Lecture Notes in Production Engineering

Michael Abramovici
Rainer Stark
Editors

Smart Product Engineering

Proceedings of the 23rd CIRP Design Conference, Bochum, Germany, March 11th–13th, 2013

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Preface

Dramatic progress in the fields of embedded microdevices, mobile communication, software and computing power have not only changed our daily life but will rapidly reshape industrial products, engineering processes and organizational structures. “Industry 4.0”, “Cyber-Physical Systems”, “Ubiquitous Computing” and “Internet of Things” are only a few examples of buzzwords trying to reflect these revolutionary changes which will lead to a convergence of the real physical world and the permanently growing digital world.

Smart Product Engineering – the topic of this conference – attempts to address these tremendous changes of both industrial products and engineering processes. In the context of product creation“smart”is not only a new fashionable word but refers to the following meanings:“clever“, “intelligent“, “ingenious“ and “agile“. **Smart products** are a new generation of products equipped with microsensors, computing power and mobile communication capabilities i.e. smartphones. However, not only consumer goods but also industrial products can become “smart”if embedded intelligence is applied.Then they are able to react instantly to environmental changes and to communicate with IT infrastructures or with other products. **Smart Product Engineering** describes processes, methods and tools for the creation of these smart products. Engineering processes could also exploit the newest IT developments in order to reduce and better integrate the increasing task complexity. In the last five years, a wave of research initiatives, start-up companies and marketing campaigns have addressed the new “smart” topic.

These “smart” developments offer huge opportunities to enhance task efficiency and to create more sustainable products. In orderto exploit these opportunities it is necessary to provide new, highly interdisciplinary methods,organization concepts and IT tools. The papers included in this book give an overview of the main research activities and the industrial practice towards Smart Product Engineering.

The 23rd CIRP Design Conference continuesa long tradition ofprestigious design conferences organized under the aegis of the International Academy for Production Engineering (CIRP). The conference was jointly organized by Ruhr-

Universität Bochum (RUB) and byTechnischeUniversität Berlin (TU Berlin). For over 40 years, both organizing universities have been worldwide pioneers in the development of product design methods and tools. The conference was organized in cooperation with the German Academic Society for Product Development - WiGeP.

Over 160 proposals were submitted for the conference. The international scientific program committee selected 98 academic and industrial papers from over 20 countries for presentation during the conference and for publication in these proceedings.

We would like to express our gratitude to all paper authors, keynote speakers, session's chairs and all participants for their contribution to the success of the conference. Our grateful thanks also goto all supporting industrial partners who made this conference possible. We also thank the conference organizing committee, especially the chief organizers Mr. Akamitl Quezada (RUB) and Mr. Maik Auricht (TU Berlin). Finally, we thank the publisher as well as the typesetting team for their support throughout the publication process.

We hope that the content of this book will offer useful andvaluable input for research, teaching and industry.

Bochum and Berlin, January 2013

Michael Abramovici (RUB)
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Smart Engineering for Smart Products

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Abstract. Smart Engineering aims at a new approach for describing, designing and dimensioning Smart Products. Design methodology is far advanced and provides both a systematic approach to develop new products as well as appropriate methods to support development tasks in specific development phases. Within this development process the communication capabilities of Smart Products, the structure of communication among Smart Products as well as executing functional operations triggered by communicated messages is not described yet.

This new approach for the description of Smart Products introduces products' states specification to derive the description of functional behavior as well as the execution of working procedures. In this contribution a basic systematic analysis of both sensors for communication and internet based communication protocols is presented to enable appropriate products' states. Based on this analysis a framework approach for processing events will be presented. The Smart Engineering approach will be demonstrated finally within an application scenario.

Keywords: Smart Engineering, Smart Products, Cross-Product Communication.

1 Introduction

Smart Engineering comprises a new procedural paradigm for describing, designing and dimensioning Smart Products. The new innovative approach of Smart Products results from the concept of Cyber-Physical Systems which requires products being equipped with embedded systems, sensors and actuators as well as the ability to communicate with other Smart Products. These new features challenge engineering as product engineering and development has to take into account consistent and reliable product behavior as well as product states in a products' application context using a Cyber-Physical Systems environment.

The concept of Cyber-Physical Systems is considered as a fundamental approach to enable the development of Smart Products. The main features of Cyber-Physical Systems are sensors, actuators and embedded intelligence as known from mechatronic and adaptronic systems. The basic difference to existing approaches is the intersection of theories of computation and dynamical systems theories [1]. Lee describes two complementary approaches called "cyberizing the physical" for specifying physical subsystems with computational abstractions and interfaces and "physicalizing the

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cyber" for expressing abstractions and interfaces of software and network components to represent physical systems' dynamics in time [1]. Furthermore Cyber-Physical Systems are considered as a breakthrough technology to develop the "Internet of Things" [2, 3]. A major approach for developing Cyber-Physical Systems is the design of a logical level, where both, the functionality of the physical systems and the system states, are to be specified. Brooks et. al. have studied model engineering using multimodeling techniques showing benefits of the augmented state chart model [4]. Own experiments using a LEGO Mindstorms environment confirm the increasing importance of specifying the logical state occurrence and the logical level of Cyber-Physical Systems [5].

While Cyber-Physical Systems are considered as a fundamental basis of Smart Products, their features are even more advanced due to their embedded intelligence. Smart Products are aiming at embedded intelligence enabling products reacting autonomously due to their communication with other Smart Products in a predefined environment e. g. a production environment. Due to the high industrial potential the German Ministry of Education and Research has identified Smart Products and Smart Factories as a key element of their initiative called "Industry 4.0" [6, 7].

To enable the development of Smart Products an advanced approach for engineering is required. This approach is called Smart Engineering and its target is to describe, to design and to engineer Smart Products. The importance of Smart Engineering has been discussed and clearly identified by acatech [8]. The main requirements comprise advanced methods for multidisciplinary product development, awareness for human acceptance and advanced engineering education [8]. Furthermore a major task in Smart Engineering is the precise and quantified definition of the products' states, functionality and behavior. For Smart Engineering a profound knowledge of sensor technologies, actuator technologies, control logics and communication protocols is required. Therefore, a basic analysis of sensor and actuator technologies as well as an analysis of communication protocols is provided.

Within this paper a new approach for describing, designing and dimensioning Smart Products is presented. Smart Engineering is based on the products' states specification to derive the description of the functional behavior and the execution of working procedures due to the received messages. Received messages are sent after being triggered by both, internal and external events. In this paper externally triggered events using internet based communication protocols are of major interest. Furthermore the integration of this approach into the product development process is described.

2 Smart Engineering

Virtual Product Development is far advanced. Appropriate product development and design methodologies have been developed and extended continuously. Pahl and Beitz [10], VDI guideline 2221 [11] and the so-called V-model (VDI guideline 2206) [12] are considered as state of the art. New approaches are aiming to integrate the challenging innovation of Smart Products into a product development and design methodology as proposed by Nattermann and Anderl [13]. The latter is a consequent extension of the V-model to the so-called W-model. Major progress is the integration of systems engineering approaches into the design methodology enabling cross-discipline product development and design.

Smart Engineering even extends systems engineering by enlarging system borders to the environment where Smart Products communicate and operate. Communication between Smart Products and their situative operation is a fundamentally new feature and a challenge for engineering. To meet this challenge a profound understanding of products' states is necessary which requires appropriate sensors, actuators and communication protocols. Furthermore it is strongly required to understand the Smart Products' states as states dedicated to the single products as well as to corresponding states of multiple Smart Products in an application environment.

2.1 Smart Products

Smart Products are mechatronic products equipped additionally with embedded systems enabling communication with other Smart Products using in particular existing internet technologies. An innovative approach is the application of Cyber-Physical systems in mechatronic products. Smart Products are enabled to know about their operational states, to monitor and to control their physical processes. They obtain awareness about their environment and their operational states, they interact with their environment by sending messages and triggering events, they are designed to draw decisions due to situation analysis and they are enabled to act autonomously.

Classification of Smart Sensors. Smart Products are created by the application of Cyber-Physical systems to mechatronic products. They add communication capabilities to Cyber-Physical mechatronic components. The communicating devices of such Smart Products consist of sensor systems, actuator systems and modules with embedded control software for data processing.

Such actuator systems consist of an active element and a sensor element which measures the current states of the active element. In the traditional understanding both, sensor and actuator systems are typically able to communicate internally controlled by their embedded systems.

Fraden, Isermann, Nordmann and White therefore developed classifications, grouping e.g. sensors, mainly regarding the measurement category or the power source [16, 17, 18, 19]. Other classification exists like Isermann who classified sensors as thermal, mechanical, electrical, chemical or physical sensors [17].

The existing classifications of Fraden, Isermann Nordmann and White are not sufficiently specified for the description of sensors for Smart Products. A new classification is needed which considers different criteria. To explain these criteria it is necessary to clarify the overall definition of sensors and their impact. Sensors will not only be used within the entire Smart Products, but for the communication between Smart Products. Extending the traditional understanding of Smart Sensors including only communication using message exchange via Bus systems [20], within this paper the understanding of Smart Sensors explicitly includes the communication via potential bus systems and internet connections. The major progress is that future Smart Sensors will be identifiable through an IP address (internet protocol address). Consequently communication between Smart Sensors is performed based on digitally represented messages. Mechanisms for avoiding measurement uncertainties and observational errors are provided by the sensors themselves. The mechanisms are not taken into account within the classification, but must be considered in the requirements of the product development process.

The main difference between Smart Sensors and Smart Products is the higher complexity resulting from the integration of embedded control software in Smart Products. Thus Smart Sensors can only react on predefined states and Smart Products are able to handle complex operations. Smart Sensors as well as Smart Products interact within their communication network. Both are treated to be smart, located however in different categories shown in the metric in the following chapter 2.2. In order to reflect the new understanding the traditional sensor classification of Nordmann, Fraden and Isermann is used and extended additionally.

Communication between Smart Products. Smart Products are enhanced by communication capabilities. In comparison to mechatronic products communication is no longer restricted between components within one product. Smart Products instead are able to additionally exchange information with other Smart Products and trigger events on each other in order to transform their corresponding internal states. Thus they send messages including specific information. Information and events both can contain sensors states, but in comparison events additionally envelop a request for a specific action [14].

To communicate with other Smart Products, a Smart Product uses its embedded control software as an active sender. Thus every time the Smart Products reaches a phase to act and to communicate, it is able to send data which another Smart Product is able to receive. There are three possibilities of communication between Smart Products: synchronous - the system reacts on the other system immediately, asynchronous - the system takes time to react on the other system and quasi-synchronous. Cyber-Physical systems aim to communicate synchronously, but in reality communication is mostly quasi-synchronous using online connections based on internet protocols. A physical and a logical connection as well as standardized communication protocols for a fast communication of Smart Products are requested.

Smart Products' communication is differentiated into different grades of mobility: wired, wireless or a mixed form of both. Wired communication uses physical wired connections like the modular connector RJ-45 or USB cables. They are physically connected; sometimes using multiple, additional hops like repeater, bridges and hubs. Using wireless communication instead Smart Products are not physical connected. They are linked using wireless telecommunication technologies like radio frequency communication, microwave communication or infrared communication. Due to alterable infrastructure for communication, a mixed form of wired and wireless communication exists. It uses both types, but only one form exclusively at one time.

Connecting and arranging multiple Smart Product results in different communication networks. Within these networks various protocols for communication are used. The analysis of commonly used internet protocols [21] like FTP, OSCAR or XMPP, shows that the selection of the protocol is not restricted. Theoretically every open or propriety format can be chosen allowing quasi-synchronous or synchronous communication.

For engineering Smart Products the understanding of joint dynamics of software, networks and physical processes is required. A classification of Smart Products' communication within an appropriate metric for the different combinations of Smart Products' communication is discussed below.

2.2 Methods for the Development of Smart Products

For describing, designing and dimensioning Smart Products, a framework for processing the communication addressing these communication combinations is needed. Although design methodology for mechatronic products is far advanced a framework for developing Smart Products does not exist. Approaches like the V-Model [12] do not provide systematic approaches to develop Smart Products' communication. The framework presented in this paper introduces a systematic approach based on the W-Model to treat triggered events and received messages. Capabilities to fully integrate this framework are given in order to support development tasks in the specific development phase.

Metric of Smart Products' Communication. Concerning the given classification of Smart Products' interaction states four combinations of different communication configurations can occur: passive-passive, active-passive/passive-active and active-active. During the functional analysis of Smart Products within the product development process a combination of Smart Products can be ranked using this metric (see Fig. 1):

- Passive-passive: Case 1 represents two Smart Products, sender and receiver. Both can only send their states and do not trigger events.
- Passive-active/active-passive: In case 2 and 3 one of the Smart Products, either sender or receiver, acts active and is sending its states and events. The other Smart Products may send its states and will process the received events with predefined actions.
- Active-active: Case 4 describes the active interaction of two Smart Products. There exists a toggle of sending and receiving states and events. The processing of events may be the execution of predefined operations or the receiver is able to ask actively for states of the Sender. The states and events sending and processing can be executed in parallel.

Interaction States of Smart Products. Smart Products' interaction is based on the exchange of messages. Triggering events and processing information transform the internal states and impact the relation between Smart Products. In order to understand and describe the Smart Products' communication, this approach defines seven different Smart Products´ interaction states (see Fig. 2):

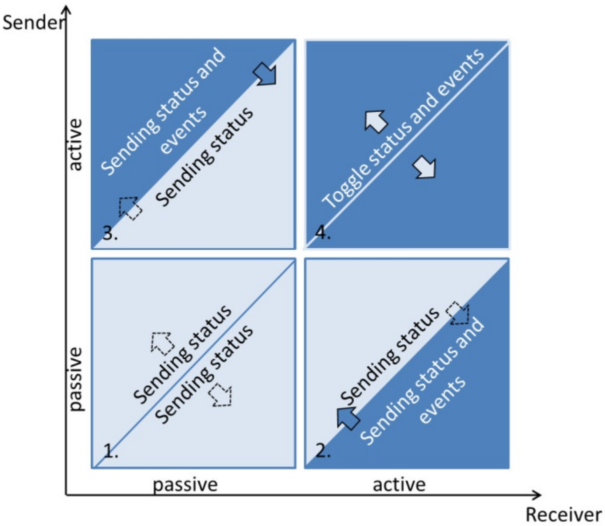

Fig. 1. Metric for Classification of Communication of Smart Products

- Pending: Initially Smart Products are in pending states. No knowledge and hence, no connection between any Smart Products exists.
- Paired: A pairing operation is performed by coupling two devices together. No exchange of information or events has been executed yet.
- Exchanging: During the process of sending or receiving Smart Products start exchanging messages.

In case of processing events:

- Processing: After exchanging messages, information is processed within the Smart Product. Any form of internal processing or external interaction like new events or message exchanges can be initiated.
- (Paired): The sender of messages falls back to the paired states described above.

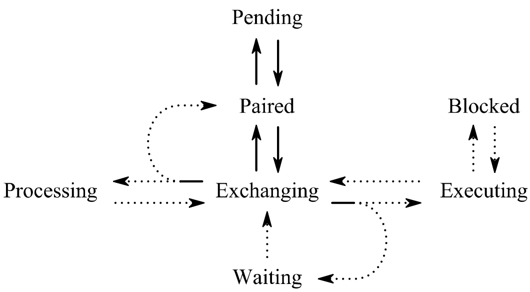

Fig. 2. Interaction States of Smart Products

In case of triggering events:

- Waiting: The events' sender stays on hold waiting for a response. Control mechanisms in case of failure e. g. after a timeout can be executed.
- Executing: The receiving Smart Product proceeds to the executing state. Processing received messages and received requests, the Smart Product initiates an operation or a response message. The Smart Product has to respond based on the received request.
- Blocking: If needed, the Smart Products' interaction state is transformed to "blocked".

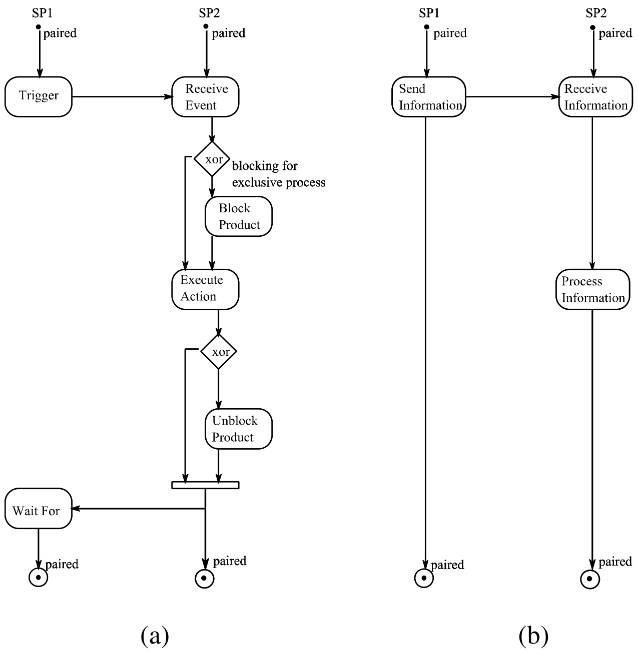

Fig. 3. Scheme for processing simple logics: (a) processing events and (b) messages

Exchanging messages and triggering events during Smart Products' communication involves not only the transformation of the internal state, but also the transformation of the above presented interaction states. A Smart Product passes through its states. Therefore, transformation logics to transform between appropriate states have to be provided. In Fig. 3 two examples for processing information and triggering an event are given. Complex interactions can be described by combining these logic examples. Further extension of the logic examples is possible.

Integration into the Functional Design Phase. To support the development process of Smart Products the approach described is used as a first step in the functional design phase.

Based on predefined requirements in earlier phases of product development the communication is categorized using the introduced classification and then is further detailed by the application of the given metric. Sending of information, triggering of events and controlling of executed procedures is then modeled resulting in different interaction states. Using these product states' and the traditional understanding, the required sensors for each Smart Product can be chosen. The approach therefore fits into the W-Model [13].

3 A Smart Engineering Scenario with LEGO Mindstorms

Based on the presented framework a representative scenario built with LEGO Mindstorms has been developed. The scenario consists of two Smart Products: a robot and a bottle. The bottle will be opened by the robot. The bottle is equipped with a display showing the states of the bottle top. All scenarios illustrated in the metric description shown in Fig. 1 are covered by this application.

