless the owner defines their requirements in the contract, the models delivered will vary widely from project to project, and from modeler to modeler. Beyond the creation of a performance-based specification for building information deliverables, there is also a need for a methodology to establish the value of this building information to resolve disputes regarding errors or omissions in the specified deliverables (London 2011). This will inevitably lead to the development of a set of internally coordinated, but task-specific, specifications. In the context of the buildingSMART alliance, projects aimed at creating such specifications are called "information exchange" projects (East 2011a). A key motivation of information exchange projects is to ensure that efficiencies gained by streamlined business processes offset the cost of upgrading software and change management (Duarte 2012).

OBJECTIVE AND APPROACH

While control cycles are the basis of virtually all industrial activities, the facility acquisition process differs significantly from most industrial processes in several ways. These include (1) the lag time between project phases, (2) the variety and number of stakeholders, (3) the variety of software tools used, and (4) the changes introduced throughout the process. This paper introduces a domain-independent framework for building control. The framework is composed of four parts: (1) documentation of design resource requirements, (2) capture of as-designed, as-built, and as-operated facility models, (3) comparison of the as-operated sensor information to the resources needed to operate the facility, and (4) identification of appropriate corrective action.

Effort on this program of work began in 2008 with the creation of a test bed to ensure that efforts on multiple individual projects could be coordinated. Next, projects documenting information exchanges for design processes affecting facility sustainability were conducted. The exchanges necessary to capture building automation and control systems data were defined. Next, the structures needed

to compare facility requirements with actual performance were defined, and a prototype framework developed. Finally, a new data mining and clustering algorithm was developed and tested. This effort resulted in the creation of an adaptive building control and feedback system. Several tests of the extensibility of this framework were also conducted. Now that these projects have been concluded, this paper summarizes this program of work and introduces the overall facility control framework.

TEST BED

A variety of commercial software is used to initiate, plan, design, build, maintain, manage, and operate facilities. The likelihood that proprietary information provided by one commercial software system will be available to any of the parties downstream is small. Proprietary information delivered during the course of a long-duration project may no longer be supported by the time that the project has concluded. Therefore, the creation of a building control framework spanning the facility acquisition process requires the specification of open-standard data exchanges. As a result, the facility control framework was based on the Industry Foundation Class (IFC) Model (ISO 2013). Many commercial software systems currently support the exchange of information in IFC version "2x3". In 2013, the model was updated to version "2x4" or simply "IFC4."

Building Models

Standardized data repositories, in fields of study other than building informatics, contain thousands of banks of scientific data sets and test cases (Marcial 2010). The first open repository for building information was established at the University of Auckland (Amor 2010). Much of the contribution to this initial repository came from buildingSMART international, whose sample models have traditionally focused on software-unit testing for specific building information, such as the geometric representation of steel connection details. To support the development of an overall facility control framework, this project developed a new repository of building information models called the "Common BIM Files" (East 2012). For three buildings, a set of related model files were developed.

The three models correspond to facilities found in many residential, commercial, and campus settings (Johnson 2011). The smallest model was developed from a duplex apartment building design introduced to the United States in December 2009 (East 2012). The IFC 2x3 Coordination Model View Definition file for the duplex apartment building is shown in Figure 12-1. The second model was created from standard drawings and criteria for a two-story office building (USA 2013). The third model was created from a redacted set of construction drawings for a medical/dental clinic. Redacted operations and maintenance manuals are also provided with this clinic model.

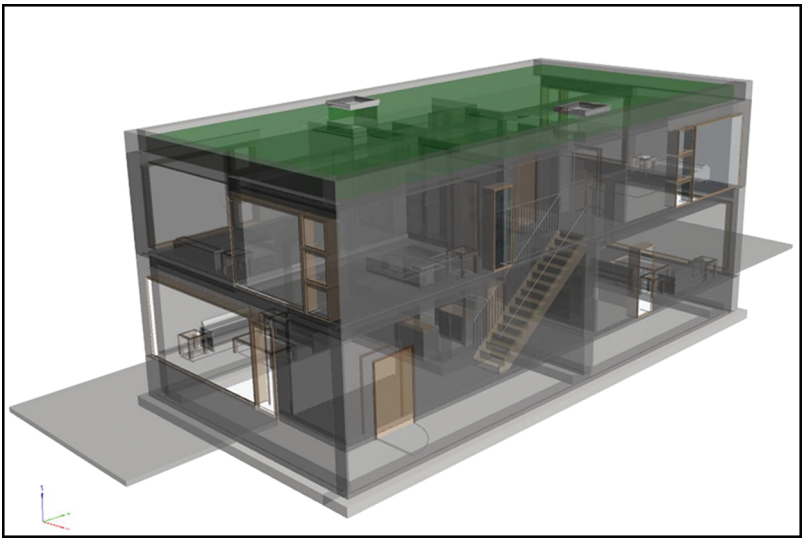


Figure 12-1. Duplex architectural model.

The number of architectural elements in these three models is shown in Table 12-1. During this effort, some problems were encountered with inappropriate mapping of native authoring tool objects to higher-order objects in the IFC model. Some details of these issues, for readers familiar with IFC modeling, are addressed in the following paragraphs. For example, the count of IfcFurnishingElements contained both furniture and casework, which a typical designer, builder, or owner would consider to be different classes of object. Similarly, ifcFlowTerminals contained all plumbing model objects regardless of their capacity as actual flow terminals. For example, toilet grab bars and bathroom mirrors were incorrectly exported as ifcFlowTerminals by the commercial design software used to develop these models.

Table 12-2 summarizes the objects from the Mechanical-Electrical-Plumbing model files of the Duplex Apartment project. These models were also developed using IFC 2x3. Due to changes between IFC 2x3 and IFC4, several objects in the current model are mapped to entities depreciated in IFC4. For example,

Table 12-1. Count of architectural model object types

	Duplex	*Office*	*Clinic*
ifcSpace	22	99	269
ifcDoor	14	102	254
ifcWindow	22	69	71
ifcFurnishingElement	61	7	118
ifcFlowTerminal	105	31	3155

Table 12-2. Summary content count of MEP models

	Duplex	*Office*	*Clinic*
IfcEnergyConversionDevice	16	3	16
ifcFlowController	6	12	173
ifcDistributionControlElement	2	0	5
IfcFlowMovingDevice	4	25	154
IfcFlowStorageDevice	0	1	3
IfcFlowTerminal	105	1456	3155

IfcEnergyConversionDevice includes both electrical transformers and air-cooled chillers. The more precise mapping in IFC4 would have required these objects to be exported as ifcTransformer and ifcChiller objects. Several other components that might have been better mapped to more precise object types are found under the depreciated IFC 2x3 object ifcFlowMovingDevice. These include Variable Air Volume (VAV) boxes, air handling units, and fans. Probably the most over-specified type in the IFC 2x3 models was IfcFlowTerminal, which included air diffusers, electrical receptacles, fire sprinklers, and lights. Other objects were more appropriately mapped. For example, valves and strainers were both correctly mapped to ifcFlowController objects.

Since the initial publication of the models in 2010, progress has been made by software vendors to create models whose information matches that found on the equivalent contact drawings. This progress has been, in part, due to the publication of a series of these three models models. The improvements made to design software exports can be found in the sample files submitted by software vendors participating in buildingSMART alliance Challenges.

Tool Kit

In addition to having a common set of test models for this project, the team also developed a common software tool kit based upon bimserver.org (Beetz 2010). This tool kit meets several important criteria that promote its use as a research and practice instrument. First, the performance of the tool kit has been benchmarked against large building models. Thus, techniques developed for research purposes may scale to realistically sized projects. This is important since the underlying platforms of many research prototypes are unable to scale for production. Second, the tool has attracted talent from practitioners and researchers who want to use a building-information server without having to invest the time to develop underlying functionality outside their main research objectives. Next, an open-source development platform provides transparency and repeatability – hallmarks of high-quality scientific research. Finally, the licensing of the bimserver.org allows the tool to be used for both research and commercial applications. Both the size of models allowed and the scope of server licensing may help research outputs to be more quickly used by their intended beneficiaries.

The first contribution to bimServer.org made during this project was to transform and test building information submitted against Construction Operations Building information exchange (COBie) specification (East 2013). The purpose of COBie is to exchange information about managed and maintained assets during the life of a project. Specific sets of building information, such as those needed for construction handover, are defined in the United States National Building Information Model Standard as subsets of the overall IFC standard. These IFC subsets are called Model View Definitions (MVDs). All MVDs apply the same underlying IFC model representation to solve their specific problem. The difference between model views may be characterized by the list of included objects, their required level of detail, and business rules that enforce specific characteristics required by the associated business case.

Differences between MVDs may be found, for example, when comparing the Coordination Model View Definition and the MVD found in the COBie project (which will be referred to simply as COBie). These differences arise because the Coordination View contains information needed to detect geometric collisions while COBie contains information about managed assets. Clearly there are some aspects shared by both data sets. For example, concepts for facilities, floors, and equipment are shared. But there the similarity ends. The Coordination View includes structural elements, architectural walls and details, plumbing piping and fixtures, and Heating, Ventilating, and Air Conditioning (HVAC) piping, ducts, and equipment. Of all of those objects, only the spaces, plumbing fixtures, and HVAC equipment (and similar products) are necessary to catalog the managed assets required by COBie.

The level of detail in the Coordination View also differs from that needed in COBie. The Coordination View contains the detailed geometry of each item in its data set. Information about the geometry of material layers, such as insulation thickness on structural and fluid-distribution elements is also in the Coordination View. COBie, as a catalog of managed assets, does not require such specificity. The only geometric concept in COBie is that of spatial containment. Containment information in COBie is required to ensure that the building occupant is able to find the physical location from which each asset is maintained.

Finally, there are differences in business rules that define the quality of the information in the two model views. The Coordination View only requires that there be a globally unique identifier for each object. COBie, on the other hand, is intended for human uses related to facility operations, maintenance, and asset management. As a result, the COBie business case requires the names of all COBie assets to be unique. Without such stringent requirement, a service order that says "Change the oil in Compressor-05 in Room 003" would be ambiguous.

MVDs specify the information content required to streamline a well defined business processes but do not, necessarily, mandate the physical format of how that information is delivered. The default format for an MVD is the IFC STEP Physical File Format (SPFF). Not all computer programmers and users will be interested in learning the details of SPFF. A key innovation of the United States National BIM Standard (NBIMS-US) is that formats other than SPFF are

acceptable if non-ambiguous mappings can be defined. Given that the eXtinsible Markup Language (XML) is the cornerstone for the majority of current cloud computing applications, NBIMS-US has allowed mappings to a variety of XML-based schema. For example, COBie data may be prepared in any one of three XML-based schemas. ifcXML transforms STEP files directly to XML according to rules developed by the STEP community. While this format is recognized by buildingSMART international, it has not gained wide acceptance due to the size and complexity of the required schema. The next format is a National Information Exchange Model (NIEM) compliant XML schema suitable for programmers who may not want to learn the details of SPFF but who are eager to use facility asset information provided in a clean XML schema with an existing, United States user base. The simplicity of this XML schema led the authors to name this style of presentation "COBieLite."

Since COBie information needs to be verified and checked by people, a practitioner-accessible XML format for COBie data has also been provided. SpreadsheetML is an XML-based spreadsheet schema used by commercial spreadsheet software. It is often the case that those learning about COBie consider SpreadsheetML to be the standard, this is not the case. COBie is a specification of a required set of data about managed assets. Data meeting the COBie specification may be presented in SPFF, ifcXML, COBieLite, or SpreasdsheetML.

Regardless of the presentation format, the ERDC Tool kit is able to transform between these formats. The translation mappings are published both in the COBie Responsibility Matrix (East 2011) and the COBie standard published in NBIMS-US V3. These transformations ensure that SPFF files converted to other formats have zero loss of the information required by the COBie specification. This does not, however, mean that the files are perfectly the same. Small differences arise due to schema mapping rules because some schema contain information not needed by other schema. For example, in SPFF, the Globally Unique Identifiers' (GUID) of some linking objects are not maintained when that information is transferred to XML-based formats. Such differences are outside the scope of COBie requirements since the underlying asset information is not affected. Software vendors who have extended their Coordination View files to include COBie have also used the tool kit to filter out geometric information in the Coordination View that is not required in COBie. While it is possible to have COBie information transformed between XML-based and SPFF presentations, the contents of that transformation are based on the requirements of the COBie business case alone.

The tool kit's second application was to evaluate the format and referential integrity of files submitted for testing against the COBie specification. The tool kit has been used by over two-dozen commercial software systems to verify COBie compliance. Verification and validation rules in the tool kit are represented using the Schematron Definition Language (ISO 2006), a royalty-free standard from the International Organization for Standardization (ISO). Schema standardization efforts such as the US National Information Exchange Model (NIEM) use Schematron to represent complex validation rules for XML documents. Developing rules based on an established validation language, as opposed to hard-coding

the rules into the toolkit applications, provides more opportunities for collaboration and extensibility.

With the development of a common set of building information models, and the tool kit as the basis for working with those models, the team set about defining the information needed to effectively manage the natural resources used in a facility. This effort began with the evaluation of the expected resources required for the facility to perform its mission. Systems supplying heating, cooling, electricity, and water were also defined. One final model view was also required to capture information generated by building automation and sensor systems. The paragraphs below describe these efforts.

MODELING RESOURCE REQUIREMENTS

Building requirements are specified during the planning and architectural programming phase of a project. Discussions between owners, planners, and architects document the activities that are to take place within the facility. The architectural program is a set of information that describes one specific approach to meeting the needs of these activities. The most common artifact produced during the programming stage is the Room Data Sheet. The details provided with each room are, to a large degree, governed by the sophistication of the owner. Large owners will often have complete templates for the requirements of each type of space; smaller owners will not. The open standard specification of building programming (Jerving 2011) has been demonstrated in several public buildingSMART alliance meetings. The name of this specification is the Building Programming information exchange (BPie).

The typical set of programming information is not, however, sufficiently defined to describe the use of water, electricity, and other natural resources needed to enable the required activities. Additional necessary information includes the occupancy of the facility and parameters describing resource consumption (Chasey 2012). Occupancy information includes the building code classification of the facility, the various types of occupants using the space, and the expected and peak usage duration of these occupants. Parameters for required resources based on those occupancy levels were developed for water, electrical power, HVAC, and lighting. These parameters are applied based on relevant building codes and on the equipment installed in each building space. Properties mapping these parameters to specific equipment were identified in Kalin (2013) and (Fallon 2012).

MODELING RESOURCE-INTENSIVE SYSTEMS

Given the widespread interest in issues related to sustainability and energy modeling, this project focused on design disciplines whose systems require the ongoing use of natural resources within the built environment. The systems

selected for investigation under this project, therefore, were the HVAC system (Hitchcock 2012a), the domestic and waste water distribution systems (Chipman 2013b), and the interior electrical distribution system (Chipman 2013a). For each project, business-process models documented the information exchanges needed to support the coordinated design stage of a project. Teams of subject-matter experts and practitioners validated each result. These process models were developed using Business Process Modeling Notation (BPMN) (OMG 2011) to ensure that the resulting work would be compatible with requirements for submission of this information to the NBIMS-US. Each process model was organized into "swim lanes" according to responsible party. The owner, architect, design consultant, and product manufacturer each had its own swim lane. Within a given lane, the level of detail of the tasks differs from that of the level of definition in Critical Path Method (CPM) schedules. The level of detail required for these process models only defined activities that produced or required information to be consumed or produced by others in the process.

Figure 12-2 provides an example business process model describing the actions and information needed for HVAC schematic design. The overall project contained several such process models. For the HVAC schematic design process, three horizontal bands (swim lanes) were needed to model the business process at the appropriate level of detail. The bottom lane contains those activities accomplished by the architect. Of course, the architect does many other types of activities, but only the activities shown in Figure 12-2 are those related to the HVAC schematic design process. The top lane contains activities completed by the HVAC consulting engineer. To emphasize that the purpose of this business process model is to identify information flows, a middle lane modeling these information flows is added to the diagram. This middle lane explicitly names each set of information provided by the architect to the consultant and identifies those information objects that are required, or are produced as part of the HVAC schematic design process.