To clarify the application of the given framework an active/passive combination of Smart Products is described further. The bottle actively searches for a robot to open its bottle top. It can trigger two events: gathering information about the robot's current states e.g. if it is in blocked state and triggering the opening process. The robot is only able to react on two simple predefined tasks: send a message enveloping its information and open a bottle at a specific requested location. It is able to navigate independently, but self-controlled by detecting objects and calculating an appropriate path to a destination.

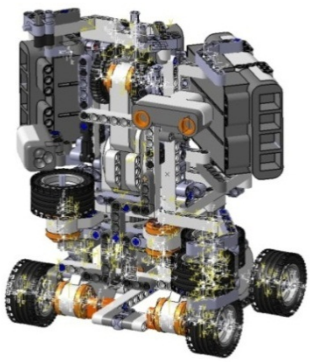

Fig. 4. LEGO Mindstorms robots as Smart Product

Performing the functional design description this state based approach helps to clarify the collaboration between the two Smart Products, also classifying it as an active-passive combination. Thus, based on the given metric this Smart Engineering task is a combination of a Smart Product which is able to processes complex events and a Smart Product which is only able to process elementary events. Elementary events correspond directly to the framework approach introduced in chapter 2.2.

4 Conclusion

The development of mechatronic products is far advanced, but does not yet provide methods to engineer and develop Smart Products. The Smart Engineering approach introduced in this paper introduces a method to describe, to design and to dimension Smart Products based on a specification of products' states embedded in the functional phase of the product development process.

Based on a classification of Smart Products' communication new products are developed using this metric. By the application of this metric development of Smart Products and their communication can be identified in order to describe and to design the exchange of messages between Smart Products, including information and triggering events.

The described approach of this paper is currently further evaluated. The improvement of the used methods and the technical support tools are subject of this evaluation.

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New Perspectives in the Quest for Unification of 'Lean' with Traditional Engineering Design Methodology

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Abstract. In an increasingly competitive business world, engineering companies need to improve their capability in developing products that offer high value to customers. In this connection, the *Toyota Product Development System*—commonly referred to as 'Lean Product Development'—is a benchmark for effective, new practices across industries. *Lean* contains many of the same elements as *traditional* engineering design methodologies, developed in the 1970-80s, which describe systematic design and engineering processes. However, the former differs through its philosophical nature—rather than being a methodology or tool—as well as its focus on increasing effectiveness through waste reduction.

In this paper, a literature review of the traditional, systematic product engineering/development methodologies and the more recent lean concept is conducted. Both approaches are analyzed, providing a discussion as to what extent traditional methodologies include elements of lean-thinking and to what extent the associated product engineering processes are lean.

Keywords: product development, lean, design methods research.

1 Introduction

Nowadays, engineering companies operate more and more globally in increasingly competitive markets. Outsourcing of production and algorithmic engineering tasks to so-called low-cost countries is an obvious countermeasure to increase company benefits in terms of cost reduction; however, this does not guarantee long-term competitiveness. The only permanent solution is to improve a firm's capability in inventing, developing, and producing innovative, new products that provide high value to customers. In addition, companies need to launch new products earlier than their competitors—before new technology emerges or the market changes. These challenges raise the need for more effective engineering design methodologies for developing and bringing valid, new products to the market place. To establish a basis for effective and efficient new-product development (NPD) strategies, it is necessary to understand their origin and evolution by considering the history and the context in which these methodologies have been developed.

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Traditional methodologies, developed in 1970-80s, describe processes to systematically design and engineer a product [5-7], [14], [19-20], [23]. More recently, in the context of effectiveness in manufacturing and product development, Toyota's way of solving engineering problems is often referred to as the benchmark. Multiple researchers have studied Toyota's Product Development System (TPDS), commonly denoted Lean Product Development (LPD), concluding that Toyota's practices are superior to any other firm with regard to productivity in NPD [8-10], [21]. The lean concept—whose primary goals are to reduce waste, time-to-market, and cost while improving quality—has more recently been applied to the process of solving design and engineering problems in product development (PD). It seems that many of the elements found in traditional PD are applied under a new terminology in LPD, but with a somewhat different focus. While traditional PD provides specific, detailed step-by-step guidance to designers and engineers, LPD represents more a mind-set with basis in a set of principles, focusing on the entire system and its practices.

In the following, a literature review of the traditional, systematic PD methodologies and the more recent LPD concept is conducted. Both approaches will be systematically analyzed at detail level, providing a discussion as to what extent traditional methodologies include lean-thinking and to what extent the processes are lean. In this context, the main research questions are: What is new about lean? What does the lean notion bring to NPD—and what is the origin of the methods employed? What is lean about traditional product engineering—and what are the differences, the commonalities and the complementary attributes of traditional and lean methodologies?

2 Traditional Product Development Methodology

Renowned researchers as Rodenacker [19], Pahl and Beitz [14], Hubka [7], Roth [20], and several others, describe methodologies for PD and engineering, developed in the 1970s and 80s, guiding designers and engineers to systematically find solutions to technical problems. Their aim is to provide a methodology to design, engineer and develop desirable solutions that satisfy a set of requirements. However, these methodologies are not the first approaches for systematic engineering and PD. The origin of systematic engineering methods is back in the 1940s [15], [17], and are developed from system theory, machine elements, and product specific approaches. In the development to follow, the PD research community was concerned with increasing the number of engineering principles within the framework of an increasingly structured engineering process, which was divided into different phases (e.g. VDI 2221 [25]). The classical approaches mentioned in the beginning of this section are benchmarks in this context, representing the so-called traditional PD methodology. These methodologies have been adapted to trends and state-of-the-art during the last few decades, for example axiomatic designs [16], [22], product structuring in modules, platforms, and architectures [15], [25], or stronger focus on customization and the whole product life-cycle, while the PD-phases remained essentially the same.

All the above-mentioned authors more or less describe a holistic approach to engineering design; each one providing an individual contribution. In addition, everyone uses the same main structure to develop a product, which can be summarized through the following phases: At first, the main task has to be defined, including in-depth understanding of the problem, which is defined in a requirement list. Then the problem is abstracted into 'black-boxes' [7] or functions, which are decomposed to more abstract sub-functions. In the next phase, different principal solutions are combined to establish (several) concepts. After an evaluation the most promising concepts are chosen for further work. Then, the preliminary layout or the basic product structure is defined, followed by elaboration of the detailed solution, which includes all design features, bill of materials, production methods, etc. All the examined approaches introduced a well-defined engineering methodology, guiding product engineers through the process step by step. The primary emphasis is on tasks required to find solutions to technical problems at design and engineering levels; ones that are driven by engineering excellence rather than process efficiency and cost.

3 Lean Product Development

The TPDS is the main source to what many, right or wrong, consider synonymous with so-called LPD. The concept emerged in the mid-1990s and has its origin in lean manufacturing, starting with the Lean Automotive Factory and evolving into the Lean Factory with emphasis on cost reduction, quality improvement, and delivery [8-10], [12], [24], using a system perspective. Based on an excessive study of TPDS, Morgan and Liker [13] introduced 13 lean principles within the dimensions of process, technology and people. The process-principles are the most interesting ones in terms of the contents of this paper, since the two other dimensions touch more on factors in execution environments outside product engineering. The primary objectives of LPD are to minimize waste, improve quality, reduce time-to-market and cost, all driven by the desire to create value to the customer. Here value may be characterized as any activity that transforms a new product design in a way that the customer is both aware of it and willing to pay for [10]. While waste is easy to detect in manufacturing (visible, physical objects), separating value from waste is more difficult in PD since the work-product is information and there are no physical objects to which value can be assigned. In general, waste can be divided into two categories. Type 1 waste includes activities that do not create value that the customer is aware of, but is still necessary to enable value generation (e.g. administration, coordination, testing, validation, checks, etc.). Type 2 waste is pure waste that does not create any value (e.g. defects, waiting, underutilization of people, etc.).

An important part of the lean philosophy is learning and continuous improvement [13]. Based on the Deming-Cycle [11] improvements and iterations are done continuously in small steps, aiming to reach the ultimate goal of a perfect solution by following a learning-spiral with each cycle closer to the target than the previous one. Although these iterations could be considered waste (type 1) at micro-process level, they are necessary to maximize the value of the overall outcome seen in a system perspective. In addition, by capturing knowledge for later reuse the learning cycle is a source of organizational learning, providing strategic value for the company. In the lean literature, the learning cycle is called PDCA-cycle (Plan, Do, Check, Act) [21] or LAMDA-cycle (Look, Ask, Model, Discuss, Act) [22]. In the first step (Look) the problem is observed and data are collected. Then, it has to be checked what is known about the problem and why this problem exists. Following, a model (prototype, sketch, etc.) to support articulate thinking is established. As the fourth step (Discuss), the problem and possible solutions are discussed with experts, and finally the solution is implemented (Act). In the quest for perfection, the cycle does not stop here but restarts from the first step again; this time at a higher level of knowledge. In the LPD philosophy, knowledge is effectively captured and communicated using 'knowledge-briefs' [8], or so-called A3 reports [21] named by the paper size format used, aiming to visualize problem, goal, process, and solution, and risk elements in a standardized form, depending on the application and problem formulation.

One methodology, often referred in the context of LPD is the so-called set-based concurrent engineering (SBCE) [10], [12]. In contrast to a single (point-based) approach, multiple alternatives are explored in parallel and systematically narrowed down through analysis and testing. Within the set of concepts, one is a proven no-risk alternative concept that can be selected as a fall-back in case the others do not succeed. The weaker concepts are successively 'killed' on the way, following a 'survival-of-the- fittest' strategy. Lastly, only the best and most robust solution that fulfills all requirements remains, hence increasing the opportunity for innovation while reducing risk and development time. SBCE is a method aimed at frontloading resources to reduce late and expensive design iterations.

In summary, LPD it is not just a methodology for engineers, it is a way of working, organizing, and making the PD processes more effective, considering both engineering and product management (PM) problems at engineering and management levels.

4 Comparison of Traditional Product Development and Lean Product Development

It appears that traditional PD and LPD cannot be directly compared to each other, since their overall goals are different. Traditional PD describes a systematic approach of well-defined steps, explaining engineers what to do to create a product that solves a given (technical) problem. LPD, on the other hand, introduces a way to make engineering processes more effective to improve the outcome for a company with value being the driver. It describes how processes have to be done to make a company more competitive by pulling value from customers and up the value chain. Lean is more a philosophy and a mind-set, rather than a detailed methodology to solve engineering problems [27]. Hence, traditional PD explains which steps have to be conducted and what has to be done in these steps, whereas LPD describes the working philosophy around the PD process. However, LPD and traditional PD are not contradictory in any respect. It is possible to apply the lean principles to (all) known engineering methods defined in traditional PD. Lean complements traditional methods by including managerial factors such as effectiveness (e.g. short time-to-market) and waste reduction (e.g. people, money, rework). Table 1 summarizes some key characteristics of both.

Table 1. Characteristics of Traditional Product Development and Lean Product Development

Goals of Traditional Product Development	Goals of Lean Product Development
Gives specific 'work instructions' to mainly engineers at detail level	Gives visionary and directional strategies for the entire company at system level with PD being the core component
Methodology that provides engineers with tools for solving a wide range of technical problems, and developing and designing products	A company-wide PD system aimed at maximizing value to the customer or user, within the constraints of value to other stakeholders [1]
Focusing on developing the best technical solution (high quality) with basis in engineering excellence	Focusing on using an effective process to develop an overall optimal (customer) solution from a system perspective, including operational and strategic management
Use of knowledge and ideas to create solutions for technical problems	Effective capturing and reuse of knowledge and ideas for increased learning, and to develop solutions with highest possible value in the eyes of the customer
Can solve unknown problems and improve existing products; i.e., offering methodologies for both	Strong basis in known processes with predictable outcome (continuous improvement), minimizing technical risk within PD, i.e. after program definition
Follows parallel or sequential processes, aiming to solve the task as well as possible	Follows parallel processes, aiming to solve the task fast with effective use of resources

In the following, traditional PD will be examined with regard to lean elements in order to answer the following question: In which way are traditional PD approaches *lean*? Six different approaches in the category of traditional PD methodologies and one approach of integrated PD—ones that are commonly referred as benchmarks in traditional PD—are analyzed in the context of lean. The findings are summarized in Table 2, which relates a set of lean principles to the reviewed approaches of traditional PD. The lean 'principles' chosen here represent a broad selection of lean components, which are based on the ones introduced by Morgan and Liker [13] and adapted to the scope of this paper. Notice that if a lean component is indicated with an 'x' it is a part of the traditional PD approach, and vice-versa.

Rodenacker's [19] approach is one of the early ones in systematic engineering design, with the basic approach still being applied in methodologies today. Rodenacker aims to find solutions for the cause-effect relations stepwise through logical, physical, and structural working principles. He uses a learning cycle similar to PDCA with the steps: information retrieval, information processing, information output, and checking. Capture, reuse and extension of knowledge all are part of Rodenacker's approach, which are important for continuous improvement.

Tjalve's [23] contribution to the design methodology is mainly form variation. Product solutions and alternatives are developed by systematically varying size, number, structure and shape of the design elements. Tjalve uses a learning cycle, called 'product synthesis', similar to lean. He proposes that the criteria vary from phase to phase and have an increasing number of details, based on details from the former step. This reflects the lean principles continuous learning and improvement.

Pahl and Beitz [14] provide a linear, holistic, systematic engineering design process to help design engineers find solutions for products by the use of different tools. They suggest that a PD methodology should save time, reduce work load, speed-up understanding and help maintain active interest. Further, they want the different functions concerned with development of a product to collaborate early. Problems should be detected early and clearly defined in the requirement list together with customer needs. Pahl and Beitz refer to a learning cycle, similar to the LAMDA cycle: confrontation, information, definition, creation, evaluation, decision, solution. They interpret the design process as a dynamic control process that continues until the information (content) has reached a level for optimum solution. Here it should be noted that many lean approaches follow the same strategy.

Roth [20] introduces design catalogs for engineers. 'Effects', 'effect owners', materials, etc. are systematically structured in catalogs, which make knowledge capture and reuse simple, providing the design engineers a set of standard solutions and recommendations. Roth states that it is important to define the correct problem statement early and to attack problems at the root cause. He does not explicitly use expressions such *customer* or *customer value*, which are important drivers within LPD. However, customer (value) may still be considered as part of his approach since customer satisfaction is mandatory for the success of a product. Roth applies engineering catalogs, which is essentially similar to the knowledge-brief approach [8], [21] within lean. Experiences, standards, and former product solutions can be documented in a visual engineering-friendly way by both approaches. The catalogs, which give fast and clear overview of alternatives, represent a knowledge-based approach to product development. Catalogs can be adapted to the design process of a certain company, and can also be extended. An additional core component of lean is the use of standardization and checklists. For instance, standard tables (and check lists) are used for the gathering of requirements, and these can be adjusted and extended to meet new challenges. In LPD a similar approach is employed by alternative concepts such as *house of quality* and *quality function deployment* (QFD).

Ehrlenspiel [5] discusses the influence of engineering design on product costs, including life-cycle costs. He proposes a number of opportunities to reduce product cost by correct selection of design features, production methods, materials, and good collaboration between different departments inside a company. Cost reduction opportunities lie in standardization of products, which is lean, by for instance using modular product concepts with standard parts or assemblies and customer-specific adaption of parts and assemblies. Ehrlenspiel uses *value analysis* to identify unnecessary costs, aiming to determine which product functions are absolutely necessary to accommodate the task that has to be accommodated to satisfy the customer, which can be associated with reduction of waste, meaning *lean design*. This methodology is also consistent with *value engineering*, which was developed during World War II [27]. Further, Ehrlenspiel encourages close communication between teams and short lines of communication, which supports the pull concept in lean. However, his approach is a more specific approach, guiding engineers to use cost reduction methods in detail, whereas LPD to a more extent approaches system problems.

Hubka et. al. [7] introduce a theory for technical systems, which needs to have transformations (functions), organs (e.g. functional interfaces) and parts (components), where the organs represent the link between two components or one component and the user. Hubka proposes a kind of SBCE; several concepts, which are determined after each design phase, are developed in parallel up to a certain detail level and evaluated. Concepts that are strong enough are carried forward. The evaluation at the end of each phase is based on the status, the experience and learning of previous work, and the customer specifications. This resembles the lean principles of continuous learning, reuse of knowledge, and focus on customer value.

Hein et al. [6] introduce one approach that considers PD in a broader perspective, so-called integrated product development (IPD). This is a more holistic approach that includes engineering design, production, marketing, and organization. IPD seeks to integrate methodologies used in different departments of a company toward common goals, procedures, and attitudes. The customer is of key importance, since s/he ultimately decides if the product becomes a success or not. Hein points out that the market is getting more competitive, which requires shorter development time, less production costs, and fast and continuous implementation of new technology for active adaption and renewal of today's products. Focus is not just on the product itself, but the entire execution environment, which is necessary to make the product successful in the market place. Hence, IPD makes a step forward from pure engineering design methodology in the direction of LPD and product management (PM).

Table 2. Lean Elements in Traditional Product Development Methodology (Legend: - not mentioned; (x) implicitly mentioned; x mentioned)

Lean Principle	**Ro-den-acker**	**Tjalve**	**Pahl, Beitz**	**Roth**	**Ehr-len-spiel**	**Hubka**	**Hein**
Continuous control of requirements	-	x	x	x	(x)	x	x
Front load of the PD process	-	-	x	x	x	-	x
Understanding the customer	-	(x)	x	-	x	x	x
Integrate customer and supplier in complete development	-	-	-	-	-	-	-
Parallel processes	-	x	-	-	(x)	x	x
Increase standardization, reduce variation	-	x	x	x	x	x	(x)
Continuous improvement of product	x	(x)	x	x	x	x	x
Continuous improvement of process	(x)	-	x	-	-	-	x
Capturing and reuse of knowledge and experience	x	(x)	x	x	(x)	(x)	x
Capturing past knowledge in checklists	(x)	-	-	x	x	(x)	-
Short and precise knowledge capture	-	-	-	x	-	-	(x)
Early include all different departments	-	-	(x)	(x)	x	-	x
Learning Cycle	x	x	x	(x)	x	x	x
Set-based concurrent engineering	-	-	-	(x)	-	x	-
Solving the roots of problems	(x)	-	x	x	x	-	x

This literature review shows that many elements of the LPD concept have been developed under different headings many years before the term lean was coined in the Western PD vocabulary. Learning cycles, knowledge capture and reuse, continuous improvements, and customer value all have been elements of the product engineering literature for several decades. What is new, associated with lean, however, is its strong focus on effectiveness and waste elimination. Hence, traditional PD methodology delivers engineering tools for development of high-quality products, whereas LPD in addition targets effectiveness.

5 Product Development, Product Management and Lean Product Development in a Historical Perspective

In the section above it has been shown that many elements of LPD have their origin from the traditional product design and engineering research community. LPD does reuse traditional approaches to a great extent, applying a different terminology in many cases. Moreover, basic engineering methodology is not part of the lean literature, which rather represents a holistic approach to improve the PD productivity. Some of this may be explained by the historical development of PD or LPD. Figure 1 shows a principal interpretation of historical progress of PD, PM and LPD literature, illustrating the development of the three fields and an increased overlap towards right.

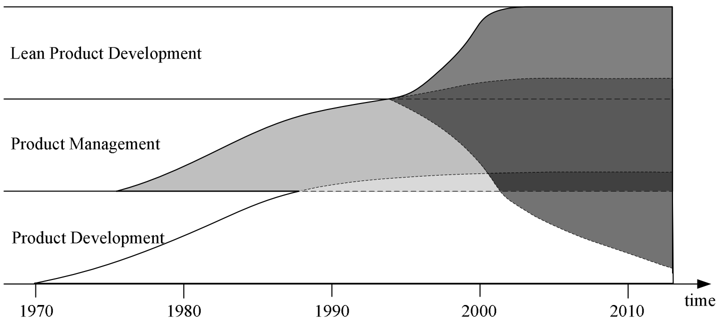

Fig. 1. Development of traditional PD, PM and LPD literature

First, traditional PD started out as a research field in the 1970s, describing methodologies to systematically solve engineering problems and develop advanced products.

Later, throughout the 1980s and 1990s, the amount of PM research increased gradually. In PM, approaches to improve financial performance, innovation, differentiation and new-products' success in the market are introduced as well a holistic business view of marked, product and production in integrated PD [6]. Cooper [2-3], for instance, introduced strategies for successfully driving products to market, like product and technology strategies, portfolio management, and stage gate processes. PM and PD complement each other, since both are important to successfully create and deliver the right product but from different perspectives. This may be illustrated by the two approaches increasingly overlapping each other.

In the late 1990s, yet another approach, namely LPD, emerged from (US automotive) companies' need of being competitive in a global market. Supplementary to the other two approaches, lean puts emphasis on customer, value, waste reduction, and increased effectiveness primarily with basis in the engineering perspective. Lean methods can be applied to—and are becoming increasingly part of—both PM and PD, as symbolized by the overlapping shaded areas. For instance, Cooper [4] realized several of the problems associated with the PM perspective that forms the basis for the classical stage-gate process, and updated his view towards a more process-driven organization, introducing 5-6 concepts directly from LPD.

Today's strong focus on lean methods can be explained through increasing market pressure, forcing companies to reduce time-to-marked and cost while improving innovation. This means that the competitive frontiers drift from, say, engineering excellence and workmanship towards efficiency of process, multi-disciplinary teams, collaboration, supplier integration, networks, knowledge management, organizational learning etc. In this respect, LPD seems to be an important strategy for bridging the gap between traditional engineering-oriented PD and more business-oriented PM.

6 Conclusions

This review and discussion helps to better understand the differences of PD approaches and their historical development. The results show that many of the core elements in LPD have their roots in traditional PD, but under different names and headings. It appears that several classical methods have been reborn under a new common terminology called *lean*. Lean has its origin—or should we say rebirth—in Japan, and was brought into the context of product development by US researchers [8-10], [12-13], [24], [26]; in many cases—purposely or accidentally—not fully considering the methods' original references in the design and engineering community. The good thing about this is that the new 'wrapping' helps bring the methods out to a greater community outside the academic world, including practical engineers, managers and CEOs, boosted by popularization of an approach to an outermost important challenge for many of today's companies: NPD performance.

Nevertheless there are new elements in LPD. LPD adds effectiveness, waste reduction and competiveness to the traditional approaches and makes them evolve and adapt them to today's competitive challenges. It is also demonstrated that the lean concept, when applied to PD, to some extent fills the gap between traditional product engineering (in the engineering community) focusing on micro-processes, and product innovation management (in business-economics community) focusing on macro-processes. To be successful in the marketplace, a combination of both traditional, PM, and LPD appears to be a good approach, applying both the engineering guidance of traditional PD and making processes effective by LPD.

Some very interesting questions in this context are: How did Toyota develop a lean culture and from whom did they adopt their methodology; and how did US and European companies develop the revolutionary products and technologies that have served as a fundamental pillar of productivity growth in the 20th century, decades before the notions 'lean' and 'lean product development' were coined?

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Procedural Model for the Virtual Commissioning on the Basis of Model-Based Design

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Abstract. There are many methods for the development of new products. One of them is model-based design. This article is dedicated to the usage of this design method for the reduction of the time required for the commissioning of manufacturing plants. For this purpose, the method of virtual commissioning is combined with the model-based design which makes it possible to create a procedural model. The presented approach assists the developer in order to save time during the actual commissioning and thus reduce costs. The presented approach is validated on an application example.

Keywords: virtual commissioning, production system development, model-based design, systems engineering.

1 Introduction

Growing competitive pressure requires the commissioning of manufacturing plants to be done in shorter time. However, this is restrictedby the increasing complexity of such plants. Today the achievement of modern mechanical products (like these plants) is affected by the close interaction of mechanics, electrics/electronics, control engineering and software engineering. This circumstance is expressed by the term “mechatronics”. Advanced mechatronic systems lead to a considerably increased system complexity due to their functionality and internal interaction. In addition, the involvement of different domains requires an effective and continuous cooperation and communication between all developers during the whole development process. The conceivable development of information technology opens up fascinating perspectives for the design of future technical systems, which go far beyond current standards.

To analyze the system behavior as early as possible models are increasingly used. There are many possibilities for the design of mechatronic systems such as the "Design Methodology for Mechatronic Systems" [1] or the "Design of Intelligent Mechatronics (ENTIME)" [2]. The foundation for these development methods is a model-based approach. During the model-based design both the functions and the behavior of a mechatronic system are considered. Models that are created in this manner can be used for several analysis purposes [1].

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The foundations which are formed in the design phases turn into real plants which have to be commissioned. During the commissioning of a plant often different topics merge: the clarification of the functionality of components and plants, the continuation of software development, the functional test of the software, the parameterization and optimization of the automation software and the acceptance test. Those work contents are temporally rather undefined. They are cost extensive because they take place during the installation process. Hence they are fraught with risks and can delay the planned commissioning drastically [3].

An approach to reduce the time until start of production is virtual commissioning, which is a commissioning of the real control system and the original software in combination with a virtual plant. For the control system the behavior of the virtual plant is adequate for starting up and running both. The simulation model for the virtual commissioning consists of the behavior model, reproducing the logical behavior of the machine and the kinematics model visualizing the movement behavior of the machine in all relevant degrees of freedom. Research has already shown that thereby the time for the commissioning decreases and the quality of the control program of the production system increases [4-5]. However, the effort for the modeling is very high and often compensates the time advantage which leads to the fact that the cumulated time required until start of production of the plant is not reduced [6].

The basic proceeding of the virtual commissioning in the presented approach is similar to the procedure suggested in [4]. In [4] new models are created for each commissioning process. Our approach is to adapt and simultaneously use the models created during the model-based design also for the virtual commissioning. In this way time is saved and hence the overall costs are reduced.

By this integrative approach, synergy effects can be utilized. Both the functions and the behavior of a production system are modeled. Such models can subsequently be used for analyses, which make it possible to reduce the costs and the development time of new production systems. A further advantage results from the use of solution patterns[1]. They allow the use of existing solutions for specific system elements or system components, in particular the simulation models.

This contribution focusses the procedural model, in which the virtual commissioning is integrated in the model-based design process. For this purpose, we point out in section 2 the model-based design adapted for the planning of engineering plants. We consider also the choice of the modeling depth for the behavior models in the model-based design. In section 3 we present the procedural model itself. The procedural model is validated on an example in section 4. Finally the major points are summarized in section 5.

2 Model-Based Production System Design

The following section treats the adaption of the model-based production system design described in [7] for the purposes of virtual commissioning. First a general overview is given followed by a detailed explanation of the main design phases.

[1] A solution pattern is an abstract representation of a class of solution elements and describes [...] its structure and behavior in a generalized form (see [7]).

The life cycle of manufacturing plants comprises the phases conceptual design, detail design, manufacturing and assembly, operational phase and finally redistribution. The procedural model of virtual commissioning on the basis of model-based design presented in this paper focuses on the first three phases (Fig. 1). It is modeled in the style of the VDI 2206 guideline [1]. The phases conceptual design as well as detail design are each divided into the tasks of the basic cycle of system design determination of objectives, synthesis and analysis [8].

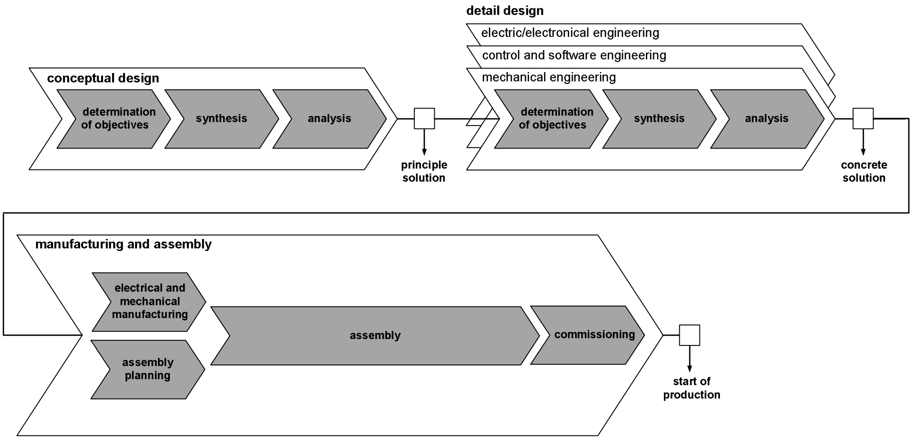

Fig. 1. Production of Engineering Plants

The process images are displayed in an abstract way. Iterations may occur at any time. As seen in Fig. 1 the conceptual design phase ends with the principle solution. This is the starting point for the detail design in which the concrete solution is developed in the particular specialized disciplines (e. g. mechanical engineering or control engineering). The manufacturing and assembly starts with the concrete solution and ends with the start of production. In the following are describe the three phases in detail.

2.1 Conceptual Design

The conceptual design phase starts with the determination of objectives. Fig. 2 illustrates the certain steps of this phase. First of all an analysis of tasks and environmental boundary conditions is conducted. As soon as the application scenarios have been defined and the description of the requirements is established the function hierarchy can be drawn up, which is the last step of the completion of the determination of objectives of the conceptual design.

The phases run through during the process of synthesis are presented in Fig. 3. It starts with the building of active structures and the system modularization. The modularization should be carried out under the aspect of a modular product concept being focused on the recovery of components. It is structured under a design-oriented and functional view. Subsequently, the solution patterns for the single module are

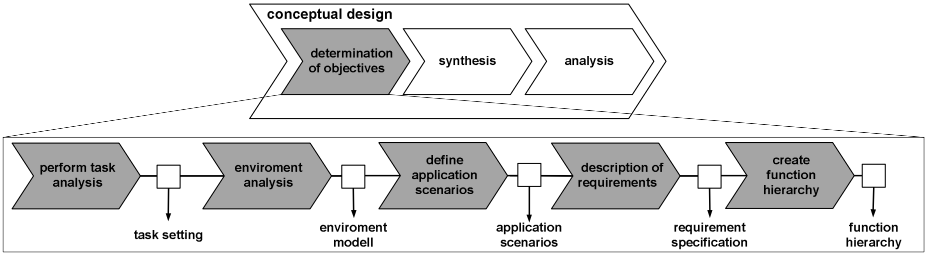

Fig. 2. Process steps of the determination of objectives as part of the conceptual design [7]

examined and selected. Solution patterns in plant construction are such modules being previously built or being purchased by third parties. It is especially identified whether a solution pattern already exists or whether a new development is required. In the following the behavioral model and the first approximate shaping are being established. Afterwards, the selected modules are detailed. This phase is necessary, if a superior machine control is to be used. It should be specified, for example, to which module the sensors and actuators have to be assigned, or whether they are independent modules. Finally, the modules have to be integrated into the entire system. The modularized entire system represents the completion of the synthesis phase.

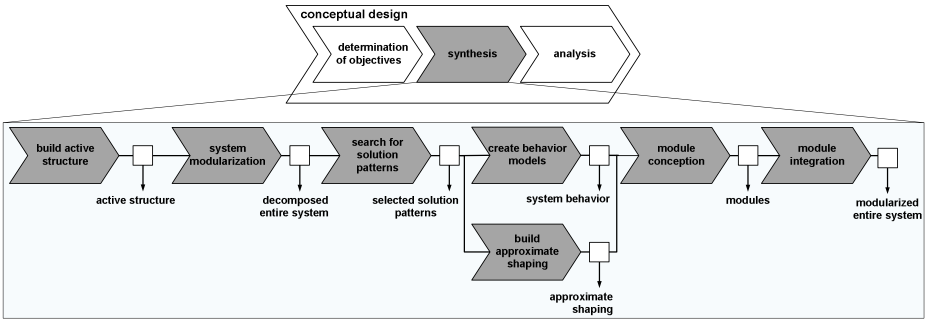

Fig. 3. Process steps of the synthesis as part of the conceptual design (see [7])

The last step of the conceptual design is the analysis (Fig. 4). At first the object of analyzing is defined. This is done by comparison with the task settings from the determination of objectives phase. The established system design has to fulfill the requirements. Then, the analysis is performed. Finally, analysis results are evaluated, which leads to a principle solution. This depicts the completion of the analysis phase and the whole conceptual design simultaneously. In the principle solution it is stated of which line components the plant consists and which manufacturing technologies are applied.

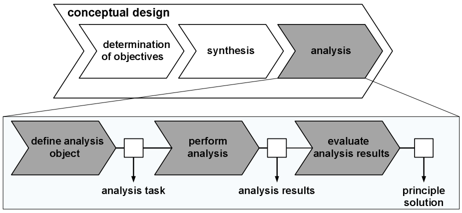

Fig. 4. Process steps of the analysis as part of the conceptual design [7]

2.2 Detail Design

The detail design phase starts with the principle solution that has been developed in the conceptual design. The detail design also comprises three steps: determination of objectives, synthesis and analysis. These are carried out in the different domains (Fig. 5). As they are not relevant for the virtual commissioning, they are only shortly described, see [7] for more detailed information. Important for the detail design is the selection of solution elements[2] for the beforehand used solution patterns in the first step. In the course of the process the results are being matched. For this purpose behavioral models are applied to make sure that the individual modules are compatible. The results of the individual domains are integrated into an entire solution (Fig. 5). At the end of this phase a concrete solution is available.

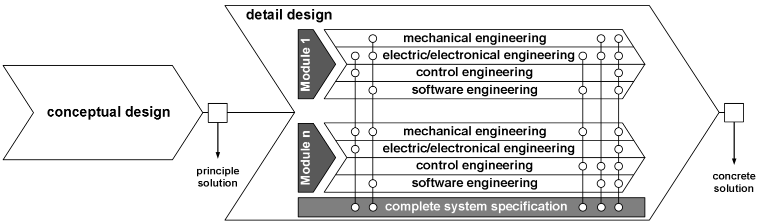

Fig. 5. Concretization of the principle solution [7]

2.3 Manufacturing and Assembly

The manufacturing and assembly phase consists of four steps (Fig. 6). These are the mechanical and electrical manufacturing as well as the assembly planning, which are performed in parallel. Subsequently, the assembly takes place. First of all the mechanical structure is arranged and then the electric installation is executed. This phase is terminated by the commissioning process. Here the plant is transferred to the expected state. As the case may be, assembly and commissioning process can be repeated, when the plant has to be set up at the manufacturer's site already. At the end of this

[2] Solution elements are implemented and proven solutions - assemblies, modules, software libraries, etc. - to meet a function of the entire system (see [7]).

process the integration into the consisting production street and the acceptance of the plant is conducted. The phase is accomplished with the transition into regular operation, the start of production.

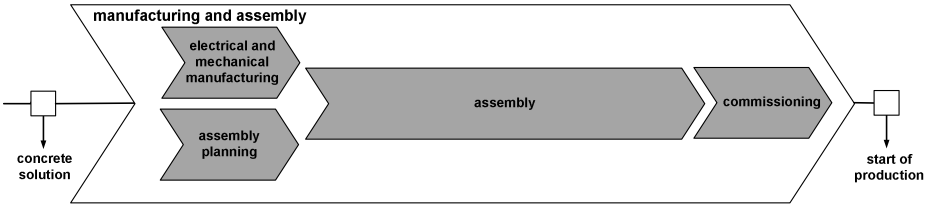

Fig. 6. Process steps of the manufacturing and assembly

2.4 Modeling Depth

For many of the previously described phases behavioral models are needed. The developer of these models has to decide individually what level of detail (modeling depth) he indicates. In general, models should be as detailed as necessary but as abstract as possible. This decision is very subjective and needs a high level of system understanding and experience [9]. For this reason, in [10], a methodology for selecting the modeling depth was defined. This is also of utmost importance for the virtual commissioning. Therefore, it is explained shortly at this place.

Central point of the methodology is the definition of different modeling depths. For the virtual commissioning three levels are necessary. These are the idealized function, the basic feasibility and the system-specific behavior. In the following the three levels are shortly defined (for detailed information and examples see [10]).

Level 1 – idealized function
The models are logically and not physically modeled. It means that these models contain time-discrete state machines. This level does not allow the representation of the dynamic behavior. Only time-discrete values can be reproduced.

Level 2 – basic feasibility
These models also comprise time behavior and can be modeled physically. The models are strongly idealized without consideration of side effects (e.g. friction). At this level, solution patterns are employed for modeling.

Level 3 – system-specific behavior
This level contains models that are physically modeled and side effects are considered in a simple manner (e.g. linear friction). The solution patterns at this level are replaced by solution elements.

3 Procedural Model

The procedural model correlates the previously defined phases with the levels of modeling depth. Basically all system components can be modeled in different levels of modeling depth. Each modeling depth represents the time from which it can be used. For those modules which can be modeled in an abstract level of detail, the modeling process is completed at an earlier stage. It specifies what information must be available to proceed with a more detailed modeling depth. The advantage of the procedural model is the well-planned approach in which the level of detail increases continuously.