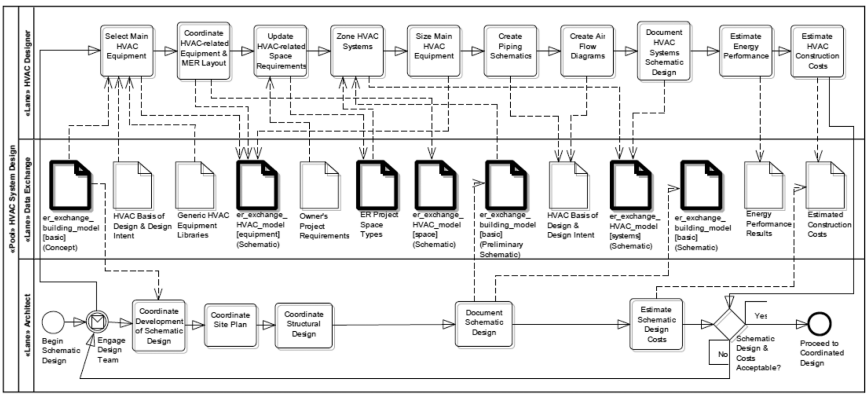


Figure 12-2. HVAC schematic design process model.

The goal of the process-modeling effort is not to develop a comprehensive model of everything, but for subject-matter experts to articulate the minimum sets of information needed to achieve the specific objectives of the project at hand. In the case of the HVAC schematic design process, subject-matter experts identified seven of thirteen information exchanges as the minimum set of required information. Three of the omitted exchanges pertained to the documentation of design requirements and intent. The three other exchanges provide reports of HVAC design to other, related business processes.

Once a set of process models was complete, the contents of all information exchanges were documented and collated. For most exchanges, there are similar sets of information needed to support different processes. For example, information about name of the project and general layout of the building is a set of information created by an architect and then reused in many exchanges. For a given modeling project, the collated set of process models and exchange requirements is called, in the context of the buildingSMART, an Information Delivery Manual (IDM). The buildingSMART alliance does not currently maintain a master list of exchange requirements developed for multiple projects.

The next steps were to begin mapping these exchange requirements into the underlying IFC data model specification. The compiled set of these specifications for a given purpose is the MVD.

Once the specifications were completed, a test of the ability of commercial software to produce conformant IFC files was accomplished for the HVAC (Hitchcock 2012b), water (Fallon et al. 2013a), and electrical (Williams 2013) system. Illustrations of MVDs for Duplex Apartment Building are shown in Figures 12-3 through 12-5. An early-stage design, such as that found in Figure 12-1, will include both the architectural elements and the architect's expected placement of lighting, plumbing, and other products that provide the owner an idea of the final location of

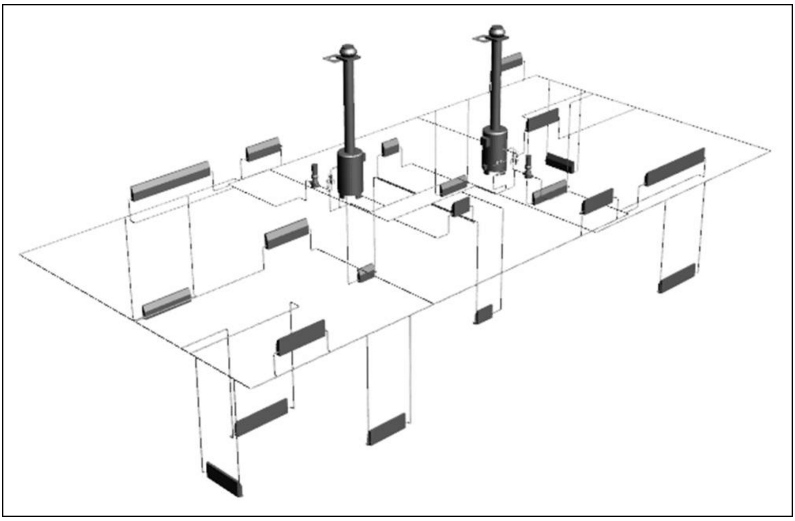


Figure 12-3. Duplex HVAC model.

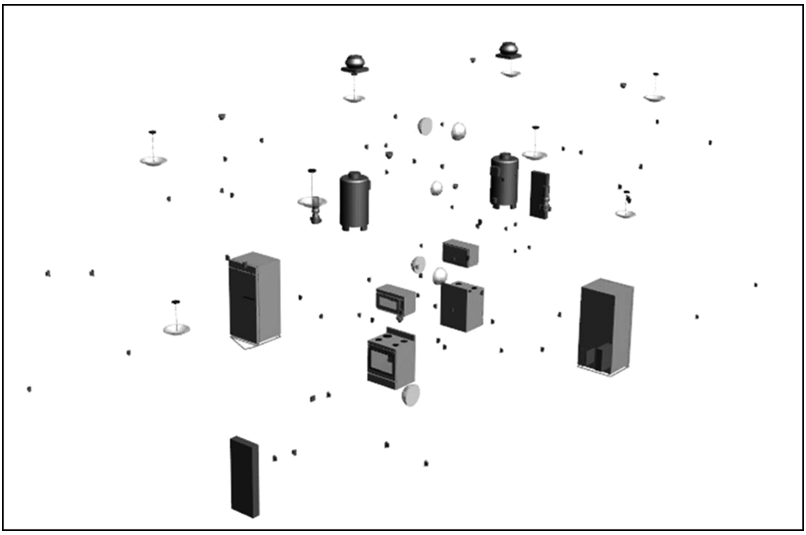


Figure 12-5. Duplex electrical model example.

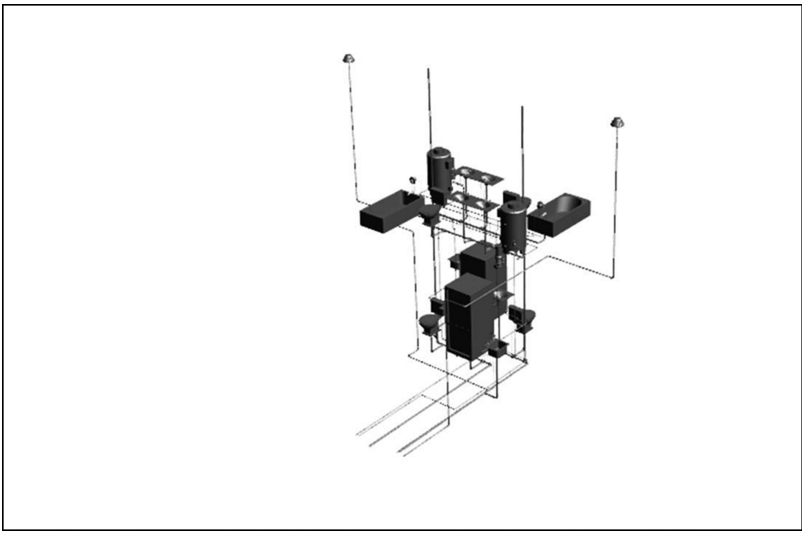


Figure 12-4. Duplex plumbing model.

such products. The final placement of HVAC, water, and electrical components are, necessarily, updated by the specific design disciplines as the design progresses.

As the design passes from the architectural model to the coordinated design stage, additional models are created for each design discipline. The design for the heating and ventilation system of the duplex included the use of a combined hot water heater used for domestic and heating purposes. The HVAC model,

Figure 12-3, illustrates (1) each components of the HVAC system, such as radiators and fans, (2) the assemblies of fans ducts and vents needed to provide proper ventilation in bathrooms, and (3) the connections that allow thermal transmission fluid to flow between the boiler and the radiators.

The duplex plumbing model, Figure 12-4, provides the detailed placement of each plumbing fixture, as well as each of the two combination hot water and heating boilers found in each of the two apartments. In addition to the placement of the equipment, the connections between those components are shown with one-inch water supply piping. The plumbing model provides a good example of the need for multiple model views. While the architectural model, Figure 1, is able to show a plumbing fixture as a single object, the model used for plumbing design requires more detail. For example, the single model of a sink with a fixture and drain must be modeled as three distinct parts: hot and cold water supply valves (or combined valve) and waste drain. Such detailed modeling is required since the capacity of each supply and waste water line is used to support pipe sizing and gray water analysis.

The electrical model, Figure 12-5, provides the final location and properties of electrical components such as receptacles, lighting, and appliances. As with the plumbing model, detailed information is required to allow design work to proceed. An electrical distribution panel, for example, must be modeled as an enclosure box with individual circuit breakers. Specific properties of the conduit and wiring that connects electrical devices is also required since, according to traditional design practice, electrical raceways are typically not shown on contract drawings.

While modeling the geometry of individual components has been implemented for many years in the Coordination View, modeling the connections between these components and assemblies, until recent updates to commercially available software, has not been practical. This is because physical connections between pipes or ducts do not always close in actual design practice. Even if all physical connections "touched," the direction of flow could not be established with geometric information alone. Connections in IFC are defined using ifcPort objects. ifcPort explicitly identifies the upstream and downstream side of the connection. The use of ports is required in each of the discipline MVDs. In the HVAC MVD, ports are required on all equipment, valves, ductwork, and piping. In the plumbing MVD, ports are required on all fixtures, valves, and piping. In the electrical MVD, ports are required for all electrical devices. Properties sets on these ports define the needed types of conduit and conductors for the circuit. Analysis of the capacity of commercial software to support the requirements of these MVDs was also conducted as an additional part of this project.

MODELING SENSOR SYSTEMS

In order to compare information about the actual behavior of a facility with its expected behavior, another information-exchange format and an open standard repository of sensor data needed to be created. The Building Automation

Management information exchange (BAMie) was developed to link closed-loop control data points to assets being measured. BAMie defines the components, assemblies, and connections of a control system, and defines where sensor components (that publish sets of data at a specified frequency) can point to measurements of specific building components. BAMie does not specify the range of values, or associated units, but does specify the IFC representation for addressing in a variety of protocols such as the Open Building Information Exchange (oBIX) (OASIS 2006), LONWORKS, and BACNET.

FACILITY CONTROL FRAMEWORK

When the project team stepped back from the discipline-specific details of each MVD, and that of the sensor system model, a pattern of information emerged that helped to guide the work that went forward. This pattern begins with the specification (BPie) of the expected minimum requirements that the finished facility must meet. Next, the components, assemblies of components, and systems that support services meeting those requirements may be specified (i.e. HVACie, Sparkie, and WSie). Finally, measurements about the performance of those services (BAMie) may be captured by extracting information trapped in closed-loop control systems. Table 12-3 summarizes the standards that comprise the Framework Model.

During the development of the Table 12-3 specifications, information from existing NBIMS-US was also re-used. The primary technical content of the NBIMS-US V2 was the Construction Operations Building information exchange (COBie) standard (East 2011). In the Building Programming information exchange (BPie) specification, information pertaining to room data sheets, spatial requirements, required equipment, and finishes are expressed in IFC format. Comparing COBie and BPie provides a good example how model views may be created from similar shared underlying concepts. Both COBie and BPie share ideas about spaces and equipment. BPie represents the plan for such assets. COBie provides the as-designed and as-built results. There are, however, some differences between COBie and BPie. One new modeling concept is required for BPie. That concept is "Space Type." Concepts in COBie related to maintenance, warranties, and other handover information is also removed from COBie when creating BPie.

Table 12-3. Framework Model specifications

Content	*HVAC*	*Electrical*	*Water*	*Sensor*
Design Requirements	BPie	BPie	BPie	-
Components Assemblies Connections	HVACie	Sparkie	WSie	BAMie

In the HVACie, Sparkie, WSie, and BAMie specifications, COBie MVD information may also found by extracting information about the managed assets found in each of these systems. For example, in HVACie information about a chiller can be exported into a COBie MVD. Information about the components in each of these systems, found in the COBie MVD, is a subset of the overall system model. The system MVD also includes the assemblies of component into assets such as chillers and electrical distribution boards. Also, the physical and logical connections between these assets are defined. The application of the system-specific MVDs within the context of both IFC 2x3 and IFC4 have been evaluated and examples provided through the buildingSMART alliance.

The use of the Framework Model specifications, shown in Table 12-3, may also be evaluated based on coverage of shared business process. An outline for life cycle facility asset-management business processes was initially developed in East 2010. A follow-on study further specified and documented these exchanges, and produced 25 exchanges that develop from owner's planning documents through to construction handover (Fallon 2013d). These exchanges were validated with a group of subject-matter experts. The coverage analysis is provided in Table 12-4. The first column of Table 12-4 provides this validated list of business processes. These processes begin with publication of an owner's standard room data sheets and product requirements (Phases 01-03). The programming phase of the project defines the requirements for the spatial and equipment assets to be delivered (Phases 04-07). The design phase creates the documents required for builders to meet those requirements (Phases 08-13). The construction phase completes the owner's requirements by the instantiation of the required engineered environments (Phases 14-25).

To compare the scope of each MVD, Table 12-4, in columns two through seven lists each MVD in the Framework Model and identifies those project phases addressed. BPie, in column two, covers information during the programming phase. The system specifications, in columns three through six, were developed based on the design phase only. The final project in the Framework Model, COBie, in column seven, is the most mature in terms of process coverage. This difference in coverage reflects the fact that COBie became a US National BIM standard in 2012. BPie, HVACie, WSie and Sparkie are being balloted in the NBIMS-US V3 round which is scheduled to be published in summer 2014. BAMie awaits vendor implementation, but is likely to be balloted in the NBIMS-US V4 round.

CREATING A CONTROL CYCLE

If the units of measure of planned facility performance, as defined in BPie, matched the units of measure of the sensor data, as captured through BAMie, then a cycle that allows management control is possible. While the units of measure (such as temperature, lumens, or occupancy) may match, the level of detail in the information provided does not allow easy comparison. Building programming

Table 12-4. Life cycle Phase coverage

Project Phase/MVD	*BPie*	*HVACie*	*Wsie*	*Sparkie*	*BAMie*	*COBie*
01 - Facility Criteria						
02 - Design Specification						
03 - Feasibility Study						
04 - Project Definition						
05 - Space Program	X					X
06 - Product Program	X					X
07 - Request for Proposal						
08 - Design Early		X	X	X	X	X
09 - Design Schematic		X	X	X	X	X
10 - Design Coordinated		X	X	X	X	X
11 - Design Final		X	X	X	X	X
12 - Request for Proposal						
13 - Inquiry Issue						X
14 - Pre-Construction Plan						
15 - Inquiry Issue (RFI)						X
16 - Product Type Selection						X
17 - System Layout						X
18 - Submittal Package						X
19 - Submittal Issue						X
20 - Purchase Order						
21 - Product Installation						X
22 - Start-Up						X
23 - Product Inspection						X
24 - Punchlist Issue						X
25 - Turnover Package						X

specifications of building performance are based on blocks of time that represent periods of activity, such as a five-day, forty hour work week. For example, general overhead lighting in an interior office would be turned on at 0800 hours and turned off at 1630 hours Monday through Friday (assuming the facility is located in the United States). The actual information on lighting in that interior office may vary significantly from that idealized work time. For example if the workers in the office decided to come in at 0900 instead of 0800, but still work 8-hour days the pattern of work might be considered to be the same.

Vacation days during the work week would also disrupt the expected sensor data stream, but not the pattern of use of that interior office. Alternatively, if the lights in the office were on all day, every day, then this deviation from the expected pattern is likely to represent something other than the expected pattern of electrical use in that office.

The project team generalized three types of deviations in the patterns of signal data that must be resolved when closing the control cycle. The team referred to these deviations as "noise." compared to the clean "signal" provided by the more general pattern expressed in building programming data. The first type of noise is a change in the intensity, or amplitude, of the sensor information when compared with the planned usage. For example, the required temperature set-points in a room may be 68 degrees Fahrenheit during the cooling season, but the actual temperature measurement in the room will vary up and down. The second type of noise is a shift in the start and end of the pattern. For example, an office worker may start and end their day 15 minutes before or after scheduled duty hours. The third type of noise is a change to the frequency of the signal. This type of noise is most prevalent in building assets that are used for a short time by office occupants. An example of the type of pattern that would generate frequency noise is the use of a microwave or coffee pot in an office kitchenette.

To determine if it was possible to compare the clean signal of expected resource use from the noisy information provided by sensor data, the team created a test bed to conduct the analysis. Starting from an example stream of sensor data that matches the expected data pattern perfectly, our team created simulated data streams spanning the entire solution space of signal-to-noise ratio. A data-cleaning and pattern-detection algorithm was created to determine if it would be possible to evaluate the expected data stream when compared to that same data stream at different levels of noise. This algorithm considers only individual sensor data; the resolution of multiple conflicting sensors across multiple building performance dimensions is not currently included in this analysis.

The algorithm contained four specific components: noise reduction, data clustering, pattern classification, and anomaly detection (Bogen 2013). Intensity noise reduction was accomplished through the application of Fourier transforms and spectral subtraction. Frequency and shift noise were addressed through the application of an unsupervised k-means clustering algorithm. Pattern classification was accomplished through evaluating the difference between an incoming pattern and the current pattern. The identification of differences was based on a root mean square analysis. The threshold for identifying anomalous patterns was a compromise between precision and complexity. As an example, assume an occupancy sensor expects someone working a fixed schedule. If that person enters the room five minutes before the typical schedule that will likely not constitute a new pattern. If, however, the person enters the room two hours after the expected arrival time, the detection of an anomaly should be expected.

This algorithm performed well on data streams representative of assets that use resources for an extended length of time, such as office lights. The algorithm also performed well on data streams that were representative of assets that were consistently turned on several times during the day for an extended period of time during each use, such as chillers and boilers. The algorithm did not perform well on data streams representing assets used frequently during the day but whose time of use is very short (Bogen 2013).

DISCUSSION

Delivery of a Facility Control Framework, from the point of view of the facility user, should be as simple as providing the needed information and analysis routines on electronic storage media ready to be plugged into to the building sensor feeds defined in the model. At the start, the Framework would pre-populated with the signal analysis routines based on the expected patterns of occupancy defined during programming through commissioning. Once the occupants move in, the algorithm learns the actual behavior of the building occupants and learns these patterns. In operating such a facility, the facility manager would respond to changes between the expected and actual behavior of the facility and not alarms based on fixed sensor set-points.

The realization of such a vision requires that the information produced during the facility life cycle be compatible with the specifications identified in Table 12-3. To promote the ultimate creation of this framework, BPie, HVACie, Sparkie, and WSie formats have been submitted for consideration under balloting of the NBIMS-US V3. These specifications were balloted since implementation examples could be created, with a high degree of success, directly from existing design software (East 2012a).

One expected side-effect of creating a domain-independent facility control framework is that practitioners may look to use these new specifications to solve questions tangential to the designed scope of the framework's standards. Examples of such behavior can be found today for existing building information model standards. The Coordination View and the COBie standards have both been subject to out-of-scope use. For example, the "round-tripping" of Coordination View files goes beyond the scope of Coordination view, which was created to only export and compare building geometry. In the case of COBie, international examples that require asset geometry and pipes or ducts exceed the scope of COBie, which was created for the exchange of managed assets and spatial containment only.

Repurposing existing model standards may or may not be successful, depending on the amount of overlap between that specification and the practitioner's problem. Given that off-scope uses are to be expected, the authors conducted several studies to determine the brittleness of this framework. These studies were conducted concurrently with the development of the framework's standards. Since the full framework was not in place at the time these projects were undertaken, the analysis was limited to examples that evaluated the managed assets within the standards.

Automated LEED Data Preparation

The first of these studies investigated if a facility asset model compliant with the COBie standard could be augmented with information required to fill in LEED assessment checklists (Biswas 2012). Through a process of data mapping between the LEED data forms and the facility asset model specification, the additional information needed to meet LEED requirements was identified. The additional

information needed constituted, with one exception, attributes related to the design of the facility that would not be expected in a simple model of building assets. For example, the COBie.Facility object is augmented with occupancy information as a COBie.Attribute object or, in terms of the IFC standard, the simple addition of a custom ifcPropertySet. COBie.Type objects were also augmented with information about recycled content. The conclusion of this project was that an analysis tool that determines the existing quality of data from a building information model, provided in COBie format, and allowed augmentation of that model to support LEED, would reduce the time required for LEED data collection by 45%. A similar study was also commissioned to successfully demonstrate the viability of using an IFC 2.3 Coordination View building model to create "green building XML" (gbXML) formatted data (Nisbet 2008).

Automated Total Cost of Ownership Analysis

The another study investigated the way in which a building-asset model compliant with the COBie standard could be augmented to evaluate Total Cost of Ownership calculations based on expected resource utilization (Florez 2011, Nisbet 2011). In this study, the heating and lighting system of the duplex apartment model were evaluated based on the expected utilization of the facility as either a residence or as an office. In these scenarios, differences in predicted space utilization were used to develop cost curves that predicted the annual operating expense of that system. A COBie file at handover will contain the location and count of all energy-conversion devices and identify the required maintenance for each type of device in the building. Additional information needed for each alternative type of product is (1) installation, replacement, and labor costs for maintenance, (2) product life expectancy, and (3) resource use efficiency. The detailed specification of such information across multiple product types is described in Chasey 2012. Contextual inputs included (1) planning horizon, (2) building use, (3) cost of power, (4) labor and material inflation rate, and (5) energy inflation rate. With this additional information, a new model or study was not needed; this supplement to the existing building asset model allowed a simple engineering economic calculation.

Tenant Management

In many campus settings, organizational power is established by the number of facilities and or spaces under the control of a given department or business unit. While the needs of the overall organization may change over time, the precedence and prestige associated with managing a specific set of spaces may result in some groups needing more space and others needing less. Anecdotal evidence suggests that such behavior, without relevant controls, results in infrastructure overcapacity. This is because there is a limited ability of tenant managers to assess the actual usage of each assigned space. The framework described in this paper may be directly used to identify those spaces that are not being used as designed. Given common information about anomalous space utilization, management decisions about space reallocation may be rationalized.

Critical Infrastructure Management

Closed-loop control systems incorporate alarms that trigger based on set-points established at system commissioning. Only during an extensive facility recommissioning process are these set points adjusted. As a result, many facility managers report frequent "false positive" alarms. Annoyance leads to habituation, with operators ultimately ignoring (or even disconnecting) these alarms (Reason 1990). Such natural human behavior is extremely dangerous in the management of critical infrastructure, as noted by the following example. For years, as many as 200 false-positive intrusion-detection alarms per day were encountered at a facility at the Oak Ridge National Laboratory. These alarms were the result of deer and squirrel activity on warning tracks outside and inside the facility's fence line. The case in question occurred when the alarms were sounded by three elderly protesters who cut through two security fences with bolt-cutters carrying banners and paint cans. These protesters proceeded to deface one of the most sensitive buildings in the United States Government facility inventory (Priest 2012). The proposed building-control framework, had it been in place, should have been able to learn the pattern of alarms from squirrels and deer over time and alarm on a new pattern: protesters with bolt cutters.

Integrated Delivery Process

The validation of a new signal-processing algorithm (Bogen 2013) alone will be insufficient to motivate owners and practitioners to change software versions, and associated configuration and workflows, to provide the required standard facility information. While it is possible for large owners, such as government agencies, to mandate the delivery of such information, enforcement of such requirements is limited without an estimate of the impact of the process changes to deliver such information (London 2011). The author's efforts to apply lean methodology, using value-added analysis techniques for construction submittal processing (East 2011), have been applied more broadly through the development of a calculator to evaluate the delivery of asset information through the project life cycle (Fallon 2013). The results of this COBie Calculator study indicated that over 90% of non-value-added costs related to facility asset information exchanges may be eliminated.

CONCLUSIONS

Prevailing efforts related to building information modeling reflect the need to deliver facility information through a project's life cycle (East 2010). Streamlining the delivery of discipline-specific building information alone is, however, insufficient to the support the increasing demands placed on our built environment. This project has provided the framework for, and demonstration of, a domain-independent facility control framework that defines how resources required to support the mission of the facility compare with the actual behavior of the facility.

The data-mining and pattern-matching algorithm developed in this project was demonstrated to be effective for the majority of fixed assets found in typical facilities. This framework was also extended to demonstrate that additional types of building analysis, currently conducted in a stand-alone, stove-piped manner, can be conducted directly with virtually the same underlying building information. If the proposed framework is available by the adoption of NBIMS-US V3, then the cost of adding new social and engineering considerations to the daily jobs of designers is simply the cost of adding new data to the framework, not the creation of new design disciplines.

In addition to the contribution made by the domain-independent facility framework introduced in this paper, the methodology used for this project has also become a contribution in its own right. The building information models produced as demonstrations of a facility's information life cycle are available through the buildingSMART alliance under Creative Commons License. These models have been directly used to evaluate the quality of commercial software compliance with the United States National Building Information Model Standard. Educators have also used these models within their coursework. The Tool Kit developed through this project has also become widely used to transform and check models submitted for testing as part of the United States National Building Information Model Standards. Finally, the methodology used to predict the benefit of the life cycle delivery of building information model provides a validation methodology for projects whose benefits stem from process-based productivity improvements.

ACKNOWLEDGMENTS

This work was accomplished under the "Life cycle Model for Mission-Ready, Sustainable Facilities" project, U.S. Army, Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL. Appreciation is expressed to Director, CERL, Dr. Adiguzel, and Technical Director (retired), Mr. Martin Savoie, for their support and assistance during this project. Finally, the authors would like to thank the peer reviewers whose comments helped focus the paper to the final product found here.

References

Amor, R. and Dimyadi, J. (2010). "An Open Repository of IFC Data Models to Support Interoperability Deployment," *Proceedings of the 27th CIB W078 International Conference on Information Technology in Construction*, Nov 2010.

Bazjanac, V. (2008). "IFC BIM-Based Methodology for Semi-Automated Building Energy Performance Simulation," *Proceedings of the 25th CIB W078 International Conference on Information Technology in Construction*, July 2008.

Beetz, J., et. al. (2010). "bimserver.org – An Open Source IFC Model Server," *Proceedings of the 27th CIB W078 International Conference on Information Technology in Construction*, November 2010.

Biswas, T. and Krishnamurti, R. (2012). "Data Sharing for Sustainable Building Assessment," *International Journal of Atchitectural Compuring*, 10(4), pp. 555–574.

Bogen, C., Rashid, M., East, B., and Ross, J. (2013) "Evaluating a Data Clustering Approach for Life cycle Facility Control," *Journal of Information Technology in Construction*, Vol. 18, pp. 99–118.

Bogen, C. (2012) "Building Automation Management information exchange," buildingSMART alliance

Bogen, C., et. al. (2013). "Evaluating a Data Clustering Approach for Life cycle Facility Control," *Journal of Information Technology in Construction*, Vol. 18, pp. 99–118, April 2013. http://www.itcon.org/2013/6 (cited 22-Jan-14)

BRB (1985) "The 1985 Workshop on Advanced Technology for Building Design and Engineering," *Building Research Board*, Commission on Engineer and Technical Systems, National Research Council, Washington, DC.

Chasey, A., Weizel, A., and Bryan, H. (2012). "Life cycle Model of Mission-Ready, Sustainable Facilities – Planning Space Resource Utilization: COBie Representation of Resource Demands for Mission-Ready Sustainable Facilities," *Engineer Research and Development Center*, CR-12-3, May 2012.

Chipman, T., Fallon, K., Feldman, R., Williams, G., and Fadojutimi, O. (2013a). "Ontology for Life cycle Modeling of Electrical Distribution Systems: Model View Definition," *Contractor Report*, ERDC/CERL CR-13-2, Construction Engineering Research Laboratory, Champaign, IL

Chipman, T., Fallon, K., Feldman, R., Williams, G., and Fadojutimi, O. (2013b). "Ontology for Life cycle Modeling of Water Distribution Systems: Model View Definition," *Contractor Report*, ERDC/CERL CR-13-4, Construction Engineering Research Laboratory, Champaign, IL

Chipman, T., et. al (2013c). "HVACie – Heating Ventilation and Air Conditioning Information Exchange," *National Building Information Model Standard United States*, ballot submission, buildingSMART alliance, National Institute of Building Sciences.

Department of Defense (2013). "Standard Practice—Technical Data Packages," MIL-STD-31000A, 26-Feb-13.

Duarte, F., Machado, R., and Fernandes, J. (2012). *A Methodology to Transform Business Processes into Software Systems*, Springer-Verlag, 39–58

East, E., Love, D., and Nisbet, N. (2010). "A Life cycle Model for Contracted Information Exchange," *Proceedings of the 27th CIB W078 International Conference on Information Technology in Construction*, November 2010.

East (2011). "buildingSMART alliance information exchanges: Means and Methods," National Institute of Building Sciences, http://www.buildingsmartalliance.org/index.php/projects/cobie/ (cited 06-May-2013).

East, E. and Love, D. (2011). "Value-added Analysis of the Construction Submittal Process," *Automation in Construction*, Vol. 20, 1070–1078.

East, E. (2011a). "Information Exchange Projects," *buildingSMART alliance*, National Institute of Building Sciences, http://www.nibs.org/?page=bsa_infoexchange (cited 21-Nov-13).

East, E. (2012a). "Common Building Information Model Files," buildingSMART alliance, National Institute of Building Sciences, http://buildingsmartalliance.org/index.php/projects/commonbimfiles/ (cited 27-Mar-2013).

East, E. and Bogen, C. (2012b). "An Experimental Platform for Building Information Research. Computing in Civil Engineering," *Proceedings of the 2012 International Conference on Computing in Civil Engineering*, 301–308.

East, E., Nisbet, N., and Liebich, T. (2013). "Facility Management Handover Model View," *Journal of Computing in Civil Engineering, American Society of Civil Engineers*, 27(1), 61–67.

Fallon, K. and Palmer, M. (2006). "Capital Facilities Handover Guide, Part 1" National Institute of Building Sciences, NISTIR 7259, Gaithersburg, MD.

Fallon, K. and Palmer, M. (2007). "General Buildings Information Handover Guide: Principals, Methodology, and Case Studies," National Institute of Building Sciences, NISTIR 7417, Gaithersburg, MD.

Fallon, K., Feldman, R., Greenberger, J., Williams, G., Genc, H., Gonzalez, L., and Greenfield, J. (2012). "Sustainability Product Properties in Building Information Models," Contractor Report, ERDC/CERL CR-12-6, Construction Engineering Research Laboratory, Champaign, IL

Fallon, K., Feldman, R., Williams, G., and Fadojutimi, O. (2013a). "Ontology for Life cycle Modeling of Water Distribution Systems: Application of Model View Definition Attributes," Contractor Report, ERDC/CERL CR-13-5, Construction Engineering Research Laboratory, Champaign, IL

Fallon, K., et. al (2013d). "Assessment of Life cycle information exchanges: Understanding the Value Added Benefit of the COBie Process," Engineer Research and Development Center, (in press)

Florez, J. (2011) "Determining O&M Activities for BIM Integration," In-Progress Review Presentation, Construction Engineering Research Laboratory.

Forgues, D., Iordanova, I., and Chiocchio, F. (2012). "A Framework for an Integrated and Evolutionary Body of Knowledge." *ASCE Construction Research Congress 2012*: 564–573. doi: 10.1061/9780784412329.057.

Hitchcock, R., Nisbet, N., Wilkins, C., Tanis, M., Hänninen, R., and Laine, T. (2012a). "Ontology for Life cycle Modeling of Heating, Ventilating, and Air Conditioning (HVAC) Systems: Model View Definition," Contractor Report, ERDC/CERL CR-12-2, Construction Engineering Research Laboratory, Champaign, IL

Hitchcock, R., Nisbet, N., Wilkins, C., Tanis, M., Hänninen, R., and Laine, T. (2012b). "Ontology for Life cycle Modeling of Heating, Ventilating, and Air Conditioning (HVAC) Systems: Experimental Applications Using Revit," Contractor Report, ERDC/CERL CR-12-4, Construction Engineering Research Laboratory, Champaign, IL

ISO (2006) "ISO/IEC 19757-3:2006. Information technology – Document Schema Definition Language (DSDL) – Part 3: Rule-based validation – Schematron," *International Organization for Standardization*, Geneva, Switzerland.

ISO (2013) "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries," *International Standards Organization*, 16739:2013

Jerving, R. (2011). "Building Programming Information Exchange: Previous Projects and Comments," buildingSMART alliance, http://projects.buildingsmartalliance.org/files/?artifact_id=4700 (cited 27-Mar-2013)

Johnson, M. and Fallon, K. (2011). "Experimental Building Information Models," Construction Engineering Research Laboratory, ERDC/CERL CR-11-2.

Jung, Y. and Joo, M. (2010). "Building Information Modeling Framework for Practical Implementation," *Automation in Construction*, Elsevier, 20, 126–133

Jung, Y., and Joo, M. (2011). "Building Information Modeling (BIM) framework for practical implementation," *Automation in Construction*, 20(2), 126–133.

Kalin, M. and Weygant, R. (2013). "Specifiers' Properties information exchange: Minimum Building Information Model (BIM) Object Definitions," Engineer Research and Development Center, CR-13-1.

London, K. and Singh, V. (2011). "Propertisation of Building Information Modeling Mapped Against Firm Intellectual Capital," *Proceedings of Architectural Management in the Digital Arena*, Eindhoven, Netherlands, 13-14 October 2011, 143–157.

Marcial, L., Hemminger, R., and Bradley, M. (2010). "Scientific Data Repositories on the Web: An Initial Survey," *Journal of the American Society for Information Science and Technology*, 61(10).