In Fig. 7 the process model with the integrated virtual commissioning is presented. The virtual commissioning consists of the phases modeling, realization and analyzing. In the modeling phase, the behavioral models of the individual modules are set up. The virtual commissioning is performed parallel with the model-based design.

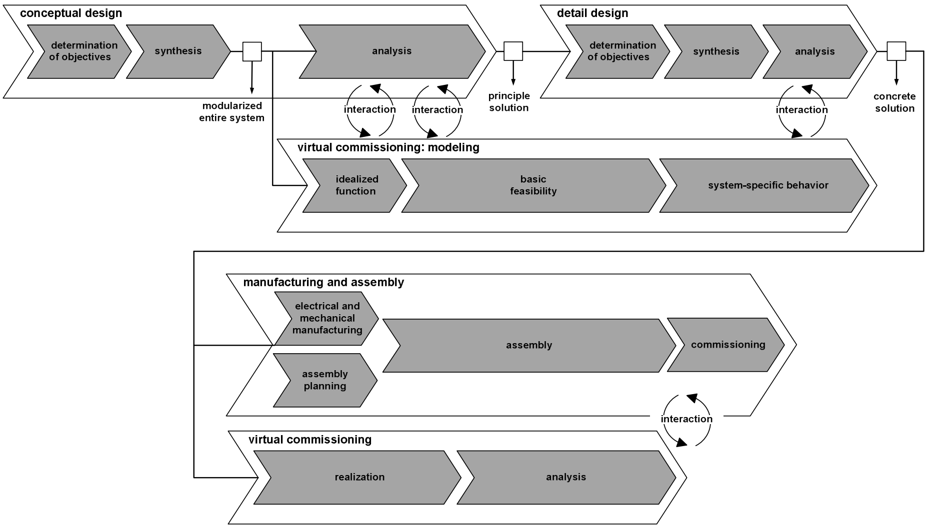

Fig. 7. Procedural model for the virtual commissioning on the basis of model-based design

The modeling at the level of idealized function can already begin in the conceptual design phase in particular if the entire system is modularized. At this time, the phases of module conception and integration of the conceptual design are run through and the entire system is divided into subsystems. Now the modeling depth for each module can be defined considering the certain requirements (see [10]). If the module consists of already existent solution patterns, the existing behavioral models can be used. Otherwise new models must be created. The models that arise in model-based design in the conceptual design phase are adjusted for the virtual commissioning to provide it with information (such as mass, length, etc.). They are applied in the analysis phase of the conceptual design. The analysis results can also be used in the model-based design to expedite the development. For the analysis phase at least modules of the idealized function of each module are required. Afterwards the module integration is evaluated and the principle solution is created. If modules need to be modeled in a more detailed modeling depth, the modeling process can be started after the synthesis of the conceptual design. All the information will lead to the already described principle solution. Parallel to the detail design the models of level 3, the system-specific behavior can be modeled. These are feasible from the time when the solution elements are selected. After selecting a solution element, the decision has been made which element should be used in this case. Now the component dependent information is available which is necessary for the detailed behavior models of the system-specific behavior. Not every system element has to go through all the modeling steps. For some it may be useful to stop after the models which represent the idealized function. For example the storage in a sorting system is not needed very detailed (see [10]). In the detail design inter alia also the software engineering is performed. Once the concrete solution is created the control program for the plant exists. From this time, the controlling can be simulated on the generated models. In the virtual commissioning even the change from a higher level to a lower level can be reasonable to increase the simulation speed. Virtual commissioning allows an early test of the control program. It takes place parallel to the manufacturing and assembly phase. Thus, errors of the control program can be eliminated in advance. In this manner, the time of plant shut down is shortened. Moreover, even an integration of the manufacturing system can be simulated. Besides the verification of software the training of operating personnel is possible. The virtual commissioning is finished with the putting into operation of the plant.

4 Application Example: Dough Production System

The above described procedural model is now applied to a dough production system (Fig. 8) to demonstrate its usage. At first, the structure and function of the system are explained.

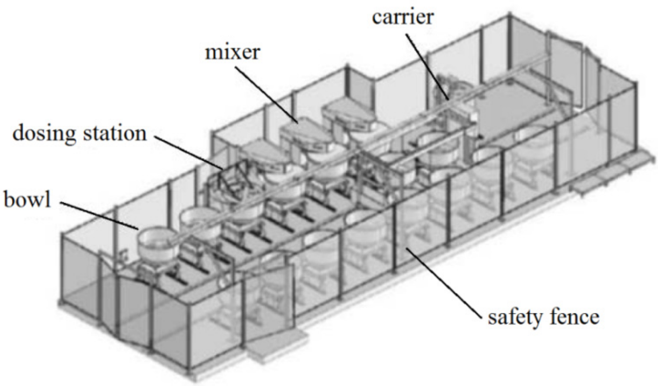

Fig. 8. Dough production system [2]

The dough production system consists of modular processing stations. These are a dosing station, filling the ingredients, a mixer to mix the ingredients and a dump tipper, to tip out the finished dough for further production. Further there are bowls in which the dough is mixed and transported. For the transport of the bowls the so called carrier is used, which carries the bowls from one station to the next. The production process is basically always the same. At first the ingredients are filled into an empty bowl at the dosing station. Then the carrier moves the bowl to the mixer. After the ingredients were mixed the dough has to rest, which is done on a resting. After resting, the dough is finished, and is tipped out for the further production process by means of the dump tipper. The system has two controllers. Firstly, the carrier controller, which controls the movements of the carrier, secondly, the central controller, which supervises and controls the entire system [2].

Below, a short overview of the model-based design of the dough production system is given. Afterwards the interaction with the virtual commissioning is pointed out. In the conceptual design phase as well as in the requirement analysis a functional hierarchy was created. At the highest level, the system had to fulfill the function of making dough. This function was divided into the sub-functions dose ingredients, transport, mix, rest and tip out. In addition, the operator security had to be considered. Then an active structure was built. This was functionally structured and modularized. From the above described production system modules were formed: carrier, bowl, dosing station, mixer and dump tipper as well as control and safety fence. Solution patterns could be found for the individual modules because the modules had already been used as processing stations in the past. These modules were part of the same type of the dough production system, and as the number and arrangement of the stations depend on the requirements of the dough production system and the available space they could be reused. For all modules also behavioral models existed because known processing stations could be used. The analysis phase of the design process had shown that the carrier did not meet the requirements. The carrier did not allow enough bowl changes and this module needed to be newly developed. For the new development the behavioral models of the other processing stations already existed, so in the conceptual design phase the integration into the entire system could be checked. This means that the correct interaction of the various models had already been ensured. In the detail design phase, the individual modules were concretized. In this case some adjustments to the existing structure were made. System integration of the individual models is possible at any time. So after the development of a new carrier the old one could be replaced.

During the detail design the control programs were developed. They could also be made of existing software modules. For the control of the new carrier also new programs were developed.

After the concretization of the entire solution, the virtual commissioning could be performed. Here, both the control of the dough production system and the carrier control were tested and the compatibility was checked. Parallel to this, the plant assembly took place. The virtual commissioning provided an early integration testing and a reduction of the commissioning time. The benefit of behavioral models increased, as they could be used for the design of new components and for the commissioning simultaneously.

5 Summary

In this paper the benefits of the integration of the virtual commissioning into the model-based design have been shown. The individual phases, which are passed through, have been described in detail. From this context, a procedural model has been developed which supports the developer in the virtual commissioning process. The different modeling depths which occur in the virtual commissioning were also briefly discussed. This classification helps the developer to create the models of the plant suitable. Finally, the procedure has been explained on a short industrial example.

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A Template for Design for eXcellence (DfX) Methods

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Abstract. Design for eXcellence (DfX) entails a wide range of goal specific design methods targeting different phases of a product's lifecycle. These methods are often not standardized and sometimes even have contradicting rules among them. As a consequence, design processes experience an increase in organizational entropy. This paper presents a template for DfX methods. The goal is to assist the industry in setting up lean design processes. The results of this research are threefold: (1) standardization of DfX design tasks and information flows, (2) facilitating the implementation of DfX methods and (3) enable benchmarking of DfX methods to purify design processes.

Keywords: Design method, Knowledge management, Design for eXcellence (DfX).

1 Introduction

Design for eXcellence (DfX) entails a wide range of goal specific design methods. The first DfX methods targeted the manufacturability of products and were developed after the 2nd world war with the aim of aiding the emerging concurrent design practices. The three most popular types of methods during this period were Design for Manufacturing (DfM), Design for Assembly (DfA) and Design for Disassembly (DfD) (all three the topic of the CIRP Dn keynote in 1992 [1]). Since then, most of the lifecycle phases of products have been the target of such methods; for instance, Design for Maintainability (DfMa), Design for Sustainability (DfS), Design for Obsolescence (DfO), Design for Supply Chain (DfSC), Design for Logistics (DfL), Design for Network (DfN), Design for Recycling (DfR) and many more. Characteristic to DfX methods is that the target is not the functional related performance of the product itself, but rather the product development aspects aiming to realize more competitive products. DfX methods are often based on designers' expertise. Its implementation depends on the company's strategies, product design philosophy and available resources (i.e. energy availability, raw materials disposition, staff education level, production system characteristics, consumer preferences, etc.). Although DfX methods are popular and widely spread in industry, their structure is highly variant as pointed out by Chiu and Okudan [2]. Furthermore, the efficiency of DfX methods as a benchmark has neither been studied nor addressed, leading to design suggestions with unknown consequences for the product lifecycle.

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Presently, established product development procedures in industry are populated with large numbers of DfX methods. Most of these methods are in fact developed in an industrial setting to support company-specific issues of Product Development Processes (PDP) or as protocols for standardizing design approaches and improving production parameters. As also concluded by Meerkamm et al. [3], such (industrial) methods are not presented in uniform structures and often do not target all steps of the design process. This potentially leads to complex concurrent design processes and increases a company's organizational entropy. The core problem is the lack of standardization of DfX methods in terms of structure and completeness such that tasks and information flows are clearly defined. As an answer to this problem, this paper presents a template for structuring DfX methods. The template is based on well accepted design theories. The end goal is to assist industry in setting up lean Product Development Processes. By providing a clear DfX structure, we strive for: (1) the standardization of DfX procedures and information flows, (2) the integration of DfX methods in a systematic and structured manner, and (3) the presentation of criteria for benchmarking DfX methods such that companies can purify their DfX procedures. All these results target the goal of leaning up design processes.

The template is the result of an extensive literature review in the fields of DfX (Section 2) and the application of design theory and methodology (Section 3). On the one hand, DfX related literature misses formal and concise descriptions of the design tasks and information types to be included into a DfX method. On the other hand, design theory and methodology literature endorses different frameworks that describe the basic building blocks of design methods from both an information flow point-of-view and from a design procedures point-of-view. To fine-tune the template, specific DfX methods have been evaluated against the developed template (Section 4). Papers are selected from the fields of Design for Manufacturing (DfM) [4-10] and Design for Sustainability (DfS) [11-17]. According to Chiu and Okudan [2], DfM and DfS are the most mature fields within DfX. The assessment concluded that the template indeed captures the required design rationales DfX methods have to contemplate.

2 DfX Structure in Literature

Given the vast amount of literature on this topic, this literature overview presents a summarized analysis of DfX review papers. The objective of this overview is to underline how other DfX researchers have addressed the issues of structure and organization in DfX methods.

Chiu and Okudan [2] have performed an extensive review of DfX methods. Their review includes a mapping between DfX concepts and methods onto the different design process phases (i.e. requirements, conceptual design, detail design and evaluation). Also, the interrelation between different DfX methods and the calculation of a maturity index that represents the level of development of the different DfX fields was studied by them. Regarding the structure, DfX methods are classified into 5 categories based on the nature of the presented tools. Organized in increasing levels of detail, these categories are: guidelines, checklists, metrics, mathematical models and overall methods. Guidelines provide directions to be followed; checklists prescribe the items that should be taken into account during certain design processes; metrics are used to quantitatively evaluate how good a product is in relation to its design goal (the X in DfX); mathematical models involve validated equations and formulas that are used to calculate system performance; finally, overall methods describe clear and systematic procedures involving several of the previous categories. This categorization describes the type of structures in a DfX method; however it does not express which design tasks are addressed by each of the methods nor the order in which the tasks should be fulfilled.

Meerkamm et al. [3] treat the structure of DfX in two ways. The first is as the relation between different DfX methods within the concurrent design philosophy. The second is in relation to the form of the DfX method. For example, if the method is made out of guidelines or in the form of checklists. There is however no statement about the design procedures and information flow within the method, nor how this flow is organized within a concurrent design.

Kuo and Zhang [18] present a review of concepts, applications and perspectives in DfX. A large number of methods is reviewed and best practices are summarized. However, there is no unified structure for framing the different procedures and information flows that each method entails.

Huang [19] proposes a framework (the DfX shell) that can be used to develop DfX tools quickly and with consistent quality. The framework consists of 7 steps that take the method developer from analysing the method's requirements through documentation and method verification. Tichem [20] developed a tool to support DfM, DfA and DfD during the conceptual design phase. The tool supports three main design functions, namely, product and lifecycle modelling, decision making and design coordination. From all reviewed literature, both cited references (i.e. 19 & 20) are the closest to presenting a structure for DfX methods. However, neither of both addresses the required design procedures and information flows in a systematic way.

3 Design Tasks and Information Flow

In general, the design process can be divided into 4 main phases [21]: (1) planning and clarifying the task; (2) conceptual design; (3) embodiment design; and (4) detail design. The first phase regards the problem statement, while the last phase aims at planning the manufacturing. Both are organizational processes. It is in the conceptual and embodiment design phases where the artefact is actually designed. Both phases are accomplished by following 4 basic design tasks: synthesis, analysis, evaluation and adjustment [22]. These 4 tasks are recursively invoked during design and the order in which they are organized defines the design strategy that is used. The synthesis task transforms a set of input requirements into a candidate solution. The analysis task calculates (either quantitatively or qualitatively) the solution's performance. The resulting performances and solutions are evaluated in order to decide whether to modify, reject or accept the candidate solution. The adjustment task is applied when the quality of a candidate solution can be improved by small alterations.

The types of information flowing among design tasks can also be categorized into 3 groups according to their role within the design process, namely embodiment, scenario and performance [22]. Embodiment regards the set of parameters describing the design object; for instance, its topology or its (material) properties. Scenario is related to the set of entities describing the flow of energy, mass or information the embodiment is exposed to. Finally, performance determines how the embodiment behaves under a certain (group of) scenario(s). Several design frameworks in academia (e.g. McMahon [23] and Webber [24]) have classified design information in these 3 groups as the information per group is used distinctly different during design.

Under this view, analysis tasks quantify and/or qualify the performance of an embodiment undergoing a given scenario. Vice versa, synthesis tasks are the process of specifying embodiment parameters such that they meet certain performance values for a given scenario. Both process flows are shown in Figure 1.

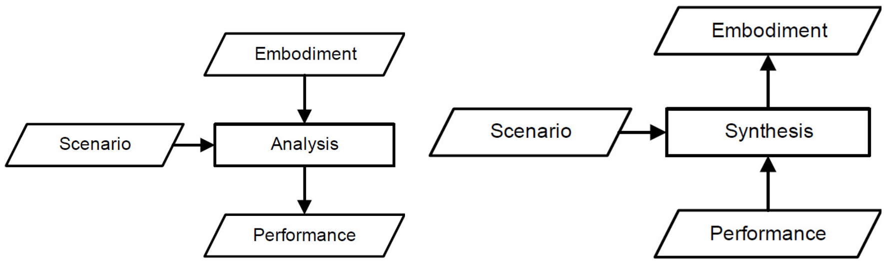

Fig. 1. Information flow for analysis and synthesis processes

Standardization of design tasks and information flow has been studied especially in the field of computational synthesis as this is fundamental for design automation (e.g. the work of [25] and [26]). A template for DfX must have methods to support each design task (i.e. synthesis, analysis, evaluation and adjustment) and a classification of the information type (i.e. embodiment, scenario and performance). Together they guarantee the structure and completeness of the DfX method. The structure describes which method to use for which task together with the information flow of each method. Completeness describes whether all design tasks are supported by the DfX method. The latter is not required; however, designers should be aware of the completeness of the methods they use.

4 The Design for X Template

The developed DfX template consists of 3 main parts: the strategy declaration, the information type declaration and the design task support method. As shown in the taxonomy of the DfX template in Figure 2, the information declaration is further classified into 3 groups: embodiment, scenario and performance; while the design task support method is classified into 4 groups: synthesis, analysis, evaluation and adjustment.

The flow of information according to their type can be integrated with the 4 design task support methods, as shown in Fig. 3. As the figure shows, the DfX template also distinguishes between known initial information and design emergent information. The following subsections elaborate on this DfX template and present examples from existing DfX methods in literature to demonstrate the use and viability of this template.