McLellan, H. (2011). "Meeting the Challenges of Building Green with LEED," *New Jersey Lawyer*, June 2011, No. 270, 29–34.

Nisbet, N. (2008). "Energy Information Exchanges," *An Energy Information Exchange Presentation*, National Institute of Building Sciences, *Annual Meeting and Aec/Ecobuild*, December 8, 2008, Washington, DC. <http://www.nibs.org/?page=bsa_energie09> (Apr. 2014).

Nisbet, N., Liebich, T., and Grobler, F. (2010) "Energy information exchange: Project Close-out Report," *Construction Engineering Research Laboratory*, unpublished technical report.

Nisbet, N. (2011). "Annualized Cost of Ownership," In-Progress Review Presentation, Construction Engineering Research Laboratory.

NRC (2009) "Advancing the Competitiveness and Efficiency of the U.S. Construction Industry," Committee on Advancing the Competitiveness and Productivity of the U.S. Construction Industry, National Research Council, National Academies Press, Washington, DC.

Object Modeling Group (2011) "Business Process Model and Notation (BPMN)," *Object Modeling Group*, http://www.omg.org/spec/BPMN/2.0 (cited 18-Oct-13).

Organization for the Advancement of Structured Information Standards (2006) "Open Building Information Exchange," Committee Specification 01, https://www.oasis-open.org/committees/tc_home.php?wg_abbrev=obix (cited 19-Nov-13).

Polly, B., Kruis, N., and Roberts, D. (2011). "Assessing and Improving the Accuracy of Energy Analysis for Residential Buildings," *Building Technologies Program*, National Renewable Energy Laboratory.

Priest, Dana (2012) "Security Lapses at Nuclear Complex Identified Two Years Before Break-In," Washington Post, http://articles.washingtonpost.com/2012-09-11/world/35495806_1_security-lapses-nuclear-weapons-security-cameras (cited 22-Apr-12).

Reason, J. (1990). *Human Error*, Cambridge University Press, New York.

Sacks, R., Koskela, L., Dave, B., and Owen, R. (2010). "Interaction of Lean and Building Information Modeling in Construction," *Journal of Construction Engineering and Management, American Society of Civil Engineers*, 136(9), 968–980.

Teicholz, P. (2004). "Labor Productivity Declines in the Construction Industry: Causes and Remedies," *AECbytes*, ViewPoint, No. 4, April 2004.

United States Army (2013) "Department of the Army Facilities Standardization Program: Brigade Operations Complex, Brigade and Battalion Headquarters," Unified Facilities Criteria 4-410-01, U.S. Army, Corps of Engineers, Savannah District, 25 January 2013.

United States Code (2012). "National Defense Authorization Act for Fiscal Year 2012," Section 2830(b)(1), http://www.gpo.gov/fdsys/pkg/BILLS-112hr1540enr/pdf/BILLS-112hr1540enr.pdf (cited 20-Nov-13)

Williams, G., Fallon, K., Fadojutimi, O., Feldman, R., and Chipman, T. (2013). "Ontology for Life cycle Modeling of Electrical Distribution Systems: Application of Model View Definition Attributes," Technical Report, CRADA-07-CERL-02, Construction Engineering Research Laboratory, Champaign, IL.

CHAPTER 13

Building Information Modeling: Analyzing Noteworthy Publications of Eight Countries Using a Knowledge Content Taxonomy

M. Kassem*
B. Succar†
N. Dawood‡

Abstract: *Building Information Modeling (BIM) tools and workflows have the potential to significantly improve the efficiency of design, construction and operation activities. Numerous BIM deliverables and their respective requirements have been widely discussed by industry stakeholders. This is evidenced by the intensity of online communications surrounding BIM topics and the accelerating availability of* noteworthy BIM publications *(NBP)s. NBPs are publically-available industry documents incorporating guidelines, protocols and requirements focusing on BIM deliverables and workflows. These publications are the product of various governmental bodies, industry associations, communities of practice and research institutions, intended to facilitate BIM adoption, and realize BIM's value-adding potential.*

A specialized taxonomy is employed to analyze 57 noteworthy BIM publications from across eight countries selected for their active BIM scene. The BIM knowledge content *(BKC) taxonomy includes three* knowledge content clusters

*Associate Professor, Technology Futures Institute, Teesside University, TS1 3BA, Middlesbrough, UK; PH (44) 164 273 8300; email: m.kassem@tees.ac.uk

†Director of Change Agents AEC, Victoria 3193, Melbourne, Australia; PH (61) 412 556 771; e-mail: bsuccar@changeagents.com.au

‡Professor, Technology Futures Institute, Teesside University, TS1 3BA, Middlesbrough, UK; PH (44) 164 273 2405; e-mail: n.n.dawood@tees.ac.uk

(guides, protocols and mandates) subdivided into 18 knowledge content labels *(e.g. report, manual, and contract). Ten of these content labels are used to analyze and compare publications from Australia, Denmark, Finland, the Netherlands, Norway, Singapore, the United Kingdom, and the United States. Preliminary content analysis is then performed which provides insight into the availability and distribution of BIM knowledge within noteworthy BIM publications. The analysis identifies knowledge gaps within publications and highlights opportunities for future research and complementary publication efforts.*

This chapter contributes to organizing BIM knowledge as contained within numerous noteworthy BIM publications and – by that - facilitates targeted access to their content. It provides a knowledge repository for construction industry stakeholder's to utilize during BIM implementation and a research base for investigators seeking to identify and address knowledge gaps across the BIM domain.

INTRODUCTION

The escalating coverage, connotation and impact of BIM concepts and tools have led to the proliferation of BIM-focused publications. Industry associations, governmental bodies and academic communities across several countries are increasingly developing and releasing a variety of BIM strategy documents, BIM adoption reports, data exchange standards, and model-based collaboration protocols. These noteworthy BIM publications (NBP)s include significant knowledge and structured guidance relating to BIM implementation, project delivery and team collaboration. However, the BIM knowledge contained within these documents is rarely analyzed as a whole or labeled accurately as to reflect their true benefit and intended use. Within numerous NBPs (refer to Table 13-1), many terms – e.g. *BIM protocols*, *BIM guidelines* and *BIM standards* – are either used interchangeably or without qualification. The knowledge content of these NBPs is thus often masked by the documents' surrogates (e.g. titles and headings) and difficult to identify and benefit from. This ambiguity necessitates a *knowledge content identification and organization approach* that (a) shifts attention away from potentially uninformative publication titles and towards their actual knowledge deliverables, and (b) facilitates content analysis, comparison and further development.

IDENTIFYING NOTEWORTHY BIM PUBLICATIONS

Noteworthy BIM publications (NBP)s are publically-available documents developed by various academic, governmental and industry entities, aimed at a wide audience, and intended to promote BIM understanding, regulate BIM implementation or mandate BIM requirements. These publications encapsulate extensive BIM-focused knowledge, represent significant domain expertise and

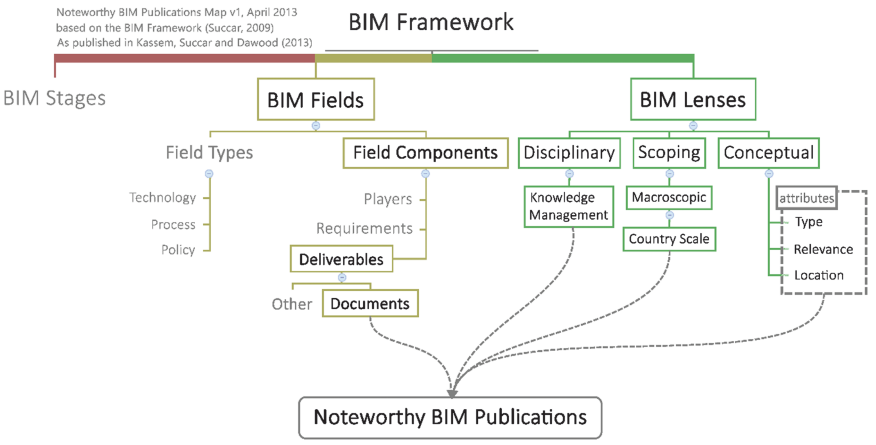


Figure 13-1. Conceptual derivation of Noteworthy BIM Publications using the BIM Framework.

are a substantial effort within the BIM domain. To assist in identifying NBPs and informing the selection process, the authors employed explicit ontological structures from the BIM Framework (Succar, 2009) as represented in Figure 13-1.

The BIM Framework and its ontological structures are intended to organize domain knowledge and facilitate its understanding. Figure 13-1 explores how noteworthy BIM publications are derived from the interaction of BIM fields and BIM lenses:

- NBPs are documents (i.e. not websites, blogs or similar);
- NBPs reflect BIM knowledge (i.e. publications focused on BIM skill are excluded);
- NBPs are the deliverables of BIM players (i.e. publications delivered by players from other industries are excluded);
- NBPs cover relevant BIM topics (i.e. publications covering pre-BIM topics are excluded);
- NBPs are macroscopic (i.e. documents aimed at small groups of practitioners or students are excluded); and
- NBPs are selected and organized by country of origin (i.e. NBPs developed across several countries are excluded - e.g. Inpro-EU[1], IDDS[2] or bSI[3]).

[1]Open Information Environment for Knowledge-Based Collaborative Processes throughout the Lifecycle of a Building, please refer to http://www.inpro-project.eu/main.asp

[2]Integrated Design and Delivery Solutions, please refer to http://www.cibworld.nl/site/programme/priority_themes/integrated_design_solutions.html

[3]buildingSMART International and their varied noteworthy publications, please refer to http://www.buildingsmart.org/

Using the framework-based delimitation, NBPs include numerous types of published documents spanning industry initiatives, peer-reviewed journals, self-published books and other noteworthy publications. However, for the purposes of targeted analysis, this chapter focuses exclusively on publications developed by governmental bodies, industry associations, research institutions and communities of practice.

The next section identifies a preliminary list of 55 NBPs from across eight countries and provides a succinct summary of their contents. These NBPs have been selected by analyzing a number of discussions conducted by/with subject matter experts (SME)s – including:

- Recommendations by industry experts identifying the relative importance of NBPs in their daily work;
- Prominence of individual NBPs in web searches when using keywords similar to "BIM guidelines USA" and "BIM standards Australia"; and
- The apparent frequency certain NBPs are referenced in online discussions similar to those conducted within specialist LinkedIn groups (e.g. BIM Experts group and BIM Consultants group).

IDENTIFYING NBP FROM EIGHT SELECTED COUNTRIES

Using the ontological structures presented in Figure 13-1, Table 13-1 in the appendix is a non-exhaustive list of 57 noteworthy BIM publications from across eight countries selected for their active BIM scene. Table 13-1 introduces a preliminary list of noteworthy BIM publications, all intended by their authors to guide BIM implementation and improve workflows and deliverables across the construction lifecycle. It includes a descriptive summary of each publication's knowledge content. Identifying Table 13-1 as preliminary reflects the risk in inadvertently excluding equally-noteworthy publications. Additional effort will be needed to identify supporting selection metrics (Kassem, Succar and Dawood, 2013) and to collect data confirming the *noteworthiness* of listed BIM publications.

Before introducing a specialized taxonomy to classify and analyse these publications, it is important to first explore the importance of well-structured taxonomies in organizing domain knowledge.

USING TAXONOMIES TO ORGANIZE KNOWLEDGE CONTENT

Taxonomies are an efficient and effective way to consolidate knowledge (Reisman, 2005). A well-structured taxonomy allows "the meaningful clustering of experience" (Kwasnik, 1999 - Page 24) and are "a means toward a number of different

ends; one of these ends is providing direction and/or guidance to expansion or generalization of knowledge" (Reisman, 1988 – page 216).

Taxonomies originated in biological sciences (Hedden, 2010) and have been used for organizing knowledge in varied domains. For example, taxonomies have been used to facilitate information interoperability and retrieval (Cheng et al., 2010); define semantic conflicts in business databases (Kashyap and Sheth 1996); organize virtual worlds (Milgram and Kishino, 1996); classify diseases (Burgun and Bodenreider, 2001); and categorize human errors in train accidents (Reinach and Viale, 2006). Also within the construction industry, several taxonomies have been developed to organize domain knowledge. For example, Zuppa and Issa (2008) explored a taxonomy documenting the prioritized interests of stakeholders and aligning their interests; El-Diraby, Lima, and Feis (2005) presented a taxonomy for construction management; Sun and Meng (2008) developed taxonomies covering change causes and change effects in construction projects; Garrett and Teizer (2009) presented a taxonomy-enabled educational system for the classifying and analyzing human errors affecting construction safety; and Wang and Dunston (2011) developed a user centric classification of Mixed Reality (MR) approaches within the construction industry.

As a *knowledge organization system* (Hedden, 2010), taxonomies play an important role in clarifying complex topics and facilitating understanding. The next section introduces a specialized taxonomy that assists in understanding the deliverables of noteworthy BIM publications and comparing their knowledge contents.

THE BIM KNOWLEDGE CONTENT TAXONOMY

There are numerous noteworthy BIM publications covering a large number of overlapping BIM topics. The knowledge contained within these publications may be masked by the document's chosen title and inconsistent use of terminology across different documents. To facilitate access to the knowledge contents across noteworthy BIM publications and enable their comparison and analysis, this chapter introduces the BIM Knowledge Content (BKC) taxonomy. The BKC taxonomy is derived from explicit ontological structures of the BIM Framework (Succar, 2009) (Succar, 2013) as described in Figure 13-2:

As described in Figure 13-2, the BIM Knowledge Content taxonomy includes three *knowledge content clusters* – Guides, Protocols and Mandates:

- **Guides:** documents which are *descriptive* and *optional*. Guides clarify goals, report on surveys/accomplishments or simplify complex topics. Guides do not provide detailed steps to follow to attain a goal or complete an activity.
- **Protocols:** documents which are *prescriptive* and *optional*. Protocols provide detailed steps or conditions to reach a goal or deliver a measureable outcome. While documents within this cluster are prescriptive, they are optional to follow unless dictated within a Mandate (see next cluster).

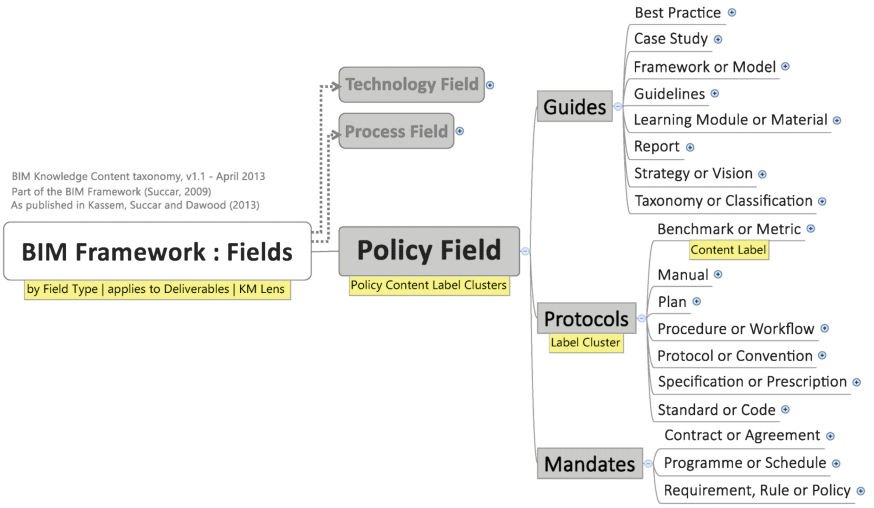


Figure 13-2. The BIM Knowledge Content taxonomy – Mind Map.

- **Mandates:** documents which are *prescriptive* and *dictated* by an authority. Mandates identify *what* should be delivered and – in some cases – *how, when* and *by whom* it should be delivered.

Each of the knowledge content clusters includes a number of *knowledge content labels* to identify and delimit specific knowledge types. Table 13-2 in the appendix lists the 18 labels and provides a summary of their BIM-specific definitions.

The BKC taxonomy explored in Table 13-2 includes three content clusters and eighteen content labels. These clusters and labels facilitate the examination of noteworthy BIM publications by "[shifting] the focus of perusal and interaction away from potentially uninformative document surrogates (such as titles, sentence fragments and URLs) to actual document content, and uses this content to drive the information seeking process" (White, Jose and Ruthven, 2005 - page 1). Also, by defining a *common vocabulary* to identify knowledge contents (Holsapple and Joshi, 1999), the BKC taxonomy is able to organize a large extent of disjointed domain knowledge into a structure that is useful, accurate and trustworthy (Forze and Di Nuzzo, 1998).