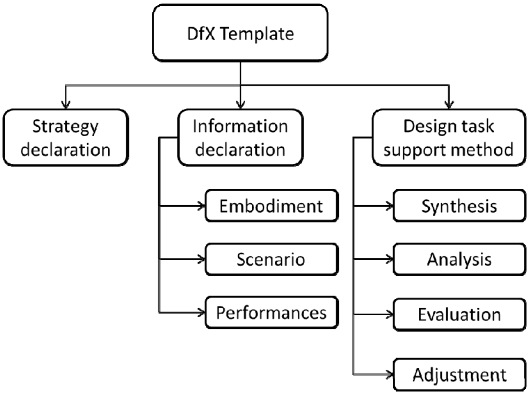

Fig. 2. Taxonomy of the DfX template

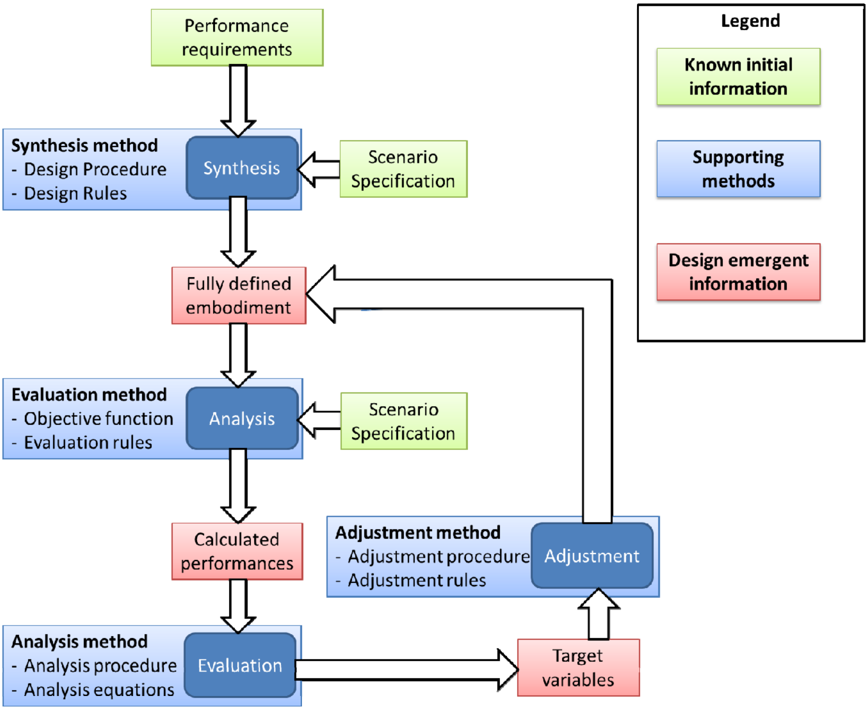

Fig. 3. Information flow and design task support in DfX template

4.1 Strategy Declaration

DfX methods are inspired and developed by taking into account company specific strategies. These strategies serve as general goals that drive company rules and guidelines. Examples of such strategies are, for instance, to save energy, to save resources, to minimize manufacturing process types or to minimize complexity. Strategies emerge from a company's strategic plan. For example, one strategy could be DfM with the goal of reusing as many existing production machinery as possible, while for another company DfM entails outsourcing as many processes as possible. Das et al. [27] present a strategy where DfX is defined as an approach for designing a product quickly, with low manufacturing cost, a minimum number of processes and handling requirements, and attains its designed level of quality.

4.2 Information Declaration

Information declaration aims to obtain a map of the parameters that play a role in the DfX method and help designers determine if the method suits their problem. The declaration, according to the template, is done by defining both the parameter names and their type. Next, the 3 information types are discussed.

Embodiment. In DfX, embodiment parameters are the properties of the artefact being designed upon which a design decision has to be made. Depending on the scope of the method, embodiment parameters describe the geometry, topology and material characteristics of the artefact. For DfX, the embodiment information declaration does not change compared to the original declarations.

Scenario. Within the scope of DfX, scenario parameters describe the boundary conditions for which the method is developed. For instance, in the case of a DfM method, manufacturing conditions would give input to the scenario parameters. As such, scenario parameters describe, among others, the characteristics of the available machine processes in a given industrial setting.

Performance. In DfX, performance is directly related to either a maximization or minimization of the X in the method. Performance has different levels of perception: product, system and eco-system [2]. For DfX, performances are related to measurements of material resources usage, energy usage or time usage. For instance, the "universal virtue" areas described by Fabricius [4]: cost, quality, flexibility, risk, lead time, efficiency and environment.

4.3 Design Task Support Method

Design task support methods for DfX consist of knowledge rules, procedures and information flows. The first are expressed in different forms; for example, equations, guidelines and checklists. Procedures determine the way in which knowledge rules are used and when and in what order a method should be executed. The information flow is discussed for each design task hereafter.

Synthesis Design Task. According to the template, the synthesis design task support method aims at aiding the designer in developing high quality solutions at low design efforts. The synthesis task is supported by design procedures and knowledge rules. As shown in Figure 3, the input information of the synthesis task is a set of known scenario specifications and desired performance requirements.

Design procedures determine the logical order in which knowledge rules should be applied. This has the aim of avoiding inconsistencies and improving design efficiency.

Knowledge rules of a synthesis support method are termed as design rules. They serve as shortcuts that determine the embodiment of a design given a certain scenario while aiming at sufficient performance. Design rules are often the result of (past) design experience.

Design rules need to be treated carefully as they impose restrictions to the solution space and have the ability to constrain more creative solutions. This can be managed by properly documenting its rationales such that modifications can be easily carried out when new insights are developed. Design rules in DfX methods are typically expressed in the form of guidelines.

Examples of such rules from the field of DfM are “minimize the variety of parts”, “simplify the structure” and “use standard parts” [5]; typical from the field of DfS are “reduce use of energy”, “reduce emissions” and “Increase amount of recyclable materials” [11].

Analysis Design Task. Also in the DfX template, the analysis design task support method has an inverted effect compared to the synthesis method where scenario and performance parameters help define the embodiment variables. The analysis support method enables the designer to calculate the performances of a designed embodiment within the scope of the DfX target scenario. Contrary to the synthesis task, analysis is based on models (e.g. factual, analytical, numerical, etc.) and the analysis results represent reality (either qualitatively or quantitatively). As DfX focuses on issues that are related to the product lifecycle rather than the product functionality itself, analysis methods tend to be qualitative and the synthesis support method tends to be based on guidelines.

Knowledge rules in analysis support methods are termed design equations. Design equations can be represented using different mathematical models (e.g. logic models, fuzzy models, algebraic models or look-up table models). Analogue to synthesis, analysis procedures determine how analysis equations are used to determine the performance of an embodiment. As analysis methods do not embed complex decision making processes, they can be automated by computer software.

Analysis equation can in the field of DfM, for instance, be formulated using historical records of manufacturing companies including figures for material, tooling, set up and labour cost as it is described by Goncalves-Coelho and Mourao [7]; in the field of DfS equations are often based on Life Cycle Analyses. Also, the eco-functional matrix presented by Short and Lynch in [15] is an exemplary analysis method.

Evaluation Design Task. The goal of the evaluation support method is to offer the designer a clear path to determine whether an obtained design solution should be accepted, adjusted or dismissed. Evaluation is often delegated to the designer’s judgement. However, for the aim of using DfX as a tool for standardization, it is important to have uniform evaluation criteria that guarantee corporate quality standards. Therefore, it is important to include evaluation design tasks into the template as a formal sub-method.

Knowledge rules in evaluation support methods are termed evaluation criteria. Evaluation criteria are presented in the form of logic relations and, in DfX, they are often found as checklists.

Evaluation procedures define the order in which the criteria have to be evaluated. In case the evaluation process determines to continue with an adjustment task to bring about improvements to the obtained solution, protocols have to prescribe how the target embodiment variables are identified and what their goal is during the adjustment task.

For instance, Van Vliet and Van Luttervelt [10] constructed a clear procedure using IF-THEN statements for their DfM method. Performance parameters are evaluated and the design is subsequently steered in the appropriate direction.

Adjustment Design Task. Adjustment support methods support designers in bringing improvements to existing solutions. The input to an improvement process is a set of embodiment parameters. Knowledge rules are termed as adjustment rules. Similar to design rules, they specify the embodiment as a function of scenario and performance parameters. The adjustment procedures determine which adjustment rules apply depending on the targeted embodiment parameters.

Typical examples of adjustment rules for DfM are “Wrong” and “Right” representations of a designed component, for instance for casting components [8].

5 Summary

This paper presents a DfX template as the result of researching the structure of DfX methods. The research was motivated by the need to standardize DfX information flow and design support methods. The template strives for both structure and completeness. This would avoid a further increase in design process entropy. First, a literature review was carried out to search for existing frameworks within DfX literature. As no formal frameworks were identified, a literature study of existing design frameworks in the field of design theory and methodology was performed. The results were used to propose a template that incorporates all relevant rationales of DfX. To finish, DfX methods in literature were assessed and projected onto the template to determine its feasibility.

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Enhancing Interpretation-Quality of Requirements Using PLM Integrated Requirements-Communication in Cross Company Development Processes

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Abstract. Fulfilling customer requirements significantly influences product success. Improving the quality of documentation is a primary objective of requirements engineering and management. Despite properly outlined requirements however, it is very common that mistakes emerge throughout the product development lifecycle due to diverging interpretations. Because if this enhancing the quality of requirements documentation to ensure a common understanding is increasingly the focus of quality improvement considerations. In response to this need, an approach was developed which uses Secure Information Transformation from Input to Output (SITIO) as an aspect of PLM integrated requirements management to provide a sustainable enhancement of interpretation-quality through linguistic pragmatics.

Keywords: Requirements Management, Quality, PLM, Product Lifecycle Management, SITIO.

1 Prerequisites for Product Success

Sustainable customer satisfaction is only achievable if customer requirements are fulfilled. Therefore, the success of a product critically depends on conformity to defined and fulfilled requirements. Companies are now realizing that, due to the increasing complexity of their products, the inevitable integration of different domains (e.g. mechanics, electrics and electronics) as well as necessary global collaboration, an exact design can only be achieved by superior quality of requirements documentation throughout the entire product development process.

In order to completely and correctly implement design requirements, these requirements must be clearly identifiable, easily and completely understood as well as correctly interpreted by the product developer responsible for realization. The process of ensuring consistent requirements interpretation is becoming increasingly complicated due to the growing trend of decentralized product creation. Because of this, current requirements definition methods are no longer sufficient.

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Therefore, new methods and IT tools, which offer adequate support for the processes of defining requirements, their distribution within and between companies and implementation of requirements are imperative for product success.

2 Transformation of Requirements in the Course of the Product Development Process

A compilation of all requirements for a new product is the first result in the development and construction process according to VDI-Richtlinie 2221 and 2222. Usually, requirements are verbally formulated up to this point. Kramer [1] proposes to divide the specification of requirements into three levels of granularity: stage 1 (statement), stage 2 (consolidation) and stage 3 (detailed definition).

Kramer‘s proposal also broadly matches the actions of the automotive industry. Within the automotive industry, customer requirements – typically requirements from a marketing perspective – are at first derived into specific properties and functions. In automotive engineering, requirements on fuel consumption, safety or spacing would be represented on a vehicle level. Subsequently, properties and functions are then detailed through different levels of granularity down to the level of an individual component (fig. 1, right side of pyramid).

The process of refinement thereby occurs across different departments and even companies – due to globally distributed suppliers. It cannot be assumed that communication between departments and suppliers refers only to a single defined level of granularity (fig. 1, total).

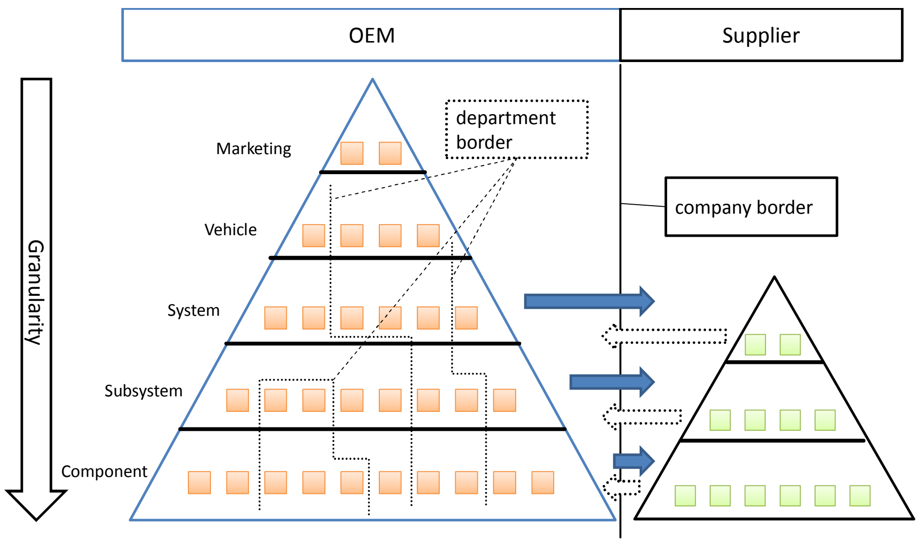

Fig. 1. Typical levels of granularity of the automobile industry

Until a detailed and final definition of a product through requirements is achieved, several steps of transforming information across the dimensions "granularity" and "department or company boarders", during which requirements are verbally formulated, explained, discussed and subsequently detailed, are necessary. Within each of those transformational steps there is a risk that requirements are misinterpreted, fundamental elements are missing, or some context is lost.

If requirements quality cannot be ensured between each transformational step, a high degree of customer satisfaction is hardly achieved.

3 Quality of Requirements

Consequently, it is necessary to question the meaning of "quality of requirements". In general, quality is the degree to which a sum of inherent characteristics fulfills the stipulations that are postulated for an object [2]. Today, requirements management essentially focuses on completeness and formal correctness of requirements. ISO 9000:2005 constitutes that high-quality requirements are achieved through adequacy, completeness, unambiguousness and consistency as well as through the ability to verify them. The VDA-standard with a proposal for a structure for component requirement specifications takes this one step further. The VDA-standard [3] lists unambiguousness, identifiability, traceability, necessity, non-redundancy, comprehensibility, completeness and consistency as significant criteria.

The aforementioned requirement characteristics often results in a demand to formulate more extensively detailed requirements than previously practiced. This can lead to higher levels of effort and therefore, to an increasing need for resources during requirements documentation. In order to counter-balance this, another approach for automatic test requirements would be necessary. Technically, this is done by checking requirements on so-called "weak" and "stop" words. Thereby, the primary goal is to ensure unambiguity by avoiding fuzzy wording like could, should, or would for example.

The described procedure to ensure high-quality requirements is not sufficient since a significant weakness still exists. This can be recognized by considering the communication model (fig. 2).

Previous approaches focus on the sending end (fig. 2, detail A). These approaches are formulated on the idea that it is only necessary to stipulate complete and correct requirements and that the receiving end will automatically interpret them correctly. However, practice shows that correct interpretation of formulated requirements is an essential problem in requirements management (fig. 2, detail B).

An additional problem results from the existing mindset: compilation and interpretation of detailed requirements costs resources and time. In most cases, especially in well-rehearsed development teams, experience shows that it is not necessary, perhaps even cumbersome, to formulate requirements in every detail. While interpreting such requirements, employees are losing time by evaluating information that is already known.

Hence, the goal must be to find approaches for requirements management which succeed in dramatically enhancing interpretation-quality of requirements while flexibly adjusting the level of detail for formulation of requirements on the receiving end.

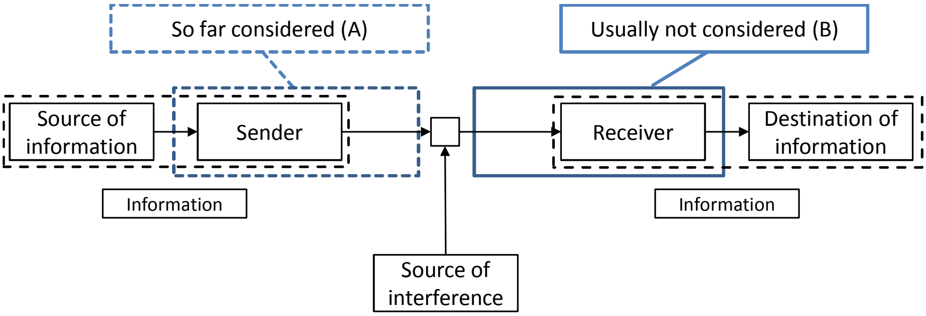

Fig. 2. Communication Model according to Shannon & Weaver [4]

4 Aspects of Linguistic Pragmatics in Requirements Management

This problem focuses on linguistic pragmatics. In essence, the context of a person that interprets or encodes information also has to be considered in requirements management. This context can be embraced with the personal frame of reference of a person. The personal frame of reference describes how a person views and interpretes the world and the information he consumes. This is partly dependent on the learned schema in which information is internally filed. It also depends on one‘s point of view, which results from the role in which the person is acting within the interpretation [5]. Based on the employees in the product development process, the relevant frame of reference is basically illustrated in the aspects represented in figure 3. Alternately, it is contingent on aspects of the learned scheme, which includes one’s native language, cultural context, and accumulated work experience (fig. 3, point A). It can also be driven by aspects of the role that a person occupies in a company (fig. 3, point B). The personal frame of reference is mainly influenced by the professional domain (mechanical, electrical / electronics, mechatronics), the role and the associated technical issue. The analysis and classification of influences of the frame of reference is a complex issue that necessitates further research in the context of requirement management. However, it can be stated that people who exchange requirements must match their frames of reference in order to interpret them correctly (for example through conversation and documentation). The design of the previously described SITIO method raised the question: how can this aspect be easily implemented in requirements management? The aim is to adjust and anchor the frame of reference in the methodology as well as take advantage of existing highly matching frames of references of persons in the process chain so that in such cases, the effort in formulating requirements decreases with a simultaneous increase in quality.

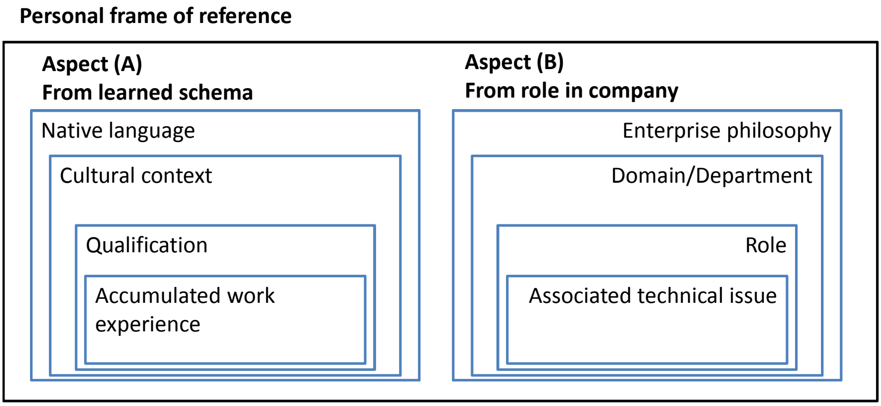

Fig. 3. Relevant aspects of the personal frame of reference under considerations of the product development process

5 Secure Information Transformation from Input to Output

In the context of industrial research, the authors have developed a methodical approach, which incorporates an all-supported integration of requirements management into an open PLM platform, such as a Teamcenter. A particular overvalue of such integration is the system supported reproducibility of the dependencies of requirements among themselves and their practical implementation in a component design or an actual construction. This allows a quick and inexpensive handling of changes of the product without delay and interference of the system or break in communication. One aspect of this methodology is SITIO (Secure Information Transformation from Input to Output). It focuses on ensuring the quality of requirements transformation on the dimensions of "granularity" and "departmental or enterprise boundaries". Through the use of SITIO, it can be ensured that the participants in the process chain maintain a common understanding during all transformation steps of requirements.