Analysis of BIM Publications Using Knowledge Content Taxonomy

The BIM knowledge content taxonomy includes 18 content labels intended to analyze the BIM knowledge contained within publications and other knowledge sources. Ten of these labels have been chosen from across the 3 content clusters and applied to the 57 noteworthy BIM publications from eight different countries (Table 13-1). The distribution of these content labels is explored in Table 13-3 in the appendix.

The 57 noteworthy BIM publications analyzed in Table 13-3 include a substantial sum of specialized BIM knowledge. However, the coverage and distribution of this BIM knowledge varies significantly across the eight countries. Table 13-4 shows the quantities and types of BIM knowledge content labels identified within the 57 noteworthy BIM publications from eight countries.

Using Tables 1, 3 and 4 as a guide, the following paragraphs provide a succinct analysis of the BIM knowledge content available to stakeholders within each country:

Australia

As indicated by surveys and workshops conducted within the last few years, BIM tools and workflows are increasingly being adopted across the Australian construction industry (BEIIC, 2010) (buildingSMART, 2012). These surveys however do not clarify BIM adoption rates across all disciplines or the quality/consistency of BIM deliverables.

Using the Noteworthy BIM Publications as an indicator, NBPs emanating from Australia show an abundance of reports discussing the benefits, risks and challenges of BIM implementation. While many of these publications overlap in arguing the case for model-based workflows and suggesting roadmaps for industry-wide adoption, only a few publications provide implementation steps or detailed protocols for industry practitioners to follow. These represent a handful of seed BIM specifications and procedures (AMCA, 2012) (NATSPEC, 2011) (ANZRS, 2011) which have been developed and highlight significant knowledge gaps that still need to be addressed. For example, Australia's NBPs do not include a BIM-ready classification system - similar to UniClass2 (UK) and OmniClass Table 21 (US) – which is key for uniform exchanges of model objects, cost information and other metadata.

Tables 13-3 and 13-4 also identify a lack in *mandates* – typically developed by governmental units or large client bodies – that define BIM requirements and thus encourage BIM adoption. With the absence of such mandates, industry associations and advocacy groups – not governmental bodies - are still the main players who are "actively driving the development of standards and protocols for the generation and exchange of building information" (CIBER, 2012, page 19).

In summary, the unequal distribution of NBPs across the three *content clusters* highlights a fundamental challenge facing industry stakeholders in Australia: overlapping guides, insufficient protocols and a complete lack of governmental mandates.

Denmark

Denmark is one of the first countries to actively develop BIM guidelines and protocols. Their earliest version of their BIM guidelines called BIPS (BIPS, 2008) was released in 2007. Also, BIM deliverables were partially mandated on public sector projects worth more than DKK 40M ($7M) and architects, engineers and contractors working on government projects were required to use a number of

Table 13-4. A summary of BIM knowledge content labels from the eight countries

	Guides				*Protocols*				*Mandates*	
	Case Study G2	*Guideline G4*	*Report G8*	*Strategy or . . . G9*	*Metric or . . . P1*	*Manual P2*	*Procedures or . . . P4*	*Specifications . . . P6*	*Contract or . . . M1*	*Requirement . . . M3*
Australia	1	4	3	1	0	2	2	1	0	0
Denmark	0	2	0	1	1	1	0	1	0	1
Finland	0	2	0	1	2	0	0	0	0	2
Norway	1	1	1	1	0	1	0	0	0	1
Singapore	0	0	0	1	0	0	0	0	0	1
The Netherlands	0	1	0	1	1	0	0	2	0	2
United Kingdom	1	2	3	3	4	1	1	0	1	1
United States	3	8	2	1	5	1	4	4	11	5

new digital routines, approaches and tools (Kubba, 2012). Additional guidelines for digital collaboration between stakeholders were issued in 2008 (refer to DK 05 in Table 13-1). A simple analysis of the time each guide and mandate was issued indicates a steady process of developing guidelines and mandating BIM on projects of increasingly smaller value over time. Indeed, in 2010, BIM was mandated on all projects worth more than DKK 20 M ($ 3.5 M), a 50% drop from the previous threshold of DKK 40M ($7M) (refer to DK 06 in Table 13-1). Moreover, this already low threshold was further decreased following the decision of the Danish Government to mandate BIM on all central government projects worth more than DKK 5M ($ 870K) (Building SMART, 2011b). Also, the Danish Digital Construction initiative (refer to DK 06 in Table 13-1) specified that stakeholders working on public construction projects should use the following four means: (1) electronic tendering submission system based on a specified bill of quantities and a portal for submitting tenders; (2) a project web environment for participants to share project data and exchange documents, drawings and specifications; (3) 3D models interchangeable in IFC format to be used across all project lifecycle phases; and (4) electronic hand-over of data from the construction project as relevant for facility operation (Det Digitale Byggeri, 2010).

It is important to observe strong BIM leadership in Denmark is stemming from the public sector (i.e. from the Palaces and Properties Agency, Danish University, Property Agency and Defence Construction Service). Also, as early as 2006, 50% of architects and 40% of engineers in Denmark were using BIM in some parts of their projects (Kubka, 2012).

The distribution of NBPs emanating from Denmark provides a clear picture of the country's BIM landscape. NBPs are well-distributed among the three clusters (Guides, Protocols and Mandates). However, the number of legal documents and case studies in Denmark is surprisingly low despite the aggressive digital procurement routes adopted in Denmark since early 2007. Also Table 13-3 indicates a lack in both BIM workflows to clarify project processes and assessment tools to manage BIM competencies.

Finland

Finland exhibits a considerable commitment to BIM adoption by both the public and private sectors. As evidenced by NBPs listed in Table 13-1 both public and private entities have been collaboratively involved in conducting BIM pilot projects and developing BIM guidelines since the early 2000s. Also, according to Kiviniemi (2007), BIM surveys conducted in Finland report high BIM adoption rates by architects (93%) and engineers (60%). The Finnish BIM guidelines, based on an R&D project called 'ProIT', were also widely supported by industry (Kubba, 2012). Finally, Senate Properties, the government owned enterprise responsible for managing the property assets of the Finnish state, started requiring BIM/IFC on their projects in October 2007 (Senate, 2007b). Finland is now seeking to replicate the success and acknowledgment gained as an early developer and adopter of BIM in the building sector across the infrastructure sector. Some major research efforts, such as the Infra FINBIM have been initiated with the aim of establishing a

systematic shift, into the Finnish infra sector, from to intelligent BIM-based service production that considers the entire life cycle and all sub-areas, actors and functions (INFRA FINBIM work package, 2013).

The distribution of NBPs emanating from Finland (Table 13-3) indicates several gaps within the protocols and mandates clusters. Multi-volume, discipline-specific BIM guidelines (refer to FE 01 in Table 13-1) provide an introduction into the fundamentals of product modeling yet do not introduce any data exchange specifications. Also, despite that clients can request the use of BIM for design validation, energy simulation, structural analysis and other analyses, there are no publically-available contractual guidelines that address liability issues, compensation matters and intellectual property rights. Furthermore, there are still no available metrics to assess the BIM capabilities of organizations or documented workflows to assist in streamlining BIM project delivery.

Norway

The Norwegian BIM guidelines called "Statsbygg Building Information modeling Manual – version 1.2" were developed in coordination with the American National Institute of Building Science's NBIMS (National BIM Standard) (Wong et al., 2009). Statsbygg is the Norwegian government's key advisor in construction and its building commissioner, property manager and property developer. Statsbygg conducted several pilot projects using Industry Foundation Classes (IFC)s starting in the early 2000s (refer to NO 01 in Table 13-1). Following these, BIM guidelines were developed (NO 05) and BIM was mandated on all public sector projects starting from 2010 (NO 02). However, although the demand for BIM is promoted and mandated by the public sector, industry associations have also been active in developing their own BIM manuals. For example, the association of Norwegian Home Builders developed their own BIM manual (refer to NO 04 in Table 13-1) to provide practical advice associated with BIM processes, modeling and utilization (NHA, 2011).

NBPs emanating from Norway include a higher concentration of *guides* as opposed to *protocols* and *mandates* (refer to Table 13-3). Among the gaps detected are the absence of metrics or benchmark to facilitate performance assessment/improvement and no defined BIM workflows to assist in structuring model-based exchanges. Although BIM has been mandated on all projects starting 2010, there are still no contractual documents that address the specific legal and intellectual property issues arising from BIM implementation.

Singapore

Public sector organizations in Singapore such as Building and Construction Authority (BCA) -in collaboration with private entities such as the Construction and Real Estate Network (CORENET) - are taking the lead in adopting and mandating BIM adoption. The BCA, an agency under the Ministry of National Development, delivers many programs to raise awareness including workshops, roadshows and promoting success stories (e.g. ArtScience Museum, Housing

projects by the Housing and Development Board) (BuildingSMART, 2011b). The agency also assists industry stakeholders to build capability and capacity through the BCA Academy that deliver BIM training programs to equip public sector consultants and contractors (Building SMART, 2011b) and a 'BIM Fund' that partially covers the costs for BIM adoption by organizations (Building SMART, 2011b). Finally, the BCA has mandated a phased BIM implementation program: larger projects are required to use BIM for their architectural designs by 2013 and for engineering designs by 2014; and smaller projects, both architectural and engineering designs by 2015 (refer to SG 01 in Table 13-1).

It is also important to note that Singapore pioneered a BIM-specific 'e-Submission System' (eSS) that supports IFC and allows AEC organizations to submit their project documents over the internet (CORENET eSS, 2009). Singapore also has ambitious goals to increase overall BIM adoption rates to 80% by 2015 - as stated in their BIM roadmap (refer to SG 01 in Table 13-1) - up from 10% in 2008 and 25% in 2011 (buildingSMART, 2011b).

Analysis of Singaporean's NBPs (refer to Table 13-3) indicates a holistic and top-down approach to BIM adoption. While labels from all the three clusters exist within the analyzed NBPs, BIM assessment benchmarks for BIM capabilities and competencies are still lacking. This is somewhat unexpected given the on-going BIM training and certification program driven by BCA. Also, with the exception of BIM workflows adopted from Penn State's Computer Integrated Construction (CIC) Research Group (Penn State, 2010), Singapore's BIM guide (refer to SG 02 in Table 13-1) still lacks well-documented workflows to guide BIM project delivery.

The Netherlands

The Dutch BIM guidelines called "Rgd BIM Standard" (refer to NL03 in Table 13-1) and the Dutch BIM Strategy (NL 01) has been first issued in 2012. BIM deliverables - through the IFC format – have been mandated on all projects worth more than €10M starting from November 2012. According to Dr. Alex Vermeulen, director of Rgd, A&A, the expectations behind the guidelines and strategy is that models of existing buildings should be delivered using both proprietary and non-proprietary formats (i.e. IFC) and kept live throughout the building's lifecycle (Building SMART, 2011b). The Dutch guidelines also identifies the legal responsibility covering BIM exchanges and adopts levels of development (LOD)s from the "AIA E202 – 2008 BIM Protocol Exhibit" as a basic measure to identify model-based deliverables. Also, the Dutch guidelines employ 'BIM Quick Scan' (refer to NL 01 in Table 13-1), a benchmarking tool developed by TNO, for assessing the BIM performance of organizations.

Analysis of Dutch NBPs reveals a balanced distribution across the three content clusters despite the relatively recent release of these publications. This indicates that Dutch BIM policy makers may have benefited from the experiences of other countries. Finally, and similar to other reviewed countries, there are still no documented BIM workflows or procedures to reflect the specific attributes of the Dutch construction industry.

The United Kingdom

The United Kingdom has been active in developing strategies and BIM policies for improving the performance of its construction industry. In May 2011, the UK Government published its "Government Construction Strategy (GSC)" (refer to GB 02 in Table 13-1) which emphasized the need to develop standards for enabling all members of the supply chain to work collaboratively through BIM. The strategy also announced that the "Government will require fully collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum by 2016" (refer to GB 06 in Table 13-1).

A "BIM Task Group" bringing together the expertise from industry, government, public sector, institutes and academia, was formed and tasked to deliver the Government strategy. The first version of the UK BIM guidelines was then developed and released in 2013 (GB 07) and identified three major milestones (called maturity levels) for industry to aim for: Level 1 (2d/3D CAD file based collaboration), Level 2 (BIM file based collaboration), and Level 3 (fully open and integrated web service environment). The Task Group then went on to mandate deliverables to be at Level 2 by 2016. Compared to Singapore which mandated Level 3 UK-equivalent by 2015, the UK strategy seems much less ambitious. However, this phased approach to BIM implementation - recommended by a Strategy Paper to the Government Construction Client Group (refer to GB 04 in Table 13-1) – actually reflects how most UK firms are still at Level 1.

To support the implementation of BIM Level 2, several NBPs have been lately released. These include 'BS 1192' by the British Standards Institution (BSI) which establishes a methodology for managing the production, distribution and quality of construction information. The British BIM guidelines also contains some contractual guidance covering intellectual property rights and the incorporation of BIM protocols into all direct contracts between the employer and the project team members.

In addition to the publications sponsored/released by the UK government and BSI, industry associations are also playing a significant role in releasing NBPs. For example, the Royal Institute of British Architects (RIBA) has updated their popular RIBA 'Outline Plan of Work' to include a 'BIM Overlay' (RIBA, 2012) reflecting the changes BIM introduces to different project phases.

NBPs emanating from the UK incorporate nearly all knowledge content labels. However, despite the recency of most of these publications, there are many similar deliverables and much duplicated effort (refer to Table 13-3). Organizational assessment metrics (refer to GB 03 in Table 13-1) are still elementary and not based on grounded research. Also, with the exception of workflows showing 'data-drop stages for COBie'[4] there are still limited documented workflows which clarify BIM implementation or collaboration procedures.

---

[4]For an example, please refer to http://www.bimtaskgroup.org/wp-content/uploads/2012/03/COBie-data-drops-29.03.12.pdf, last visited April 29, 2013

United States

The United States is the most prolific producer of noteworthy BIM publications. This is primarily driven by the numerous industry bodies (e.g. AGC, AIA and NIBS), governmental agencies (e.g. GSA, USACE, USCG, and NIST) and local authorities (e.g. NYCDDC and OHIO DAS) which have been actively developing their BIM guides and mandating BIM use since 2007. According to McGraw Hill Construction (2012), BIM adoption rates among contractors, architects and engineers in 2012 are at 74%, 70% and 67% respectively.

Many US noteworthy BIM publications, especially those developed by governmental agencies, are addressed to contractors or intended to facilitate the delivery/handover of facilities to operators upon construction completion. NBPs with a more holistic view are those developed by the NIBS (refer to US 04 and US 19 in Table 13-1) which continue to act as reference documents for other institutions and bodies. For example, the "National Building Information Modeling Standard" (refer to US 19 in Table 13-1) covers most topics related to BIM implementation and collaboration and includes a BIM capability maturity model for performance assessment.

NBPs emanating from the US are well distributed across all three content clusters - guides, protocols and mandates. Some of these NBPs are very similar and represent a partial duplication of effort among industry bodies (e.g. between US 02, US 06 and US 07 in Table 13-3) and among local authorities (e.g. between US 07 and US 16 in Table 13-3). Another significant characteristic of US NBPs is the availability of workflows and procedures covering all project lifecycle phases (e.g. US 09 and US 10). Also, US NBPs include an abundance of mandates (e.g. contractual templates and procurement requirements) (Table 13-4) developed by governmental agencies and large client bodies. These mandates represent a clear indication of the leading roles these bodies play in shaping and driving industry-wide BIM adoption. This is reflected by the extensive effort undertaken to develop a set of information exchange specifications (e.g. US20 in table 13-1) covering all disciplines and facilitating data capture throughout a facility's lifecycle.

COMPARISON OF BIM KNOWLEDGE CONTENT ACROSS COUNTRIES

The BIM knowledge content (BKC) taxonomy is used to analyze noteworthy BIM publication (NBP)s across eight countries selected for their active BIM scene. This taxonomic approach allows comparisons to be drawn between different publications and between different countries. As a tiered classification, the three label clusters with their distinct properties (*guides* are descriptive and optional; *protocols* are prescriptive and optional; and *mandates* are prescriptive and dictated) - provide an insight into the BIM scene of each country. Some countries have a balanced distribution between clusters (e.g. Singapore and the US) while others have an unbalanced distribution and even lack knowledge contents within a specific cluster (e.g. Australia).