Figure 4 shows the process of a transformation of a formulated requirement. Person A formulates the document of requirements. This input document is passed to person B for further detailing. Person B transforms the requirements to a more detailed level of granularity. Then, person B passes the resulting output document to the successor in the process chain (comp. in figure 4, person C) who, for example, accomplishes the construction task. In recent requirements management, the quality is essentially ensured by tests, which by SITIO are considered by realizing the process step "Craftsmanship". In this process step, (fig. 4, ②) [6] a responsible person from the department of person B tests the output document on formal compliance with agreed quality standards and compliance with the established process flow. The focus is on reviewing on non-redundancy and consistency of the by person B prepared information. SITIO adds two other elements to the process: "Fitness-for-use" (fig. 4, ① & ④) and "Conformance" (fig. 4, ③). The step "Fitness-for-use" (fig. 4, ①) focuses on the correct interpretation of the input document by person B. This person confirms which points of the document are in his view fully understandable and reflects his understanding in an outcome document or in a work meeting with person A. Person A contrasts his original intention with the understanding of person B. If Person A believes that person B has understood all requirements of the input unambiguously, completely and understandably; person A releases the information for actual processing by person B. If the input document displays any weaknesses, the input has to be reviewed by the respective author of the information until all weaknesses are eliminated.

In succession, person B conducts the actual transformation process, by, for example, specifying the requirements of the input document to a finer level of granularity and by recording the results in an output document. The first step to release the so-created document, as described above, is the step "Craftsmanship". To ensure that the output document properly reflects all requirements that are specified in the input document, the step "Conformance" (fig. 4, ③) follows. Here, person A examines the output document accordingly. Only then, the output-document is released and transmitted to the follow-up activity and the procedure described begins again. By the two elements "Fitness-for-use" (fig. 4, ① & ④) and "Conformance" (fig. 4, ③), a review of the requirements on the receiver side is realized. Moreover a benefit is the precise assignment of the organizational responsibility for the process steps. Thus, person A cannot withdraw on having described all necessary information in the input document. She also has to take the responsibility that person B has understood the statements correctly.

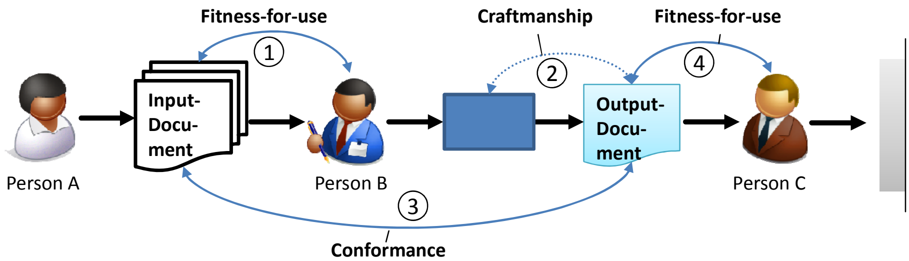

Fig. 4. Basic concept of SITIO

6 IT-Supported SITIO Process and the Use of Personal Frame of Reference

At the first glance, the introduction of additional steps in requirements management through SITIO appears to be more time consuming, especially in the context of the currently prevailing tendency to demand more detailed definition of requirements. However, upon closer inspection, it becomes apparent that an additional expense is already justified by ensuring requirements are of high quality and by avoiding subsequent errors. The two process steps "Fitness-for-use" and "Conformance" are already used in the industry because an adjustment to match the frame of reference of the participants is essential for a proper understanding of the requirements. However, these are implicit processes which are only conducted by sheer necessity and driven by the participants themselves. If the transformation of requirements is implemented on a IT basis by means of SITIO, the formerly implicit communication processes are then explicit. This results in the organizational systemization of communication processes being based on defined workflows, which are handled by the PLM platform and are traceable and transparent.

In addition, effects of decreased effort by matching frames of references could be used and anchored in the company by implementing SITIO. Such an implementation could lead to a cost and effort reduction when compared to the previous process.

The implementation is realized, for example, with the open PLM platform Teamcenter. The demonstrated process flow in figure 4 is modeled by Teamcenter through the "workflow engine". Thus, the communication, the document exchange and release of documents are realized directly through the system. It is thereby possible to maintain auditable traceability (i.e. the link and Traceability) between input and output documents at subchapter and paragraph level on the level of revisions.

The steps "Fitness-for-use" and "Conformance" account for the effect of effort reduction from already existing common frames of references. Teamcenter allows mapping roles and organizational classification together with the qualifications of the participants in requirements management, so that during the procedure of transformation an analysis of participants can be conducted and subsequently the degree of commonality of the frames of references can be analyzed.

Because of the analyzed overlap of the frames of reference, it is possible to provide different documentation templates based on the existing frames of reference. The various documentation templates require a contextual detail of the requirement documentation so that unnecessary, because already known, information can be omitted. In this way, the communication effort between the parties of process chain at elevated quality of the information transformation could be reduced accordingly. As a result, the processes accelerate and therefore, reduce costs while increasing quality.

7 Summary

Through the use of SITIO information loss and distortion of information in the process of requirement transformation can be minimized.

Currently used criteria to maintain quality were expanded through integration of "Conformance" and "Fitness-for-use", the process will be systematized and embedded in the organization.

The transformation of requirements is bundled and can be system-based implemented by means of open PLM platform, such as Teamcenter.

The work effort for the preparation of requirements can be reduced by the utilization of the effects of the personal frame of reference while the quality of requirements increases. Therefore, SITIO provides a methodological tool for requirements management, which improves the process.

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PLM-Centered Support of Active Virtual Customer Integration into the Product Creation Process

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Abstract. Within the last decades the position of customers has changed from a passive recipient to an active co-designer in the value creation. Successful innovators use competence within an extended network which particularly includes the competence of customers. Therefore the ability to allow information about customers and their needs to flow into the process of product creation is decisive. But todays methods and IT-Tools often do not achieve the desired results in innovation projects. In order to improve the active virtual customer integration into the process of product creation; this paper presents a Product Lifecycle Management (PLM)-centered research environment with a ubiquitous mobile frontend. A process outline for the provision of product descriptive data from a PLM system to a mobile device and the information return, back into the product creation process is included.

Keywords: Virtual customer integration, Open innovation, Product Life Cycle Management, Mobile computing, Research environment.

1 Introduction

Due to the ongoing globalization and the shortening of the product life cycles, the pressure increases on companies to improve their innovation processes. Technological change has reduced both, the development time of products and their life massively, which is very clearly seen in products from consumer technology and the automotive industry. Due to the dynamics of global trade high-wage countries, post-industrial societies need to compensate for the disadvantages of location compared to low-wage countries through knowledge and innovation. Gary Hamel summarizes this difficulty:

"We've reached the end of incrementalism. Only those companies that are capable of creating industry revolutions will prosper in the new economy."

The focus in innovation research, therefore, no longer fails to occupy the role of innovation as a driver of growth and profitability. This was clearly proven by the science, e.g. Thomke [1]. Now it is important to explain how innovation occurs and how innovation processes can be optimized. A key approach is based on the paradigm shift to

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open the innovation process and to integrate external perspectives and participants. For this purpose, the term open innovation was formed by Chesbrough [2], [3].

Within the last decades the position of customers has changed from a passive recipient to an active co-designer in the creation of value. Successful innovators use competence within an extended network which particularly includes the competence of customers [4], [5]. Numerous studies have shown that early integration of customers in the development process can increase the success of innovations clearly. In many industries, it is the customers who are responsible for the most successful developments [6]. Therefore, the ability to allow information about customers and their needs to flow into the process of product creation is decisive [4].

In this context, numerous methods (e.g. lead user) and tools (e.g. user toolkits, virtual customer integration platforms (VCI) and virtual customer environments (VCE)) have been developed to integrate both, in-house and external customers in the innovation process, respectively the product development process. But as Schroll [7] points out those methods and IT-Tools often do not achieve the desired results in innovation projects. So it is necessary to reconsider existing approaches.

This paper describes the current state of ongoing research work which has set itself the goal to establish a link between the so far singular considered innovation and product creation processes and to reduce the existing deficits of customer integration tools. For this purpose the development of a ubiquitous active customer integration environment which is directly integrated with the product creation IT-Backbone, the Product Life Cycle Management (PLM) system is presented.

After a general introduction in chapter 1, chapter 2 gives an overview of existing relevant solutions and the roles of customers in the customer integration. In chapter 3, the research environment is presented. Chapter 4 provides a summary and an outlook.

1.1 Challenges

The aim of the so-called virtual customer integration (VCI) platforms is the collection of need information and implicit and explicit solution knowledge in all innovation process phases. This is achieved by the digital implementation of the methods of customer integration in a fully virtual environment like an internet platform. As Rohrbeck et. al. [4] showed, in the year 2010 thirteen out of the Euro Stoxx 50 companies had established a VCI platform. The state of the art (see chapter 2), however, has many shortcomings concerning methodical, organizational and technical aspects as well, both from a customer perspective and from a business perspective.

Nowadays for a potential co-designer there are many barriers to cross before participating in the innovation process. On the basis of an already existing product the customer first needs to identify the product (e.g. Golf V). If it’s the case that different configurations and/or variants of the product exist, a bijective identification is the best case (e.g. Golf V, station wagon, edition Rolling Stone, build year 2007, manufactured by Volkswagen AG) to ensure that the customer feedback or contribution can be associate with the right product data. But now, the customer needs to look-up a company-specific and adequate feedback channel (e.g. feedback formula on website) which is in best-case a VCI platform that supports the innovation process phase the customer wants to contribute to (e.g. idea generation for a next generation infotainment system), not knowing if such channel exists. In a last step the customer describes his idea or feedback, in best-case using structured input fields or toolsets that offer certain degrees of freedom to virtually design ideas.

In the described case, customer-generated data is largely unstructured, leaves room for interpretation, and is not consolidated and not assessed. Customer's innovation potential remains untapped because the customer has only a few additional inputs obtained for its innovating activities. For example interdisciplinary discourse and the provision of technical background information e.g. drawings are missing in this process. According to studies, these are particularly useful for the generation of ideas [8].

If large groups of people shall be involved virtually and active in the product creation process, the challenges for companies are summarized as follows.

- Providing a technical solution that enables ubiquitous active customer integration.
- Providing a technical solution that supports innovative customers with background information from the product development process, allowing self-assessment and refinement of contributions.
- Establishing a process that supports customers with qualified feedback and assistance from the product creation perspective to enable independent further development.
- Establishing a process that supports the collaborative aggregation, exploration and assessment of customer generated inputs in a customer community.
- Providing a technical and procedural solution enabling the direct usage of customer generated inputs in the product creation process.

1.2 Object of Research and Approach

The research concentrates on developing a holistic approach that addresses the above mentioned challenges. A modular research environment is in development that enables active virtual customer integration by using a ubiquitous innovation frontend on a mobile device with interface to a PLM system. This test environment serves the purpose to answer the research questions:

- Which data from the product creation process supports customers to innovate?
- Which data helps the product creation engineers to innovate?
- How must a technical solution be designed to integrate innovation related activities of customer and product creation engineers in a continuous process?
- How can this process be integrated with existing product creation processes?

To achieve the goal and answer the research questions, existing procedural and technical solutions have been analyzed in terms of their deficits and reusability. In a next step, test scenarios must be developed and realized in the research environment using the results of qualitative and quantitative studies concerning investment goods. Finally the developed solution needs to be evaluated and optimized for the integration with product creation processes.

The presented considerations and results are based on the results of the joint research projects BMBF-ISYPROM [9][1] and BMBF-INNOPEP[2], started in 2012.

2 State of the Art

The chapter gives a brief overview of existing approaches for active virtual customer integration. In this paper, virtual customer integration is accordingly understood as a type of intensive interaction between manufacturers and customers, which is more than market research. In other words, customers adopt the role of active co-designers of the process of innovation [6]. Active customer integration goes one step further. The manufacturer is not only opening a direct channel to collect the need information's of the customers directly and systematically, but it allows the customers to innovate themselves constantly in cooperation with the companies. As Reichwald et. al. points out, this approach is based on the recognition that customers are not only in possession of solution information. In fact, many customers have comprehensive and detailed knowledge of how their unfulfilled desires can be realized [6]

2.1 Roles of Customers in Product Creation Process

The term customer can be interpreted and defined very diverse [4], [5], [6], [7]. From an engineering perspective the differentiation of customers following the concept of Design for Innovation is applicable. The concept can be separated in four core components defined as "Design for Purchasing" (by buyers), "Design for Adoption" (by user), "Design for Impact" (on the beneficiary) and "Design for Externalities" (on outsiders) [10].

For the development of the research environment solution it is important to define the roles those customers can take up in the product creation process. A good orientation provides Nambisan (Table 1.) [11]. In his research Nambisan refers to a virtual customer environment (VCE). Concerning the mobile frontend of the PLM-centered research environment his role definition is suitable because VCEs combine lightweight virtual product creation technologies with a physical space.

2.2 Methods of Customer Integration

In the literature, a distinction between methods and technologies for customer integration is made only rarely. Bretschneider et. al. [12] offers a good stocktaking. This paper only presents essential and to a large extent technology-driven methods.

Virtual Customer Integration Platforms. VCI platforms using the internet as a uni- or bidirectional communication channel between customer and companies e.g. the customer can post ideas for new products, or discussions with a development

[1] www.isyprom.de
[2] www.innopep.de

Table 1. Roles of customers in accordance to Nambisan [11]

	Product Concep-tualizer	**Product Designer**	**Product Tester**	**Product Support Specialist**	**Product Marketer**
Nature of Customer Contribu-tions	Suggestions and ideas for new product and/or for product improve-ment	Specifica-tion of new product design; inputs on product features and design trade-offs	Identifica-tion of product design flaws; input on product prototypes	Delivery of product support services to peer cus-tomers	Diffusion of new product informa-tion; shap-ing peer customer's purchase behavior
Dominant Nature of Customer Interactions	Customer – Customer Customer - Company	Customer - Tool Customer – Company	Customer - Tool Customer - Company	Customer – Customer Customer – Customer	Customer – Customer Customer – Tool
Typical VCE Tech-nologies	Discussion forums Knowledge centers Blogs, wi-kis	Virtual product design and prototyping tools Messaging tools	Virtual product simulation tools Messaging tools	Discussion forums Knowledge centers	Discussion forums Virtual product simulation tools

engineer. The level of richness can vary from text communication to multi-modal interfaces or user-innovation toolkits, where the customer can manipulate the final product [4]. VCI tools can address customers individually or via online communities allowing to in-source creativity by enabling users to create and evaluate products, bypassing intermediaries such as market-research firms [4], [6], [12], [13].

Virtual Customer Environment. The term virtual customer environment (VCE) strongly overlaps with VCI platforms. Different to VCI platforms VCEs can offer virtual product creation technologies in a physical space enabling direct interaction between customers and engineers. Some examples for VCEs are BMW´s Customer Innovation Lab, Volvo´s Concept Lab or Ducati´s Tech Café [11].

PLM-Based Customer Integration. The idea of using PLM systems for customer integration so far has only little observance in literature. Schulte [14] developed an approach offering a frontend collecting customer feedback for virtual prototypes which is link as requirements to product structure elements in the PLM system. A similar approach was presented by Stark et. al. [9]. In the joint research project ISYPROM a model-based integration of a collaborative idea management tool and the requirements engineering component of a PLM system was realized. Table 2 shows the delta of presented methods and the desired PLM-centered solution.

Table 2. Delta between characteristics of existing and desired solution

	VCI	VCE	PLM	PLM-centered
Product identification	-	-	-	x
Mobile frontend	partially	-	x	x
Ubiquity	partially	-	-	x
PLM integration	-	partially	n.a.	x
Integration type: passive/active	x/x	x/x	x/-	x/x

Fundamentally new within this approach is the automated access to an innovation environment via product identification. Hence, in comparison barriers for customer contributions to the product creation process are reduce drastically. While other customer integration solutions have different drawbacks especially concerning the PLM-integration, the PLM-centered virtual active customer integration approach offers a seamless integration between company-internal and external innovation and product creation activities and a vivid collaboration between the involved roles.

3 PLM-Centered Research Environment

Chapter 3 presents the alignment of the proposed solutions to the PLM process, a detailed description of the technical process and the current state of development.

3.1 Alignment in the PLM Process

Figure 1 depicts the alignment of the proposed research environment in the PLM process and the information flows between OEM and customer.

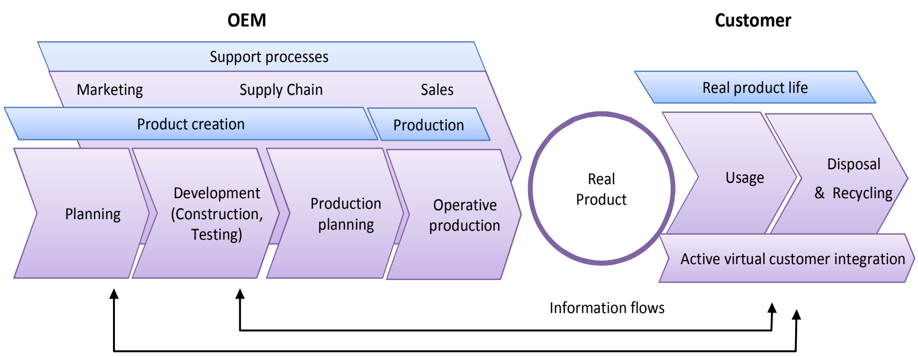

Fig. 1. Alignment of research environment and information flows in the PLM process

The bi-directional exchange of information between the customer and OEM takes place in the phases Usage and Disposal & Recycling, so in the real product life, and the phases planning and development in the product creation process. The Section 3.2 describes the technical details of the process active customer integration with reference to a scenario.

3.2 Technical Process Outline

The process, as depicted in figure 2, consists of six phases, descripted below.

Data Release and Preparation. As pointed out technical background information about existing or planed products can support self-imitated and autonomous customer innovation activities. Hence, in this process phase relevant product descriptive data in the PLM system is selected for release and prepared, in a sense of automated file format transformation, detail level reduction and information aggregation, for use in the downstream process stages. As well the addressed customer community (company internal, extend or global) needs to be selected. This process phase has to be tailored concerning different aspect due to company specific interpretations of openness (e.g. compliance to intellectual property guidelines).