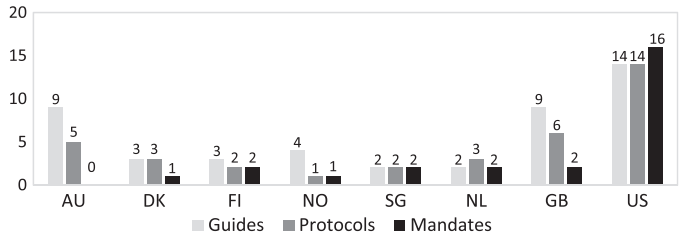


Figure 13-3. Distribution of guides, protocols and mandates within countries.

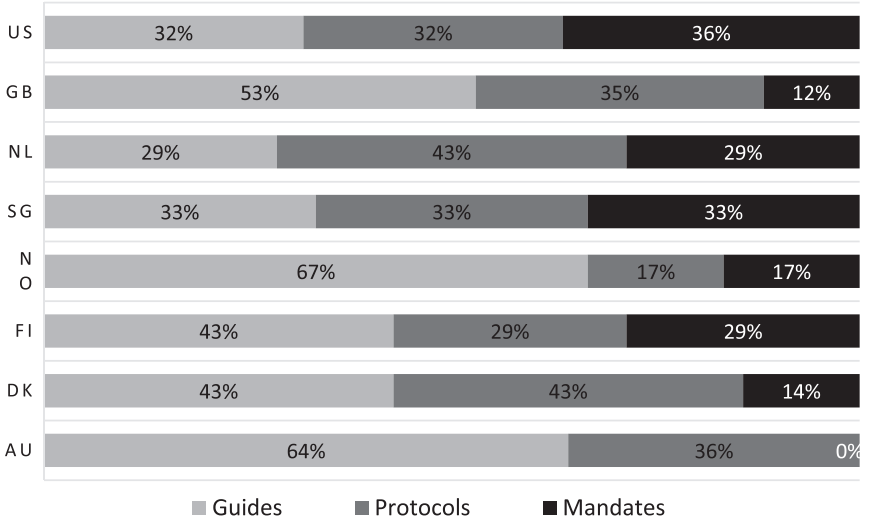


Figure 13-4. Relative distribution and comparison of guides, protocols and mandates across and within countries.

Figures 13-3 and 13-4 provide a preliminary visual analysis of the number, percentage and distribution of content labels across the noteworthy BIM publications of the eight selected countries. Figure 13-3 highlights the large number of publications emanating from the US and the UK by collating the number of BIM knowledge content labels.

Figure 13-3 highlights the leading position the US occupies with respect to generating the largest number of NBPs across all three clusters. It also specifically highlights the large number of mandates emanating from the US as compared to all other surveyed countries.

Figure 13-3 highlights the leading position the US occupies with respect to generating the largest number of NBPs across all three clusters. It also specifically highlights the large number of mandates emanating from the US as compared to all other surveyed countries.

Figure 13-4 highlights the relative distribution of NBPs across the three labels. It also highlights the difference between a balanced distributions (e.g. that of Singapore) and an unbalanced distribution across clusters (e.g. that of Australia).

The two charts (Figures 13-3 and 13-4) are a preliminary representation of how the BKC taxonomy can be used to analyze and compare the knowledge deliverables of different countries. While such an analysis would not reflect the *quality* of information contained within NBPs, it would facilitate their respective inspection. These charts allow a better understanding of the BIM capability/maturity of countries or even markets, a larger organizational unit within the 12-scale organizational hierarchy (Succar, 2010). Establishing the availability/non-availability of BKC labels across multiple country-specific publications is arguably a good indicator of a country's BIM maturity.

Due to ongoing investigations to confirm the selection/labelling of NBPs, this chapter will avoid an in-depth analysis of data distribution within the preliminary charts. Once data collection is complete, a separate article will provide a more definitive picture of the availability/distribution of knowledge content across different countries.

CONCLUDING NOTES

Noteworthy BIM publications encapsulate a significant volume of domain knowledge. By organizing the knowledge content across these publications, industry-wide comparative analysis and knowledge gap identification can be achieved.

This book chapter introduced a BIM knowledge content taxonomy derived from a published BIM Framework (Succar 2009) (Succar 2013). The BIM content taxonomy consists of a hierarchical cluster of 18 content labels grouped under three content clusters with specific taxonomic properties. The BIM content taxonomy can be utilized in two main ways: organize BIM domain knowledge, and enable targeted access to specific content within numerous publications.

In addition to organizing knowledge within NBPs, the BKC taxonomy provides the traditional functions of indexing support and retrieval support (Hedden 2010). The BKC facilitates indexing support through its controlled vocabulary which allows indexers to classify documents in a consistent manner. Without a controlled vocabulary, multiple documents with the same content may erroneously carry different headings. Indexers may also inadvertently use synonyms for classifying similar documents (Hedden 2010, p. 15).

Retrieval support is a direct consequence of indexing support (Hedden 2010, p. 22) and refers to the ability of a classification to facilitate searching and improve find-ability within databases. The BKC taxonomy can be readily transformed into a facetted classification with its labels (a content type facet) augmented with

additional facets – e.g. a content format facet, content relevance facet or issuer type facet (Succar 2013) (Kassem et al. 2013). The BKC can thus support both information retrieval and the faceted analysis (Kwasnik 1999) of noteworthy BIM publications by "[shifting] the focus of perusal and interaction away from potentially uninformative document surrogates (such as titles, sentence fragments and URLs) to actual document content, and uses this content to drive the information seeking process" (White et al. 2005 - page 1).

Organizing BIM domain knowledge allows policy makers and field researchers to identify gaps in their country's BIM policies and to highlight areas which require further research and development. Policy makers can also adopt or adapt compatible BIM content types from other countries and thus reduce duplication of efforts. Also, the BKC taxonomy can be used to facilitate access to knowledge spread across a large number of publications. Analysis and comparison can be continuously extended to include new publications or to generate more granular labels which pinpoint specific knowledge types.

In this chapter, ten content labels from the BIM knowledge content taxonomy were used to classify 57 noteworthy BIM publications from eight countries selected for their active BIM scene. Analysis of content availability and their distribution provided a structured insight into much published BIM knowledge. Future studies will aim to expand the BIM content taxonomy by considering more granular labels. An online database-driven, web-based prototype will also be developed to further organize domain knowledge and allow extended research findings to be efficiently maintained, managed, and accessed (Zuppa and Issa 2008). Noteworthy BIM publications from additional countries will also be analyzed and compared to provide a wider and more structured understanding of available BIM knowledge content, decrease effort duplication across the wider industry and facilitate BIM adoption.

APPENDIX

See Tables 13-1–13-3.

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
AU 01	CRC-CI National Guidelines for Digital Modelling + Case Studies (2 documents)	The guidelines document provides an overview of BIM and how it affects current mode of working. It also provides detailed information about model creation/ maintenance, modeling procedures and how to initiate large scale BIM projects. The case studies document includes the lessons learned from implementing BIM in six Australian building projects	Research body	CRC-CI 2009
AU 02	Digital modelling and the built environment, department of Innovation Industry, Science and Research	This report discusses in general terms the benefits and challenges of BIM implementation, and summarizes some of the efforts undertaken both in Australia and overseas	Governmental department	DIISR 2010
AU 03	Productivity in the buildings network: assessing the impacts of Building Information Models, report to the Built Environment Innovation and Industry Council	This report highlights the economic case for BIM adoption in Australia and suggests a road map for BIM adoption. It includes a discussion about BIM benefits, costs, challenges and opportunities and the results from a survey conducted across the sector	Industry body or association *(based on the work of a consultancy firm)*	BEIIC 2010

(Continued)

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries *(Continued)*

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
AU 04	NATSPEC National BIM Guide and Project BIM Brief template	The guide provides a summary description of roles and responsibilities, provides guidance on standards and procurement practices and introduces a BIM Management Plan template. The template is also intended for guidance and is intended to assist project participants to decide what information to be included within models at different project stages	Industry body or association	NATSPEC 2011
AU 05	BuildingSMART Australasia, National Building Information Modelling Initiative	This document discusses benefits and challenges of BIM adoption and surveys international efforts. It's main deliverable is the identification of six interdependent initiatives for government and industry to undertake: procurement, guidelines, education, product libraries, process/data exchange and regulatory frameworks	Industry body or association	buildingSMART 2012
AU 06	BIM in Practice, an initiative by the Australian Institute of Architects and Consult Australia	The initiative includes seventeen complementary papers focusing on four topics: Legal (4), Industry Outreach (7), Education (3) and BIM Management Plans (3). The papers are exploratory and include summary information intended to inform practitioners and generate discussion within industry	Industry body or association	AIA-CA 2012

AU 07	BIM-MEP AUS initiative by the Air Conditioning and Mechanical Contractors' Association of Australia (AMCA)	While focusing on mechanical subcontractors (the associations' members), this industry initiative engages widely with other industry stakeholders and delivers a set of practice guidelines, training material, certified equipment models and software extensions	Industry body or association	AMCA 2012a
DK 01	BIPS C101: CAD Manual	Outlines guidelines for CAD production and collaboration for the Danish construction industry. This fifth revision replaces "C202: CAD Manual 2005" and "3D CAD Manual 2006, Digital Construction"	Industry body or association	BIPS 2008
DK 02	BIPS C202: CAD Manual 2008, basic description	Contains guidelines and conceptual descriptions which are applicable across all types of companies and projects	Industry body or association	BIPS 2008
DK 03	BIPS F103: Object Structure 2008–June 2008	Specifies uses and data properties pertaining to construction objects (36 objects) at a given level of detail	Industry body or association	BIPS 2008
DK 04	BIPS F102: Building ICT specifications, instructions - June 2008	Part 1 (see DE 05 for part 2) defines the digital services (BIM deliverables) at different construction project phases and their requirements	Industry body or association	BIPS 2008
DK 05	BIPS F202: ICT output specification, basic description - June 2008	Part 2 explains technical and practical aspects of digital collaboration between construction project parties	Industry body or association	BIPS 2008

(Continued)

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries *(Continued)*

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
DK 06	Digital Construction: A Danish government initiative, English introduction, 2010	This strategy document aims to increase information and knowledge sharing between all AEC's actors and improve project efficiency across all phases through the use of BIM tools and workflows	Industry body or association	Det Digitale Byggeri 2010
FI 01	Senate Properties' Building Information Model Requirements 2007	This document describes general operational procedures to be used in BIM projects with a focus on the design stage. The document is in 9 volumes organized by discipline: 1: General part 2: Modeling of the starting situation 3: Architectural design 4: MEP design 5: Structural design 6: Quality assurance, model merging 7: Quantity take-off 8: Visualization purposes 9: MEP analyses	Government-owned enterprise	Senate 2007a
FI 02	Senate Properties: BIM Requirements 2007 Volume 1: General part	This is an introductory document to the Finnish BIM guidelines (see FI 03 and FI 04) and includes the general objectives for the generation and utilization of models at different project stages. This document also mandates some BIM uses from October 2007.	Government-owned enterprise	Senate 2007b

FI 03	Common BIM Requirements COBIM 2012 v1.0	Updates the "Senate Properties' Building Information Model Requirements 2007" (FI 01) by adding the following new four series: 10: Energy analysis 11: Management of a BIM project 12: Use of models in facility management 13: Use of models in construction	Government-owned enterprise	Senate 2012
NL 01	Public sector demand for BIM	Mandates BIM and the use of IFCon public projects worth more than €10M starting Nov 2011	Governmental department	GBA in Building SMART 2011a
NL 02	BIM Quickscan: Benchmark of BIM Performance in The Netherlands	An approach for assessing and benchmarking the BIM performance of companies within the Netherlands	Research body	Berlo et al. 2012
NL 03	Rgd BIM Standard, Version 1.0.1, July 2012	Guidelines for design and collaboration within BIM environment. The document describes delivery requirements and specifications of BIM extracts (i.e. IFC model, CAD drawings, measurement data, calculations, and quantity take-offs). It also adopts the AIA E202 – 2008 BIM Protocol Exhibit(Levels of Development from the US)	Governmental department	GBA 2013
N0 01	The HITOS project – a full scale IFC test	A 'full-scale IFC test' documenting experiences gained from a large collaborative BIM project	Industry body or association	Le et al. 2006

(Continued)

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries *(Continued)*

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
NO 02	Statsbygg goes for BIM	To mandate BIM and the use of IFCs on all public construction projects starting 2010	Governmental department	Statsbygg 2007
NO 03	Construction cost program: Reducing barriers - Report from interview – qualitative (in Norwegian)	A report investigating barriers to BIM collaboration. It discusses efficient construction processes and suggests measures to remove or lower adoption barriers	Government – industry partnership	Byggekostnader 2010
NO 04	Norwegian Home Builders' BIM Manual (ver1)	A manual for Norwegian Home Builders providing practical advice covering BIM processes and utilization	Industry body or association	NHA 2011
NO 05	Statsbygg Building Information Modelling Manual, Version 1.2 (SBM1.2)	Describes BIM requirements with a focus on Industry Foundation Classes (IFC)s	Governmental department	Statsbygg 2011
SG 01	All set for the 2015	This document presents Singapore strategy to achieve 80% BIM uptake by 2015 and improve the industry's productivity by up to 25% over the next decade. It also aims to mandate BIM in a phased way: larger projects are required to use BIM for their architectural designs by 2013 and for engineering designs by 2014; smaller projects, both architectural and engineering designs, by 2015	Governmental department	BCA: in BuildSMART 2011

SG 02	Singapore BIM Guide (ver 1.0)	This document provides guidelines for mono-discipline modeling and multidisciplinary collaboration; describes BIM deliverables of various project members at different project stages and their levels of detail; defines a basic BIM workflow for Design-Bid-Build projects; and offers general guidance on risk allocation, compensation and intellectual property rights	Governmental agency	BCA 2012
GB 01	Refurbishment resource efficiency case study: Manchester Central Library	A case study demonstrating the benefits of BIM achieved on a $ 61M refurbishment project	Industry body or association	WRAP 2010
GB 02	Government Construction Strategy	This document includes the UK government strategy aimed to challenge current industry business models and practices and replace them with collaborative supply chain models. This document specifies that BIM is a main enabler of this integration and announces the intention of the government to develop 'standards' that enable all members of the supply chain to work collaboratively	Governmental department	Cabinet 2011

(Continued)

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries *(Continued)*

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
GB 03	CPIx BIM assessment form	A basic form to assess the BIM capabilities of organizations	Industry body or association	CPC 2011
GB 04	BIM Management for value, cost & carbon improvement, report number URN 11/948 - A report for the Government Construction Client	This document outlines four BIM maturity levels (0, 1, 2 and 3) intended to categorize technical and collaborative working types and describe processes, tools and techniques to be used. It also includes workflows that clarify data exchange requirements at specific project milestones. It outlines a strategy to increase the BIM adoption over a five year period as part of a wider government strategy aimed to improve construction value and carbon performance and decrease cost	Governmental department	DBIS 2011

GB 05	AEC (UK) BIM Protocol Implementing UK BIM Standards for the Architectural, Engineering and Construction industry - Updated to unify protocols outlined in AEC (UK) BIM Standard for Revit and Bentley Building Version 2.0 September 2012	This document includes guidelines, specific to Revit, Bentley, ArchiCAD and Vectorworks which can be used to inform the creation of BIM elements and facilitate BIM collaboration. It also introduces modeling 'Grades', a system similar to AIA's Levels of Development (LOD)s	Community of Practice	AEC 2012
GB 06	Soft Landing Strategy	This document aims to align the interests of facility designers and construction companies with those of facility owners and operators. It also introduces a mandate for BIM by 2016 for all Central Government Department projects	Governmental department	Cabinet Office 2012
GB 07	Building Information Model (BIM) Protocol - Standard Protocol for use in projects using Building Information Models, CIC/ BIM ProFirst Edition 2013	Guides that identify model-based requirements to be produced project team members: their obligations, liabilities and associated limitations It also includes several intellectual property rights' clauses clarifying permitted uses of models, levels of development and other contractual requirements	Industry body or association	CIC 2013

(Continued)

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries *(Continued)*

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
GB 08	National BIM Report 2013	A report providing insight and opinions of UK industry leaders. It includes survey results describing levels of BIM uptake	Private industry	NBS 2013
GB 09	Building Information Modelling - an introduction for house builders	A manual explaining basic BIM concepts to UK house builders. It includes survey results describing levels of BIM uptake	Industry body or association	NHBC Foundation 2013
GB 10	First Steps to BIM March 2013 Competence A Guide for Specialist Contractors	A report to contractors explaining the BIM fundamentals, business benefits, how to get started with BIM, legal implications, roles and responsibilities	Industry body or association	NSCC 2013
US 01	BIM user guides	This document presents guidelines to develop and maintain a BIM standard	Governmental department	USCG 2005
US 02	Contractor's Guide to BIM	This document provides basic guidelines for contractors who intend start using BIM. It also discusses the impact of BIM on responsibilities and liabilities and indicated the areas of risk management for contractors	Industry body or association	AGC 2006b
US 03	Consensus Docs 301 BIM Addendum	This document globally addresses legal and administration issues associated with the use of BIM	Industry body or association	ACGA 2006

US 04	NISTIR 7259 Capital Facilities Information Handover Guide, Part 1	This document has two parts. Part 1 presents a methodology for defining the information requirements for the full facility life cycle and then develops and implements an information handover plan for a specific capital facility project. Part 2 describes describe case studies, specific standards and data forms applicable to different capital facility types, e.g., general building, process plant and transportation infrastructure.	Governmental department/ Community of practice	NIST and FIATECH 2006
US 05	Building Information Modeling: A Road Map for Implementation To Support MILCON Transformation and Civil Works Projects within the U.S. Army Corps of Engineers	A document outlining the organizational and process change needed to effectively integrate BIM into in-house and A/E designs on USACE project world-wide.	Governmental department	USACE 2006

(Continued)

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries *(Continued)*

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
US 06	Integrated project delivery: a guide	This document includes guidelines for integrating people, systems, business structures and practices into a project to increase value to the owner, reduce waste, and maximize efficiency through all project phases. It also addresses issues related to multi-party agreements such as risk and reward, liability and dispute resolution	Industry body or association	AIA 2007
US 07	GSA BIM guides series	This document includes general guidelines for GSA associates and consultants engaged in 3D and 4D activities. It also contains a section covering data ownership rights	Governmental department	GSA 2007
US 08	State of Ohio Building Information Modeling protocol	A document presenting the BIM requirements related to: requests for qualifications, agreements, bidding and contracts, list of deliverables/BIM services, and information exchange. It also addresses compensation expectations and level of development of the BIM model at for different project element	Local authority	OHIO DAS 2010
US 09	BIM Project Execution Planning Guide and Templates – Version 2.0 BIM Project Execution Planning	This document presents guidelines to help the identification of BIM goals and uses and contains process maps and template resources for the the implementation of different BIM uses	Research body	Penn State 2010

US 10	Building Information Modeling (BIM) Roadmap Supplement 2 – BIM Implementation Plan for Military Construction Projects, Bentley Platform	This document includes workflows that are specific to Bentley platform users working for USACE. It describes the workflows for site analysis, space programming, architectural design, etc., and presents interoperability requirements and training opportunities	Governmental department	USACE 2011
US 11	E203: Building Information Modeling and Data Exhibit	A document defining the levels of development (LoD), the authorized uses of BIM on projects and the responsibility for the defined LOD(s) at each project phase	Industry body or association	AIA 2012a
US 12	G Document 201: Project Digital Data Protocol Form	A document that includes a contractual form to document the 'digital data protocols' agreed upon by project stakeholders	Industry body or association	AIA 2012b
US 13	G Document 202: Building Information Modeling Form	A document that includes a contractual to document the 'BIM protocols' agreed upon by project stakeholders	Industry body or association	AIA 2012c
US 14	IPD Case Studies	This report compares twelve IPD projects - ten of which has used BIM - in terms of contractual and behavioral strategies. It also includes the results of a survey regarding IPD contractual principles and collaborative project delivery methods	Industry body or association/ Research body	AIA and University of Minnesota 2012

(Continued)

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries *(Continued)*

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
US 15	The Business value of BIM in North America: Multi-Year Trend Analysis and User Ratings (2007–2012)	This document consists of a report presenting the adoption rates and the uses of BIM in the U.S. and summarizing the results and benefits obtained from five case studies	Private industry	McGraw-Hill Construction 2012
US 16	BIM guidelines	This document includes requirements for BIM uses/services, submission and design development. It also specifies the ownership of the model including all inventions, ideas, designs, and methods contained within it	Local authority	NYCDDC 2012
US 17	Planning Guide for Facility Owners – Version 1.0	This documents present guidelines for the integration of BIM throughout the life cycle of facilities and in Owners' organizations. It also contains contractual requirements for owners.	Research body	Penn State 2012
US 18	USACE BIM Minimum Modeling Matrix (M3) V1.0	This document includes a matrix of modeling requirements for BIM deliverables to ensure the relevance of deliverables to all project stages and to the owner and facility manager	Governmental department	USACE 2012

US 19	National BIM standard – United States™ Version 2	This document superseded NBIMS-US V1 (2007) and is aimed at software developers and practitioners. For software developers, there is an array of reference standards (ISO 16739, IFc 2x3, OmniClass™ tables), model view definitions and information exchange standards. To this version 2, COBie (Construction Operations Building Information Exchange – Version 2.26) was added as the new standard for life-cycle information exchange format describing the spaces and equipment within a facility. For practitioners, there are process execution protocols, 'BIM Minimum' concept for quantity and quality of BIM information and the Capability Maturity Model (CMM) for the evaluation of the BIM capability of business practices.	Industry body or association	NIBS 2013

(Continued)

Table 13-1. A preliminary list and an indicative summary of noteworthy BIM publications from eight countries *(Continued)*

Code	*Document title*	*Summary Description*	*Issuer Type*	*Reference*
US 20	Information Exchange Projects	This document summarizes a number of information exchange projects (e.g. BIM Service interface exchange (BIMSie), Building Automation Modeling information exchange (BAMie), Building Programming information exchange (BPie), Construction Operations Building information exchange (COBie), Electrical System information exchange (Sparkie), HVAC information exchange (HVACie), Life Cycle information exchange (LCie), Quantity Takeoff information exchange (QTie), Specifiers' Properties information exchange (SPie), Wall information exchange (WALLie) and Water System information exchange (WSie)) presenting information exchange specification and aimed to enable the capture of BIM over the lifecycle.	Governmental department	USACE 2013
US 21	The COBie Guide: a commentary to the NBIMS-US COBie standard	A Guide identifying general requirements of COBie (Construction Operations Building Information Exchange) deliverables for design and construction contracts. It also includes client and owner's specific requirements	Governmental department	East and Carrasquillo-Mangual 2013

Table 13-2. BIM Knowledge Content taxonomy (v1.3): 18 content labels in three content clusters

Content CLUSTER	*Label CODE*	*Content LABEL*	*Label DEFINITION - BIM specific*
Guides	G1	Best Practice	Operational methods arising from experience; promoted as advantageous; and replicable by other individuals, organizations and teams. This *label* applies to publications which list unambiguous and detailed recommendations, and which if applied as recommended, generate similar advantageous outcomes
	G2	Case Study	Summary and analysis (descriptive or explanatory) of projects and organizational efforts. This *label* applies to both research and industry publications which share lessons learned *by others,* and cover BIM deliverables, workflows, requirements, challenges and opportunities
	G3	Framework or Model	Theoretical structures explaining or simplifying complex aspects of the BIM domain by identifying meaningful concepts and their relationships
	G4	Guideline	Compilation of several BIM content types with the aim of providing guidance to individuals, teams or organizations. Guides typically provide insight into a complex topic (e.g. BIM Implementation Guide or Facility Handover Guide). Guides typically focus on knowledge-intensive topics, while Manuals (a complementary label) focus on skill-intensive ones. Due to the generic nature of this *label*, it should not be applied in isolation but in conjunction with other labels
	G5	Learning Module or Material	All types of analogue and digital media (e.g. printed manual or online videos) which deliver conceptual or practical insight intended/suitable for education, training or professional development within industry or academia
	G6	Report	Compilation or summary of results arising from an assessment, calculation or review process (e.g. BIM capability report or profitability statement)

(Continued)

Table 13-2. BIM Knowledge Content taxonomy (v1.3): 18 content labels in three content clusters *(Continued)*

Content CLUSTER	*Label CODE*	*Content LABEL*	*Label DEFINITION - BIM specific*
	G7	Strategy or Vision	Articulation of vision, mission and long-term goals. This *label* applies to publications which identify a long-term strategy (and possibly middle-term goals/milestones) but without identifying the resources required and detailed steps needed to fulfill the strategy
	G8	Taxonomy or Classification	Classification covering roles, types, levels, elements and other structured concepts. This *label* applies to publications which introduce classifications of five or more items within a structured list; and which have a clear use in assessment, learning or implementation (e.g. construction elements, BIM roles, data exchange types or levels of detail)
Protocols	P1	Metric or Benchmark	Tools and criteria suitable for establishing levels of performance of systems, projects, individuals, teams, organizations and other organizational units*. This *label* applies to publications which include tools or explicit metrics/indicators for establishing usability, profitability, productivity, competency, capability or similar
	P2	Manual	A structured document which is intended to clarify the steps needed to perform a measureable activity or deliver a measureable outcome (e.g. BIM Training Manual). Manuals typically focus on skill-intensive topics, while Guides (a complementary label) typically focus on skill-intensive ones. Due to the generic nature of this *label*, it should not be applied in isolation but in conjunction with other labels

P3	Plan	A document describing activities to be performed, resources to be used and milestones to be reached within a defined timeframe. This *label* applies to publications describing – in adequate detail - how a specific strategy can be fulfilled or a pre-defined goal can be reached (e.g. a BIM Implementation Plan detailing how to fulfill a BIM Capability Strategy)
P4	Procedure or workflow	Structured information covering successive steps needed to fulfill an operational, rather than strategic, requirement. A documented Procedure includes the small steps needed to deliver, if executed by a competent individual, a pre-defined and desired outcome. A Workflow identifies major successive activities to be performed and decision gates to pass-through towards reaching a delivery milestone or fulfilling a project/organizational objective
P5	Protocol or Convention	Agreed or customary method of product/service development or delivery which are not *by themselves* contractually binding (e.g. keeping minutes of meetings, how to name files and frequency of exchanging models)
P6	Specification or Prescription	A set of criteria used to define or judge the quality of products (e.g. object dimensions or data richness) and services (e.g. timeliness). Specifications may or may not be a Standard (a separate label). COBie is an example of BIM-related specifications which may become a service/delivery standard over time
P7	Standard or Code	Detailed set of product/service descriptions (prescriptive or performance-based) acting as a reference to be measured against. This label typically denotes a set of specifications (a separate label) which are authoritative and test-proven (e.g. barrier-free or accessibility standards)

(Continued)

Table 13-2. BIM Knowledge Content taxonomy (v1.3): 18 content labels in three content clusters *(Continued)*

Content CLUSTER	*Label CODE*	*Content LABEL*	*Label DEFINITION - BIM specific*
Mandates	M1	Contract or Agreement	Legally-binding document and its subparts – including contractual additions, amendments and disclaimers. This *label* applies to contracts and clauses, not to publications describing or promoting them (e.g. the label applies to AIA Documents E203, G201 and G202 but not to the AIA IPD guide)
	M2	Program or Schedule	A document associating one or more classification to time and/or location. For example, a BIM competency improvement program is a document linking BIM competencies, BIM roles (and possibly other classifications) to a timeline or target dates
	M3	Requirement, Rule or Policy	Expectation or qualification mandated by clients, regulatory authorities or similar parties. This *label* applies to publications with explicit identification of requirements to be met (e.g. organizational capability or previous experience) or products/services to be delivered (e.g. a tender/bid document)

*There are 12 organizational units, each with their own unique metrics (refer to Building Information Modelling Maturity Matrix (Succar, 2010).

Table 13-3. An exploration of 55 NBPs from 8 countries using the BKC taxonomy

		Guides				*Protocols*				*Mandates*	
		Case Study G2	*Guideline G4*	*Report G8*	*Strategy or . . . G9*	*Metric or . . . P1*	*Manual P2*	*Procedures or . . . P4*	*Specifi-cations . . . P6*	*Contract or . . . M1*	*Require-ment . . . M3*
Australia	AU 01	•	•				•				
	AU 02			•							
	AU 03			•							
	AU 04		•					•			
	AU 05			•	•						
	AU 06		•								
	AU 07		•				•	•	•		
Denmark	DK 01		•								
	DK 02		•								
	DK 03					•			•		
	DK 04										•
	DK 05						•				
	DK 06				•						
Finland	FI 01		•			•					•
	FI 02				•						
	FI 03		•			•					•
Norway	NO 01	•									
	NO 02				•						

(Continued)

Table 13-3. An exploration of 55 NBPs from 8 countries using the BKC taxonomy *(Continued)*

		Guides				*Protocols*				*Mandates*	
		Case Study G2	*Guideline G4*	*Report G8*	*Strategy or . . . G9*	*Metric or . . . P1*	*Manual P2*	*Procedures or . . . P4*	*Specifi-cations . . . P6*	*Contract or . . . M1*	*Require-ment . . . M3*
	NO 03			•							
	NO 04						•				
	NO 05		•								•
Singapore	SG 01				•						•
	SG 02		•			•		•		•	
The Netherlands	NL 01				•						
	NL 02					•					
	NL 03		•						•		•
United Kingdom	GB 01	•									
	GB 02		•			•					
	GB 03					•					
	GB 04			•	•	•		•			
	GB 05				•						
	GB 06				•						•
	GB 07		•			•				•	
	GB 08			•							
	GB 09						•				
	GB 10			•							

| | | |

References

AEC (2012). "AEC UK: BIM Protocol Implementing UK BIM Standards for the Architectural, Engineering and Construction industry." <http://aecuk.files.wordpress.com/2012/09/aecukbimprotocol-v2-0.pdf> (Apr. 10, 2013).

AGC (2006a). *Consensus Docs 301 BIM Addendum*, the Associated General Contractor of America, Arlington, U.S.

AGC (2006b). *The Contractors' Guide to BIM (1st Ed)*, Associated General Contractors of America, Arlington, U.S.

AIA (2007). *Integrated project delivery: a guide*, AIA California Council, Washington, DC, U.S.

AIA (2012a). *E203: Building Information Modeling and Data Exhibit*, The American Institute of Architects, Washington, DC, U.S.

AIA (2012b). *G Document 201: Project Digital Data Protocol Form*, The American Institute of Architects, Washington, DC, U.S.

AIA (2012c). *G Document 202: Building Information Modeling Form*, The American Institute of Architects, Washington, DC, U.S.

AIA-CA (2012). "BIM in Practice - BIM Education, a Position Paper by the Australian Institute of Architects and Consult Australia." <http://www.bim.architecture.com.au> (Apr. 10, 2013].

AIA, and University of Minnesota (2012) *IPD Case Studies*, The American Institute of Architects, Washington, DC, U.S.

AMCA (2012a). *BIM-MEP AUS, Roadmap, 2012 Parliamentary Launch*, Melbourne, Australia: Air Conditioning and Mechanical Contractors' Association of Australia.

AMCA (2012b). *BIM-MEP AUS Practices: Naming Conventions and Units of Measure*, Melbourne, Australia: Air Conditioning and Mechanical Contractors' Association of Australia.

ANZRS (2011) "Australian & New Zealand Revit Standards, version 3 (2012)." <http://www.anzrs.org/> (Apr. 10, 2013)

BCA (2012). *Singapore BIM Guide (ver 1.0)*, Building and Construction Authority, Singapore, 2012.

BEIIC (2010). *Productivity In The Buildings Network: Assessing The Impacts Of Building Information Models*, Melbourne, Australia: Built Environment Innovation and Indutry Council (BEIIC).

Berlo, L., Dijkmans, T., Hendriks, H, Spekkink, D., and Pel, W. (2012). "BIM Quickscan: Benchmark of BIM Performance in The Netherlands." *Proceedings of the CIB W78 2012: 29th International Conference*, Beirut, Lebanon, 17–19 October.

BIPS (2008). "bips værktøjer." <http://bips.dk> (Apr. 11, 2013).

BuildingSMART (2011a) *Public sector demand for BIM, Newsletter n6*, Issue November 2011

BuildingSMART (2011b) "All set for the 2015, the BIM Issue." Build Smart, Issue 09, 2011

BuildingSMART (2012). "National Building Information Modelling Initiative, A strategy for the focussed adoption of building information modelling and related digital technologies and processes for the Australian built environment sector." vol. 1, buidling SMART Australasia.

Burgun, A., and Bodenreider, A. (2001). "Aspects of the taxonomic relation in the biomedical domain." In *Proceedings of the international conference on Formal Ontology in Information Systems*, vol 2001 (FOIS '01), ACM, New York, NY, USA, 222–233.

Byggekostnader (2010). "Byggekostnadsprogrammet for prosjektet Nr. 14292 Bygg Ned Barrierene Rapport fra dybdeintervju – kvalitativ." <http://www.byggekostnader.no> (Apr. 5, 2013).