Data Provision. Depending on the addressed community the released and prepared data needs to be made accessible for the customer using a suitable IT-Infrastructure (e.g. Intranet, Internet). This process phase can be fully automated using the defined parameters from process phase one. It must be ensured that the data provided remains still associated with the initial data respectively its product. This guaranties the traceability between the source and target of customer-generated information.

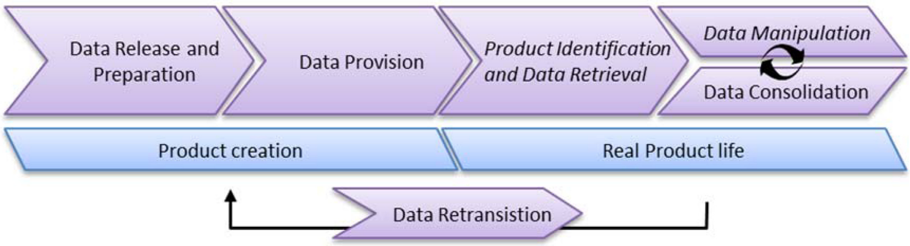

Fig. 2. Technical process for PLM-centered customer integration

Product Identification and Data Retrieval. To meet the requirements of a ubiquitous customer integration environment data retrieval needs to be designed barrier-free (see chapter Challenges). Therefore in this process phase the access to the environment is enabled by a bijective product identification. By pointing a mobile device on a product relevant data the customer likes to contribute to is retrieved.

Data Manipulation. Using a suitable communication and interaction interface the customer is enabled to initiate or contribute to existing innovation projects. Such contributions can be unidirectional, e.g. the customer can post ideas for new products or incremental innovations, vote for innovation ideas, or bidirectional, allowing discussions between the customers and engineers (see process phase data consolidation).

Data Consolidation. In this phase the customer-generated information is made accessible to a wider community for further development. In a sense of active customer integration during this phase customers and engineers can take up different roles using a web-based platform for design activities. The phase data consolidation and data manipulation are running iteratively.

Data Retransistion. Using company-specific metrics, the consolidated data are evaluated in terms of maturity. When a certain maturity level is reached data will be return into the PLM system for further development activities executed by product planer or development engineers.

3.3 Current State of Technical Realization

The current research and development activities are focused on the implementation of a ubiquitous mobile customer integration frontend respectively the process phase "Product Identification and Data Retrieval" and "Data Manipulation". For that, a model-based tracking was implemented on an Android device. This allows using tracking models generated from geometric data in the PLM system to identify real products, without using special marking approaches e.g. QR-Codes, markers, RFID etc., and tracking. Thus a translation and rotation stable overlaying of a product and its geometry was realized.

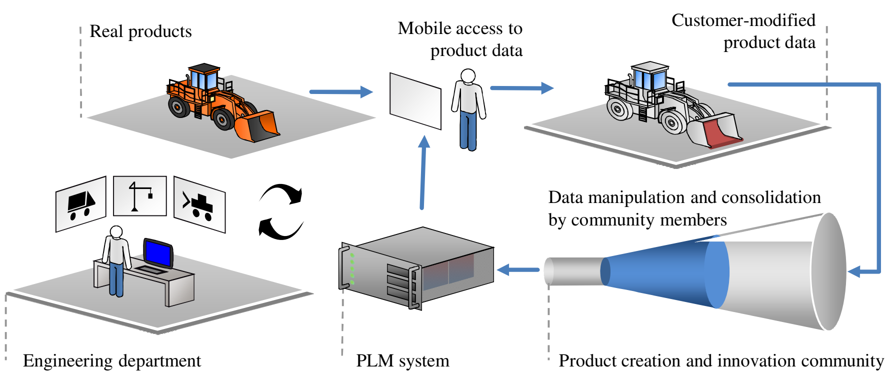

Fig. 3. PLM-centered roundtrip

The developed application so far offers opportunities to leave annotations and to document own “real world” modifications with snapshots. In both cases the customer-generated data is associated with the initial data in the PLM system e.g. drawings in the product structure. Figure 3 depicts the mobile frontend in the context of the research environment.

As seen in the figure, geometric data from the engineering department and a so called tracking model are made accessible via a PLM system. In this case Siemens Teamcenter PLM 9.0 was used. The provisioned data can be accessed by pointing the camera of the Android device at the corresponding product. After modifications have been made by the customer, data is published in a web-community for further development and assessment. After passing the innovation funnel, community-hedged innovation ideas and corresponding data is transitioned to the PLM system, respectively to the engineering department, for realization.

4 Summary and Outlook

The paper presents a new approach for the virtual active customer integration into the product creation process using a mobile device. In addition to the notion of the integration process results from the technical implementation are explained. The major befits compared to existing solutions are the drastic reduction of barriers for the participation of customers in the product creation process and the seamless integration with the PLM system on data level. Beyond that, the presented solution is capable to function as a unified cross-company access to innovation platforms.

While proof of concept has been provided for the usage of product descriptive data as basis for a ubiquitous identification of real products using a mobile device, various research needs to be conducted concerning procedural, technical and particular sociocultural aspects as well. Hence, the presented technical solution serves as a research environment for further investigations.

The design of the PLM system frontend components in development will be adjusted to the existing results and yet to be performed qualitative and quantitative surveys within investment goods manufacturers. This relates primarily to the aspects:

- mapping of customer contributions to requirements
- visualization of customer contributions in mock-ups
- feature integration for seamless community-interaction

For this purpose the project partners will be interviewed in a first stage. Based on the results a scenario will be developed and implemented which enables further assessment concerning the quality and quantity of customer generated contributions to the product creation process and refinement of the research environment itself as well.

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High Definition Product Lifecycle Management an Immersive Decision Making Environment

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Abstract. This paper describes High-Definition PLM (HD-PLM), Siemens PLM Software's vision for supporting companies make smarter decisions that result in better products. Working from the knowledge that companies in all industries are faced with increased complexity in both products and processes, HD-PLM vision builds on three core concepts: intelligently integrated information, a future-proof architecture, and a high-definition user experience. The High-Definition PLM vision enables decision makers throughout the product lifecycle to make better informed decisions more efficiently and with a higher level of confidence. This paper explains the network of technologies and capabilities to achieve a defined set of strategic objectives and the technology foundation of the core HD-PLM concept. The basics and environment are described and how HD-PLM supports a cross-domain decision making by uniting users with the people, tools and precise product-related information they need to intelligently evaluate decision alternatives.

Keywords: HD-PLM, immersive decision making environment, complexity, product lifecycle management.

1 Introduction

All industrial sectors must deal with multiple challenges and issues in bringing new products to the market and maintaining market presence once they establish a niche. This objective has grown complicated by the increased complexity of the products themselves as well as their development processes. The sheer volume of information being driven into and around the product is so great that some companies have opted to remove content rather than attempt to manage the complexity. Product development has become complicated by environmental, safety, and government regulations; worldwide development practices; and diverse global market requirements. This requires hundreds or even thousands of critical decisions to be made throughout the entire product lifecycle by different individuals from different disciplines all along the value chain. The quality and speed of these decisions can have a profound impact on the market success of a product. Yet each decision may be based on a vast and constantly expanding universe of distributed digital data stored in a wide variety of formats and originating from multiple disparate sources. Compounding this

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overwhelming challenge is the fact that many product related decisions rely on multiple areas of expertise that may be distributed across the globe.

In all of the processes a company goes through to produce a product, thousands, if not tens or hundreds of thousands, of decisions must be made, from start all the way to the end of the product's lifecycle. The faster decisions are made, the faster the process goes. The more accurately decisions are made, the fewer the problems that occur downstream. Fast, accurate decision-making is no easy feat, given all of the information that must be considered, as well as the fact that information and knowledge are spread throughout a company, its supply base, its joint venture partners, and of course, its customers.

It is no longer enough to capture, manage and integrate information. Information must be given intelligence. It must understand what it is, how and why it relates to other information, and how and where it should be used so that people don't have to hunt for it. In this approach, information is proactive, not reactive. It's there at exactly the right time, in the right context, and in the precise level of detail so that this decision – the one being considered right now – can be made as quickly and accurately as possible. The critical question for today's companies is: "Will this complexity sink you, or can you turn it into a competitive advantage?" This question offers two very real possibilities.

The HD-PLM vision can turn this massive, widely distributed and heterogeneous collection of data into knowledge, through a tightly integrated set of solutions that will permeate Siemens PLM Software's entire suite of enterprise applications. HD-PLM provides a comprehensive inter-disciplinary source of information across all product lifecycle domains and represents a virtual 3D repository of information that includes design models, simulation, manufacturing processes, and all data stakeholders need in the product development lifecycle to make the right decisions in the development process. The idea is to enable users to move through the planning, development, manufacturing, and support stages for the product lifecycle with all information necessary and accessible to accomplish each stage. HD-PLM is designed to allow and achieve the latter, thriving in the current environment by turning complexity's challenges into opportunities for customer satisfaction to provide intelligent information at exactly the right time, in the correct context, and at the precise level of detail that each person needs.

These solutions will significantly enhance decision making throughout the product lifecycle by taking users into the realm of advanced data interaction that actively applies meaning to data and intuitively presents rich information in a way that facilitates understanding. The aim of the vision is to reduce costs through more optimal engineering trade-off and engineering change decisions, by reducing unforeseen downstream negative effects.

HD-PLM Vision: Everyone in the product lifecycle makes decisions appropriate to their work, but too often it´s difficult to access the information they need from different disciplines in order to make the best decisions. Organizations can improve decision-making capacity by intensifying the use of pervasive visual information. By enabling access to product information from multiple visual and non-visual and structured and unstructured sources, and synthesizing it into a highly usable visual information, organizations can create a more complete and exploitable context for effective decision making. HD-PLM based solutions will personalize the perspective to the users' role to enable decision makers to more quickly access and understand information that used to take hours or even days to assemble and digest. Product-related information, presented in a visual context and shared across widely accessible and easily usable collaborative interfaces, helps level the playing field for collaboration across business functions, technologies, and enterprises and can contribute to manufacturers making more effective product-related decisions throughout the complete product life cycle [1]. These decisions additional will be captured for future reference when similar criteria are encountered by others. The accumulation of best practices and experiential knowledge will enable users to validate that their decisions are the best choice to increase confidence in each decision [2].

These HD-PLM advancements also have a significant impact on innovation and product competitiveness. Most product innovations are born out of market need and design creativity. By exposing deeper levels of **product** data to design teams and greatly facilitating its understanding, those teams have more knowledge available to fuel creativity and more time to implement it. The technology framework will help to eliminate decisions with unforeseen impacts on product quality, reliability and product performance. All phases of process workflows can be streamlined with everyone having rich information personalized to their task.

2 High Definition Product Lifecycle Management an Immersive Decision Making Environment

Over the years, methodologies and practices have evolved for organizing and understanding the information that drives decision making. The vision of HD-PLM is that all information is delivered to the user in the context of his or her current task, intuitively, without having to search. HD-PLM requires an architecture that doesn’t need re-invention but instead adapts and grows with every IT innovation and change in the business environment. Siemens PLM Software is delivering on the HD-PLM vision by focusing on three core concepts [3]:

- **An intelligent integrated information to delivering the right information to the right people**. Understanding the semantics of the relationship between the product-life cycle data to understand why a relationship exists. take more insightful action than by just knowing that a relationship exists. By understanding and breaking down customer requirements, the user can assign them to the functional groups that develop a product feature, while maintaining visibility of the product as a whole. In this way, the user can engage with the specific users who are impacted by a change, instead of updating everyone every time a change is made.
- **Future-proof architecture to making sure that the information user receives is in a form he can use**. What good is a PLM system that is only available in a single deployment scheme, locks into a certain set of authoring tools, or is only available on one or two devices? The focus on future-proof architecture should deploy to suit the user particular needs, whether it is a single desktop or a globally distributed supply chain. Future-proof architecture

must also allows to use the devices, tools and data that the user or the partners already have, while keeping the options open for what the user do next.

- **A high-definition user experience to making decisions effectively**. This is where the value of intelligently integrated information and future-proof architecture is most evident to the average user. The user get only the information that a user particular needs to make a decision–based on their role and the decision at hand–cutting down on information overload and the time it takes to find relevant data. That means the user is always in the right context to do his work, accomplish his tasks, presenting the information intuitively, validate the use decision rationale.

2.1 Intelligently Integrated Information Architecture

An intelligently integrated information architecture should bring plant and production information into planning and product development. This allows a much higher rate of production success – in terms of items such as cost, quality, and throughput – because what actually happens at the plant level is fed back into product development and manufacturing planning. The virtual actions of defining product and processes become much more predictive of what will happen in manufacturing. This eliminates the need for adjustments, prove outs and other time and labor-intensive remedies that were previously required when virtual planning wasn't able to address real-world plant conditions. By connecting the physical devices in the plant and the software used to plan and manage plant operations within the PLM backbone, much more knowledge of what actually happens in manufacturing can be captured and driven into the early planning stages of product and process development. To create an environment for fast and accurate decisions PLM must support:

- Systems engineering to provide a consistent process framework across mechanical, electrical, software and electronic domains
- Integration of all BOMs and BOPs to provide a comprehensive definition of the product and processes
- Integration of product development with production to provide closed-loop feedback from production to product development and manufacturing engineering

Systems engineering supports companies to capture, manage and organize information and knowledge, beginning with the voice of the customer and continuing through to service, support, and end of life. By modeling requirements and allocating them through functional and logical decompositions to physical implementation, they achieve a significant level of traceability throughout the product. They also gain a thorough understanding of the dependencies within the model. Another significant benefit is that systems modeling help drive alignment between engineering domains (mechanical, electrical, software, electronics). When coupled with configuration and change management, systems engineering can serve as a consistent process framework that drives efficiency and accuracy during development and validation processes. Synchronized, cross-domain product development is realized through a systems engineering process that leverages a comprehensive understanding of

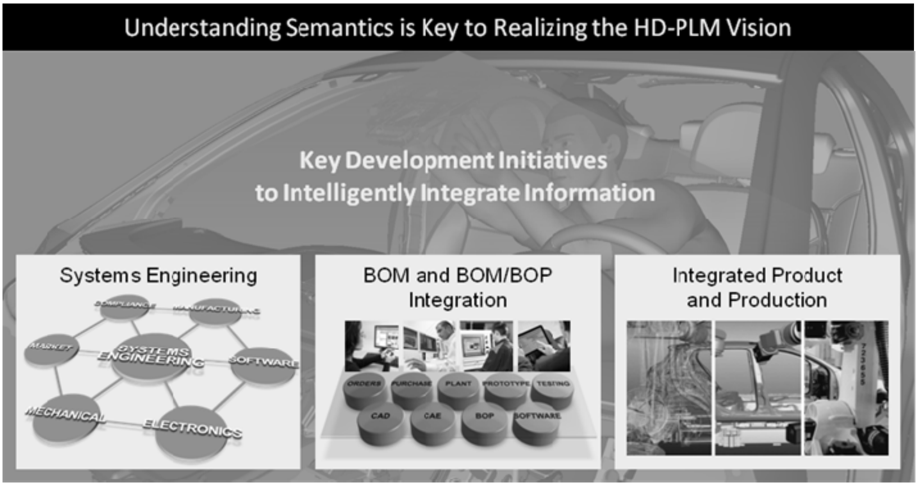

Fig. 1. Intelligently Integrated Information – Three Key Technologies

functional behavior and enables knowledge capture and re-use on the systems level. This same systems engineering process can also be applied to production, where there are four additional instantiations of the physical representation. These include: part, process, plant and the actual physical object that is produced. Incorporating production into the systems model provides a comprehensive systems view including product, process and plant.

Today's design world is dominated by solids and constraints while the business perspective is dominated by parts, features, quantity and cost. There is limited connectivity between the virtual design and business worlds where actual configuration and change happen. This prevents early virtual validation (on geometry data as well as electric and electronic simulations and other CAE-based validations). It also makes it impossible to validate saleable product configurations. As a result, it is critical to unite the different product **BOMs and BOPs**, and even more importantly, to align the semantics of these different views (usage versus product structure, for example). The **integrated product definition**, combined with the consistent process framework that systems engineering provides, delivers a number of benefits. For example, aligning the business BOM with the bill of design and manufacturing processes provides the ability to virtually validate the product by applying the configuration rules in the business BOM across all engineering domains. Now entire mechatronic systems can be virtually validated in the exact configuration in which they'll be sold. Also, the process for building those saleable different configurations can be validated in the exact ways the different plants will build them. For the first time, companies will be able to virtually validate exactly what they'll produce at a specific plant. This will dramatically reduce the amount of physical validation required while also improving first time quality.

To make intelligently integrated information happen, it is necessary to understand the meaning, or the semantics, of all the information to generate to plan, develop, build and support the product. For example: Systems engineering is getting a lot of visibility today, especially in the discrete industries. The complexity of the products and the dependencies between systems in the product has become so great that companies are looking for ways to deal with it all. One of the things SE does is to help people understand how requirements are allocated to functions => how functions are implemented through the logical architecture. And that is realized in the physical design – across all disciplines – mechanical, electronic and software. Building these systems models inside of PLM captures are important of the meaning and intent about the product. A true semantic model begins to emerge where the way information is related and the context of the relationship itself is valuable and can start to be leveraged. The capability to understand and leverage SE in the tool helps to build intelligently integrated information right into all of the products. Another example is **B**ill **o**f **M**aterial **/B**ill **o**f **P**roduction integration [4]. At this topic the relation/understanding how different BOM's relate to one another, and to build that understanding into the PLM tools. The entire product, process and production lifecycle can be thoroughly planned and analyzed in a systems engineering context. The technology can deliver this intelligently integrated view of product, process and production. By intelligently organizing and integrating systems engineering, providing an integrated definition of the product, and closing the loop between product and production, HD-PLM drives real step-change in product development and production, improving productivity, time to-market, first-time quality and ultimately helping you build the right product, and build it in the right way.

HD-PLM has high value and will resonate with everyone in the PLM landscape. Most PLM professionals make decisions as the primary aspect of their job. Whether it is deciding what material to specify: who to include in a collaborative meeting; or how something was done in the past, PLM data is a repository of what customers need to support their decision-making process [5]. Everyone in the product lifecycle makes decisions appropriate to their work, but too often it is difficult to access the information they need from different disciplines in order to make the best decisions. The technology framework based solutions will personalize the perspective to the users' role to enable decision makers to more quickly access and understand information that used to take hours or even days to assemble and digest. Decisions will then be captured for future reference when similar criteria are encountered by others. The accumulation of best practices and experiential knowledge will enable users to validate that their decisions are the best choice to increase confidence in each decision. The primary purpose of information is to support decision making. The faster an organization can deliver people the right information to make the right decisions, earlier, the more efficient their processes will be - and the lower their risk of product mistakes and costly delays. Providing this level of decision support requires a system that can bring together scattered information from across the product and production lifecycles - from planning and development through manufacturing engineering, onto the factory floor, and even into service and support - and deliver the information in a visual intuitive way [6].