Cabinet Office (2012). "The Government Soft Landings Policy." <http://www.bimtaskgroup.org/gsl-policy-2> (Apr. 5, 2013).

CIBER (2012). "Building Information Modelling (BIM): Australian Perspectives and Adoption Trends, prepared for the Tasmanian Building and Construction Industry Training Board." In G. Brewer (Ed.). Tasmania, Australia: Centre for Interdisciplinary Built Environment Research, University of Newcastle.

CIC (2013) *BIM Protocol: Standard Protocol for use in projects using Building Information Models, 1st ed*, Construction Industry Council, London, UK, 2013.

Cabinet Office (2011) *Government Construction Strategy*, Construction Industry Council, London, UK, 2011.

CPC (2011). "CPIx BIM assessment form - Construction Project Information." <http://www.cpic.org.uk> (Apr. 5, 2013).

CRC-CI (2007). "National Guidelines and Case Studies 2007-002-EP." <http://www.construction-innovation.info/index.php?id=1083> (Apr. 8, 2013).

Cheng, C. P., Lau, G. T., Law, K. H., and Pan, J. (2008). "Albert Jones Regulation retrieval using industry specific taxonomies." *Artificial Intelligence and Law September*, vol (16), Issue 3, 277–303

DBIS (2011). "BIM Management for value, cost & carbon improvement." report number URN 11/948, Department of Business, Innovation and Skills, London, UK, 2011.

Det Digitale Byggeri (2010). "Digital Construction – a government initiative." <http://www.detdigitalebyggeri.dk/english> (Apr. 8, 2013].

DIISR (2010). *Issue Paper: Digital Modelling and the Built Environment*, Built Environment Digital Modelling Working Group: Department of Innovation, Industry, Science and Research.

East, W.E. (2013). "Information Exchange Projects." <http://www.nibs.org/?page=bsa_infoexchange> (Sep. 9, 2013).

East, W. E. and Carrasquillo-Mangual, M. (2013). "The COBie Guide: a commentary to the NBIMS-US COBie standard." Engineer Research and Development Center, Champaign IL, U.S.

El-Diraby, T.A., Lima, A., and Feis, B. (2005). "Domain taxonomy for construction concepts: toward a formal ontology for construction knowledge." *Journal of Computing in Civil Engineering ASCE*, vol 19 (4), 395–406.

Forze, C. and Di Nuzzo, F. (1998). "Meta-analysis Applied to Operations Management: Summarizing the Results of Empirical Research." *International Journal of Production Research*, vol 36(3), 837–61.

Garrett, J. and Teizer, J. (2009). "Human Factors Analysis Classification System Relating to Human Error Awareness Taxonomy in Construction Safety." *Journal of Construction Engineering and Management*, vol 135(8), 754–763.

GBA (2013). *Rgd BIM Norm 2013*, Government Building Agency, The Netherlands, 2013.

GSA (2007). *GSA BIM guides Series*, U.S. General Services Administration, Washington DC, U.S.

Hedden, H. (2010). *The Accidental Taxonomist (1st Ed.)*, Information Today Inc: Medford, U.S.

Holsapple, C. W. and Joshi, K. D. (2006). "Knowledge Management Ontology." In D. G. Schwartz (Ed.), *Encyclopedia of Knowledge Management* (397–402): Idea Group Reference.

Kashyap, V. and Sheth, A. (1996). "Schematic and semantic similarities between database objects: A context-based approach." *VLDB Journal*, vol 5 (4).

Kassem, M., Succar, B., and Dawood, N. (2013). "A Proposed approach to comparing the BIM maturity of countries." *Proceedings of the CIB W78 2013: 30th International Conference*, Beijing, China, 9–12 October.

Kiviniemi, A. (2007). "Finnish ICT Barometer 2007 Tekes." <http://cic.vtt.fi/projects/vbe-net/data/2007_ICT_barometer.pdf> (Apr. 04, 2013).

Kubba, S. (2012). Handbook of Green Building Design and Construction, Elsevier: Watham, USA.

Laatunen, K. (2013). "INFRA FINBIM work package." <http://www.rym.fi/en/programs/builtenvironmentprocessreengineeringpre/infrafinbim/> (Sep. 18, 2013).

Le, M.A.T., Mohus, F., Kvarsvik, O.K., and Lie, M. (2006). "The HITOS project - a full scale IFC test." *ework and ebusiness in Architecture, Engineering and Construction: Proceedings of the 6th European Conference on Product and Process Modelling*, Valencia, Spain, September 13–15, 2006.

McGraw-Hill Construction (2012). "The Business value of BIM in North America: Multi-Year Trend Analysis and User Ratings (2007–2012)." Bedford, U.S.

Milgram, P., and Kishino, F. (1994). "A Taxonomy of Mixed Reality Visual Displays." *IEICE Transactions on Information and Systems E77-D*, vol. 12, 1321–1329.

Kwasnik, B. (1999). "The Role of Classification in Knowledge Representation and Discovery." *Library Trends*, 48(1), 22–47.

NATSPEC (2011). *National BIM Guide and Project BIM Brief template*, Sydney, Australia: NATSPEC.

NBS (2013). "National BIM Report 2013." NBS National BIM library, Newcastle upon Tyne, UK.

NHA (2011). "Norwegian Home Builders' BIM Manual (ver1)." Norwegian Homebuilders Association, 2011.

NHBC Foundation (2013). "Building Information Modelling - an introduction for house builders." Publication NF 49, Bucks, UK.

NIBS (2012). "National Building Information Modeling Standard - version 1.0 - part 1: overview, principles and Methodologies." National Institute of Building Sciences, Washington, DC, U.S.

NIST, and FIATECH (2006). *NISTIR 7259 Capital Facilities Information Handover Guide, Part 1*, National Institute of Building Sciences, Washington, DC, U.S.

NSCC (2013). *First Steps to BIM Competence: A Guide for Specialist Contractors*, The National Specialist Contractor Council, London, UK.

NYCDDC (2012). "BIM Guidelines, New York City Department of Design & Construction." Long Island City, NY.

Ohio DAS (2010). *State of Ohio Building Information Modeling Protocol*, Ohio Department of Administrative Services, Columbus, Ohio, US.

Penn State (2010). *BIM Project Execution Planning Guide and Templates– Version 2.0 BIM Project Execution Planning*, CIC Research Group, Department of Architectural Engineering, The Pennsylvania State University.

Penn State (2012). *Planning Guide for Facility Owners– Version 1.0*, CIC Research Group, Department of Architectural Engineering, The Pennsylvania State University.

Reinach, S., and Viale, A. (2006). "Application of the human error framework to conduct train accident/incident investigations." *Accident Analysis and Prevention*, vol 38, 396–406.

Reisman, A. (1988). "On alternative strategies for doing research in the management and social sciences." *Engineering Management, IEEE Transactions on*, vol 35(4), 215–220.

Reisman, A. (2005). "Transfer of technologies: a cross-disciplinary taxonomy." *Omega*, vol 33(3), 189–202.

RIBA - Royal Institute of British Architects (2012). *BIM Overlay to the RIBA Outline*, RIBA Publishing, London.

SENATE (2007a). "SENATE Properties BIM Guidelines." <http://www.senaatti.fi/document.asp?> (Apr. 1, 2013)

SENATE (2007b). "SENATE Properties: BIM Requirements 2007 Volume 1:General part.," http://www.senaatti.fi/tiedostot/BIM_2007_Vol1_General_Part.pdf, [last accessed April 10, 2013].

SENATE (2012). "SENATE Properties: BIM Requirements 2012." <http://www.en.buildingsmart.kotisivukone.com/3> (Apr. 25, 2013).

Statsbygg (2007). "Statsbygg goes for BIM." <http://www.statsbygg.no/Aktuelt/Nyheter/Statsbygg-goes-for-BIM> (Apr. 2, 13).

Statsbygg (2011). *Statsbygg Building Information Modelling Manual - SBM1.2*, Statsbygg, Oslo, Norway, 2011.

Succar, B. (2009). "Building information modelling framework: A research delivery foundation for industry stakeholders." *Automation in Construction*, vol. 18, 357–375.

Succar, B. (2010). "Building Information Modelling Maturity Matrix." In Jason Underwood & Umit Isikdag (Eds.), *Handbook of Research on Building Information Modelling and Construction Informatics: Concepts and Technologies*, New York: IGI Publishing.

Succar, B. (2013). "BIM Knowledge Content Taxonomy v1.3." Building Information Modelling: conceptual framework and performance improvement models (PhD Thesis - not published). School of Architecture and Built Environment, University of Newcastle, NSW Australia.

Sun, M., Meng, X. (2009). "Taxonomy for change causes and effects in construction projects." *International Journal of Project Management*, vol 27(6), 560–572.

USACE (2006). "Building Information Modeling: A Road Map for Implementation To Support MILCON Transformation and Civil Works Projects within the U.S. Army Corps of Engineers." US Army Corps of Engineers, Engineer Research and Development Center, Washington, DC.

USACE (2011). "Building Information Modeling (BIM) Roadmap Supplement 2– BIM Implementation Plan for Military Construction Projects." Bentley Platform, US Army Corps of Engineers, Engineer Research and Development Center, Washington, DC.

USACE (2007). "Construction Operations Building Information Exchange (COBIE): Requirements Definition and Pilot Implementation Standard." US Army Corps of Engineers, Champaign, IL, U.S.

USACE (2012). *USACE BIM Minimum Modeling Matrix (M3) V1.0 20120913*, US Army Corps of Engineers, Champaign, IL, U.S.

USCG (2005). BIM user guides, presentation from the 2nd congress on digital collaboration in the building industry, AIA Building Connections, 2005.

Wang, X., and Dunston, P.S. (2011). "a user-centered taxonomy for specifying mixed reality systems for AC industry." *Journal of Information Technology in Construction*, vol 16, 493–508.

White, R. W., Jose, J. M., & Ruthven, I. (2005). "Using top-ranking sentences to facilitate effective information access." *Journal of the American Society for Information Science and Technology*, vol 56(10), 1113–1125.

Zuppa, D., and Issa, R. (2008). "Aligning interests key to developing trust in deploying collaborative technologies in construction." *CIB W78 2008 International Conference on Information Technology in Construction*, Santiago, Chile, 15–17 July 2008.

This page intentionally left blank

INDEX

Page numbers followed by *e*, *f*, and *t* indicate equations, figures, and tables, respectively.

augmented reality 247, 283–284

BIM. *See* building information modeling
BIM-based model checking. *See* BMC
BMC: adoption of 37–38; automatic checking of regulations 48–49, 49*f*; automatic processing of Statsbygg requirements 4i*f*, 47–48; clash detection 34–36, 35*f*, 36*f*; components of 38–39; content and development of rule sets 44; coordination and reporting tools 36–37; harmonized understanding of 40–43, 41*t*, 42*f*, 42*t*; logic in 39, 39*f*; overview 33–34; software 43, 43*t*, 45–46*t*; use in Norway 49–58, 50*t*, 52*t*
building information model checking. *See* BMC
building information modeling: concept of 8–9, 9*f*; overview 6; for structural engineering and architecture students 6–7; structure and architecture synergy framework 7–8, 8*f*; in the US Air Force 96–97; in the US Army 93–96, 95*f*, 96*f*
building owners: BIM adoption by 256–257; BIM benefits to 257–260, 258*t*, 259*t*; operational difficulties 262–264; overview 255–256; research methodology 256; research results 265–274, 266*f*, 267*f*, 268*t*, 269*t*, 270*t*, 271*f*, 272*t*, 273*f*, 274*f*; resource trends 260–262, 262*t*

case studies: cyber-physical systems 211–217, 211*f*, 212*f*, 213*t*, 214*t*, 215*f*, 215*t*, 216*f*, 217*f*; facilities management 292–299, 292*f*, 293*f*, 294*f*, 295*f*, 297*f*, 298*f*, 299*f*; green building projects 153–160; project management information systems 182–184*t*, 187–190
clash detection 34–36, 35*f*, 36*f*
collaboration: fallout from contractual inertia 127–128, 128*f*, 130–131*t*; focus group interviews 121, 124–126*t*, 124–127; overview 108–110; research methodology 110–113, 112*f*; study results 113–121, 114*f*, 115*f*, 116*f*, 117*f*, 122–123*t*
cost estimation: background 64–66; overview 63–64, 64*f*; parametric 89–92, 90*f*, 91*f*, 92*f*; process of 69–73; terminology 66–69; using building information modeling 73–79, 74*t*, 76*t*
CPS. *See* cyber-physical systems
cyber-physical systems: adaptive systems 199–201; building information model forms 202–206, 202*f*, 203*f*, 205*f*; case study 211–217, 211*f*, 212*f*, 213*t*, 214*t*, 215*f*, 215*t*, 216*f*, 217*f*; deliverables 217–218; overview 196–198, 198*f*; RFID-RTLS systems 206–210, 206*f*, 207*f*, 209*f*, 210*f*

data: acquisition 233–240, 238*f*, 239*f*; preparation 322–323

facilities management: acronyms 226–229; augmented reality 247, 283–284; and building information modeling 281–282; case study 292–299, 292*f*, 293*f*, 294*f*, 295*f*, 297*f*, 298*f*, 299*f*; challenges 248–250; cloud hosting and computing 244; commissioning 240, 242–244, 242*f*; contract documents 235–236; data acquisition 233–240, 238*f*, 239*f*; FM-Dashboards 244–245, 245*f*; hyperlinking information 246–247; industry overview 225–229; information exchange 229–233, 230*f*, 231*f*, 232*f*; information handover 233–235; integrating BIM and augmented reality 284–289, 285*f*, 287*f*, 288*f*; linking BIM and augmented reality 289–292, 290*f*; overview 224, 225*f*, 280–281; owners project requirements 237–240, 238*f*, 239*f*, 241*t*; RFID technologies 245–246, 246*f*
facility control framework: control cycle 319–321, 320*t*; delivery process 324; framework model specifications 318–319, 318*t*; infrastructure management 324; LEED data preparation 322–323; modeling resource requirements 313; modeling resource-intensive systems 313–317, 314*t*, 315*f*, 316*f*; modeling sensor systems 317–318; objectives 307–308; overview 306–307; tenant management 323–324; testbed 308–313, 309*f*, 309*t*, 310*t*; total cost of ownership analysis 323

green building projects: best practices 142–144; case studies 153–160; interoperability 140–142; LEED strategy 146–147, 147*f*; organizational level of integration 154–157, 154*f*, 156*f*, 157*f*; overview 136–137; process map 147–151, 148*f*, 149*f*, 150*f*, 152*t*, 153*f*; process modeling 137–139; project execution process modeling 139–140; project/process level interaction 157–159, 158*f*, 159*f*; research methodology 144–146, 146*f*

IGBPM. *See* green building projects

MILCON: dynamic prototypes 101–103, 102*f*, 103*f*; estimation 84–89, 85*f*, 86*f*, 87*f*, 88*f*; overview 84; parametric cost estimation 89–92, 90*f*, 91*f*, 92*f*; research 97–101, 98*t*, 99*t*, 100*f*; transformation 92–93, 93*f*; in the U.S. Air Force 96–97; in the U.S. Army 93–96, 95*f*, 96*f*

PMIS. *See* project management information systems
project management information systems: and building information modeling 169–174, 171*t*, 173*t*, 174*f*; case studies 182–184*t*, 187–190; civil infrastructure 180–181; glossary 191; high-rise apartment complex 186; industrial plant 181, 185; industrialized housing 186–187; integrated construction framework 174–180, 175–176*t*; office building 185–186; overview 168–169
publications content analysis: BIM knowledge content taxonomy 333–341, 334*f*; content comparison across countries 341–343, 342*f*, 365–367*t*; identifying publications 330–332, 331*f*, 345–360*t*; overview 330; taxonomy 361–364*t*; taxonomy use 332–333

structural analysis: history of 3–4; overview 2–3; structural design fundamentals 18–19
structural design fundamentals: architecture attributes 10; differences between architects and engineers 11; engineering attributes 10–11; structural analysis 18–19; structural melody 11–14, 12*f*, 13–14*f*; structural

poetry 14–18, 16*f*, 17*f*, 18*f*, 19*f*, 20*f*, 21*f*; teaching methodology 19–23, 22*f*
structural melody 11–14, 12*f*, 13–14*f*
structural poetry 14–18, 16*f*, 17*f*, 18*f*, 19*f*
structure and architecture synergy framework: overview 7–8, 8*f*; practical applications 27–29, 28*f*; practitioner training 23–29; traditional design workflow 23*f*; workflow and productivity 24–27, 25*f*, 26*f*