2.2 Future-Proof Architecture

To provide an effective decision-support environment, an architecture must never become obsolete. It must be upgradeable and expandable to permit the introduction of new technologies and innovations. It must easily integrate with other systems because not everything is stored directly in the PLM system. It must change and morph to adapt to the changes in your business. Following core principles must guide in architecting HD-PLM.

Openness - open technology and open information. Open technology means that other companies getting actively support to release, publish and use the used technology (such as JT™, Parasolid®) to help grow in the PLM market. Open technology also means open standards, meaning to accepted standards and, if none exist, work to create standards that improve the entire PLM ecosystem. Open information means that a customer, having implemented tools to manage all aspects of their product and process development, has invested in something that is extremely valuable it must be transparent about what that information is, how it is organized and how they can access it, import to it, or export from it => to give them full and ultimate control over their information. Future PLM architecture:

Open
- Rich API set- SOA, NX Open
- Toolkits / published formats – PLM, XML, SDK, JT, Parasolid

Scalable
- Four-tier architecture
- Transparent adjustment or needs based on demands

Flexible
- Layered platform services
- Codeless customization
- Data model extensibility

Preferred device support - people who need to interact with PLM aren't just sitting at their workstations anymore. New devices such as smart phones, tablet computers and other handheld platforms are becoming the main productivity tool for many. With HD-PLM, field engineers must now visualize a part, mark it up and log issues into the PLM system from a number of different handheld devices. An issue can proceed through a review process while the field engineer is still on site, creating the real possibility for instant analysis and feedback with the customer. Sales personnel could configure a product while the customer views it on a handheld device, even to the point of visualizing configuration changes as he or she makes them.

2.3 High Definition User Experience

The topics regarding the architecture and functionality of HD-PLM are complex. The challenge is to provide a user experience that is not. To accomplish this, the HD-PLM interface must leverages the same intelligence used to deliver precisely tailored information to each user, eliminating many of the administrative tasks required to find, enter and maintain information. To create an HD user experience, four key concepts should be addressed:

- Put the user in right context for his work
- Help the user accomplish his tasks

- Present the information intuitively
- Help the user validate decision rationale

Context and Situational Sensitivity - HD-PLM should know who the user is. It should know what role the user plays and what he worked on last time he were in the system. It should know who the user collaborate with. All of this information, and more, can place the user in the right context every time he or she enters the system, reducing the amount of work he or she must do to get the necessary information on the screen to do work.

Help Users Accomplish Their Task - Web 3.0 introduces the concept of robots or agents to help people navigate their way around tasks and functions. HD-PLM adopt this same concept. Agents in HD-PLM can help the user with a variety of functions. Agents can be active or proactive depending on the type of task the user want to perform them. For **example**, if the user is working on an issue, an agent could enter all of the information required to log the issue in the system, simply through its context and situational sensitivity. Once the information is complete, the agent could then as the user for approval to submit the issue to a specified process.

Present Information Intuitively -Different users interact with information differently. For some users, 3D is how user wants to view information. Others prefer a spreadsheet view. Still others prefer graphs or charts. What "intuitive" means is dependent on the user and the task he's trying to perform. To present information intuitively, it must be in the right format, the right context, and at the right level of granularity. Presenting too much information requires significant work to find what the user want or need. The system should be able to present just the right amount for the task at hand, while giving the user the option to get more detail if required.

Validate against decision **Rationale -** Understanding why the use made a certain decision is critically important for a variety of reasons, including traceability, issue resolution and definition of best practices. The ability to capture the rationale the user used to make any decision – at any point in the product development process – is key to tracing the root cause of problems. It also allows the user to reapply the same rationale to arrive at the same decision, thus forming the basis for a best practice.

2.4 First HD-PLM Implementations

The implementation of HD-PLM technology is being delivered in NX™ and Teamcenter® via the HD 3D environment which includes Visual Reporting capabilities – such as color coding based on search results or 3D flags indicating warnings or rule violations – that provide a deeper, more intuitive understanding about the product to support effective decision-making. The technology framework based solutions also will have a very significant impact on innovation and product competitiveness. Most product innovations are born out of market need and design creativity. By exposing deeper levels of product data to design teams and greatly facilitating its understanding, those teams have more knowledge available to fuel creativity and more time to implement it. The technology framework will help to eliminate decisions with unforeseen impacts on product quality, reliability and product performance. Speed to market is a major benefit gained by faster decision-making at all levels. All phases of process workflows can be streamlined with everyone having rich information personalized to their task. HD-PLM Framework based solutions eliminate wasted time getting to the information needed to perform tasks and makes multi-disciplinary information available sooner to make decisions earlier.

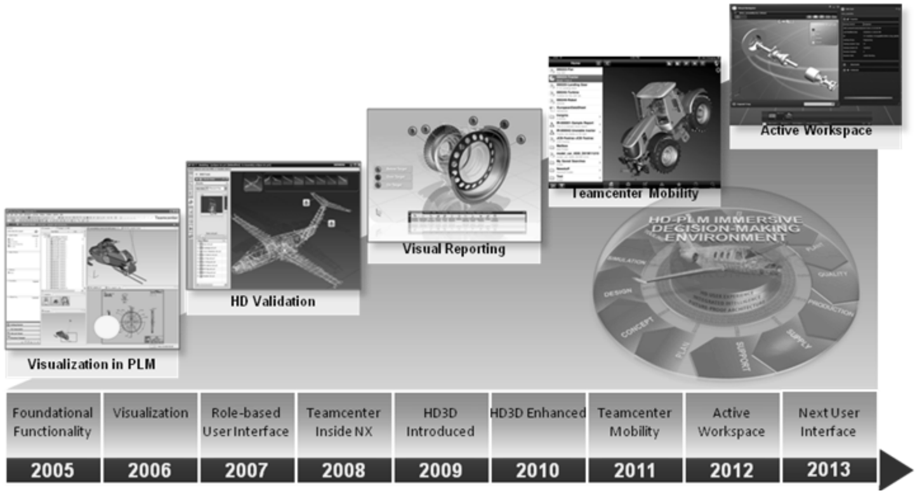

Fig. 2. Continues Improvement in HD-PLM User Interaction

3 Concluding

The question "will complexity sink you, or can you turn it into a competitive advantage?" offers two very real possibilities. The HD-PLM technology vision allows to achieve the latter, thriving in the current environment by turning complexity's challenges into opportunities for customer satisfaction. By providing intelligent information that is there at exactly the right time, in the correct context, and at the precise level of detail that each person needs, can help manufacturers in all industries achieve a new level of productivity and quality. Intelligently integrated information which allows users to manage large volumes of data but only use data in context to make the best decision. It is not the quality or the quantity of, but having the right data at the right time [7]. The HD-PLM vision builds on Siemens PLM Software's experience while expanding on state-of-the-art innovations and leveraging emerging software, hardware and connectivity technology.

The aim of this vision will be to provide a technology foundation to enable a global collaborative product development team to produce a common set of integrated software tools that will identify, capture and collate the massive amount of information available both inside and outside of manufacturing enterprises, and then apply meaning to that data using a consistent, compelling and intuitive visual environment. It is a fundamentally new way to discuss PLM and represents the beginning of a vision and development of a direction for the next several years to result in a continuous flow of innovations in products to support decision-making over the course of the next years.

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Implications of Open Innovation Approaches on Future PLM

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Abstract. Doing business globally causes the increase of very complex and dynamic processes. It demands a high level of flexibility and adaptability from the companies involved. The aim of companies is to find efficient ways in order to produce new products and to better meet customer demands. Open Innovation (OI) approaches contribute to this aim and therefore drive the evolution of future Product Lifecycle Management (PLM). Based on four scenarios, developed using scenario planning method, the implications are shown on different levels of PLM. A catalogue of requirements for PLM 2020 was drawn up on the basis of the results of interdisciplinary panels, qualitative and quantitative interviews, and of a sector-specific use case for the automotive industry. The paper discovers ways in which PLM can be made more successful in future and pinpoint challenges that PLM will have to meet with regard to OI concepts.

Keywords: PLM, Open Innovation, Scenario Planning Method, Data Management, Data Security, Human Factor.

1 Introduction

For manufacturers today, innovation is the engine of growth [1]. In order to produce new products and better meet customer demands, companies i.e. innovate in production, processes and business models. To access a broader creative potential within innovation processes, external knowledge and ideas have to be taken into account. In this sense, the term OI determines new approaches to involve people from outside the borders of the organization in the product innovation process. The key driver here is the Internet which offers access to a vast supply of resources and workforce. It is concretized in a variety of possible forms of organization of the innovation process between companies and the market. However, these relationships do need an overall organizing principle and this is one aspect that PLM intends to be. Directions of potential PLM evolutions and requirements have been in focus of the research project "Future PLM", conducted at VIRTUAL VEHICLE research center in Graz, Austria. At present the term PLM is used in several different ways, and often it is wrongly

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understood as meaning merely an IT system. Its full definition is as an approach for managing a product, including the relevant intellectual property, over its entire life cycle. PLM consists of processes, organizational structures, methods and related IT systems. Used as an overall approach, PLM has the potential to give companies the structure and orientation they need to be profitable under competitive conditions. One particular aspect, which has been considered in the Future PLM project, is the implication of OI on future PLM. Considering OI in PLM, challenges occur in different topics, e.g. acquisition and management of customer feedback data, data security and intellectual property protection, or human factors.

2 Overview of Open Innovation and Research Project FuturePLM

2.1 Open Innovation

Reichwald and Piller [2] distinguish “requirement information” from “solution information” in OI processes. Requirement information is information about the customer and market needs, i.e. information about the preferences, desires, satisfaction factors and buying motives of current and potential customers or users of services. Solution information comprises the information needed to solve specific problems and critical issues in product development and innovation processes. Management of solution information is closely related to crowdsourcing which – as stated before - is not gathering support of corporate functions and structures from the supply chain, but from the intelligence and workforce of a mass of free-time workers on the Internet. Reichwald and Piller state that this is necessary to keep the innovation-process as efficient and effective as needed. Depending on the branch often more than 50% of new developed products are not able to satisfy user-needs [3]. The development-, production-, distribution- and advertisement costs are not justified in this case and are simply gone. Therefore the “how to innovate” is focused to reduce insecurity to market and technology in an early phase of the innovation process. Innovation has to be an iterative process between company and market to use the creativity potentials of external sources. User innovations are often considered to be not radical enough because they are based on other concepts the user already is used to and therefore incremental, but this is disproved by surveys. [2]

A different definition from Henry Chesbrough is to open the company-boarders permanently to gain the necessary potential that is needed to be innovation-leader in a particular market and to gain the chance to emerge in new markets. “OI is a paradigm that assumes that firms can and should use external ideas as well as internal ideas, and internal and external pathways to market, as the firms look to advance their technology. OI combines internal and external ideas into architectures and systems whose requirements are defined by a business model.“ [4] Fig. 1 shows H. Chesbrough’s approach. The illustrations depict the difference between closed- and open innovation:

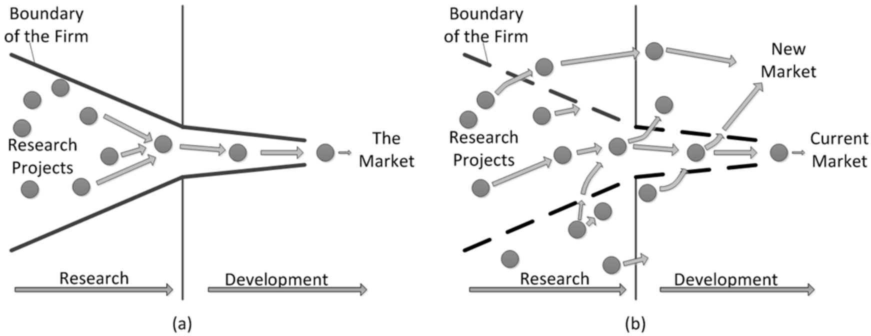

Fig. 1. Closed innovation (a) vs. open innovation (b) [4]

Chesbrough's approach was criticized later by [5] that it does not put enough emphasis on the condition of availability of knowledge. Pénin states that access to an open resource needs not automatically to be free of charge and claims that any positive price for access to intellectual property potentially restricts access. The suggested definition of OI by Pénin must encompass three constitutive elements:

1. Voluntary knowledge disclosure from participants,
2. knowledge being open (which is equivalent to say that "spillovers are not controllable" [6]), and
3. continuous and dynamic interactions among participants.

2.2 Future PLM

Within the research project Future PLM, the Virtual Vehicle Research Center in Graz investigated future demands for product life cycle management in terms of the way it manages roles and participation of people. The project intended to discover ways in which PLM can be made more successful in future and to pinpoint challenges that PLM will have to meet. The results presented here have been worked out on the basis of contributions from all project partners.

First, a common PLM definition had been set up that will be used in the scope of this paper as well: Product Lifecycle Management is seen as a strategic concept used for managing intellectual properties of a product over the entire lifecycle [7]. However, in order to foster a holistic PLM within a company, the improvement of processes and methods is a necessity. Challenges in future product development include:

- Managing the entire lifecycle of a product.
- Collaboration between different disciplines and cultures.
- Globally distributed development locations.
- Integration of customers and suppliers.

Further a catalogue of requirements for PLM 2020 was drawn up on the basis of the results of interdisciplinary panels, four derived future scenarios on product development in 2020, qualitative and quantitative interviews in automotive industry [8]. For a better understanding, the catalogue of requirements is inset in a matrix with specific levels versus topics [9]. In the catalogue of requirements the previously collected ideas and suggested solutions are clarified and documented along with their chain of effects. In this paper the focus is set on matrix intersections with the topic OI.

3 Analyzed Challenges in the Field of Open Innovation and PLM

The next subsections pinpoint some challenges in the field of OI that PLM will have to meet.

3.1 Data Management and Data Security

From the point of view of data which is generated within the innovation process and has to be managed, two major aspects have to be distinguished: marketing and engineering. Marketing data results from customer feedback and customer requirements. Customer feedback can be collected in the usage or Mid of Life (MoL) phase of a product based on the real existing product and customer experiences (usage, maintenance, service). Customer requirements can also be collected based on concepts and virtual products in early phases of the product development process.

Both can be considered as base to define and fix the requirements set for the development of new or refurbishment of existing products. Especially, social media or web 2.0 tools like forums offer a vast supply of different information sources, are developing fast, and can be utilized to collect marketing data but this data has to be analyzed and structured in order to be valuable for the definition of requirements. Another option is to develop special, questionnaire like web tools to collect data at least in a semi structured form or even enhance products with capabilities to return feedback data from usage. Another point of distinction is whether feedback data is collected on a product class in general or a single instance basis (identified product instance) which would require respective PLM enhancements.

On the other hand the crowd sourcing aspect of OI requires handling and exchange of various types of typical engineering data though here are conceptual contradictions between the required structuredness of enterprise information management and the creativity of the OI processes. The main question is how transparency in decision making and evaluation of alternatives in the OI process can be ensured and what enhancement of PLM functionalities have to be provided to suit the demands outside the inner circle of the own organization and even outside the outer circle of business partners such as suppliers or contractors. This is predominantly not a challenge with respect to IT issues since all available IT systems in this area support ubiquitous web technology but essentially with respect to legal aspects (accountability, liability, export restrictions etc.) and organizational aspects (transparency in processes, definition of the granularity of tasks and information to be transferred into the crowd sourcing community, management of the crowd etc.). Resulting data of crowd sourcing processes does not only contribute to requirements but to various tasks of engineering design and product development.

The major issue in the context of data management in crowd sourcing processes is certainly the security issue. The term Intellectual Property Protection (IPP) represents the business objective to protect the know-how of a company as part of a supply chain or engineering network against risk of industrial espionage, patent violation, and plagiarism. IPP also comprises Data Leakage Prevention (DLP), i.e. means to prevent data leakage incidents where sensitive data is disclosed to unauthorized personnel either by malicious intent or inadvertent mistake [10]. To Implement IPP, different so called Enterprise Rights Management (ERM) approaches using encryption technology are available. These control access to corporate documents by selectively granting access to certain portions of the digital content or certain operations [11] and thereby enable companies to extend security to third-party partners, suppliers and customers [12].

ERM is based on identity management (user authentication) and requires a policy server in which rights are defined, an encryption mechanism that controls access to the data, and a software or device that enforces the policy. ERM solutions focus on document exchange security which represents static content, but in typical IT solutions for PLM, content is tied to a business process and dynamically changing, i.e. rights on a document are not only defined by the identity and role of a user but especially by its status or maturity. In multiple party crowd sourcing processes, user identification maintenance of roles with respect to PLM environments will be an intricate task and prone to failure. Main requirements are that protections stay together with document wherever the document travels and the owner remains in full control, i.e. access rights can be modified or revoked at any time. This means that each access to protected documents requires access to a server as independent authority which stores access rights and decryption information and raises questions of organizational aspects for managing identities, defining roles, or classifying data.

3.2 Process

During the last few years, there has been rapid technological development and new possibilities have emerged for collaboration, communication and the management of product lifecycle information and knowledge. Some of the major changes are related to the novel possibilities offered by the emergence and, in the business sense, the maturing of web 2.0 and social media–based approaches (e.g. [13]). Social media integration in PLM has been an important trend of major PLM vendors, allowing e.g. the use and sharing of non-structured and tacit knowledge, which are problematic in traditional PDM and PLM systems. According to Stocker and Tochtermann [14] web 2.0 focusses technologies that enable users to communicate, create content and share it with each other via communities, social networks and virtual worlds - faster and easier than ever before. They emphasize the power of users to select, filter, publish and edit information, as well as to participate in the creation of content in social media [15]. To sum up, web 2.0 and social media provides quite novel and useful ways of interacting and collaborating in the innovation process, as well as for creating new information and knowledge for innovations.

Based on Chesbrough the authors Gassmann and Enkel [16] define three processes to integrate OI into the development process as shown in Fig. 2. The processes are:

- The outside-in process where ideas generated outside the company are used inside,
- the inside-out process where knowledge or products are exploited outside the current market, and
- the coupled-process where outside-in and the inside-out processes are combined.

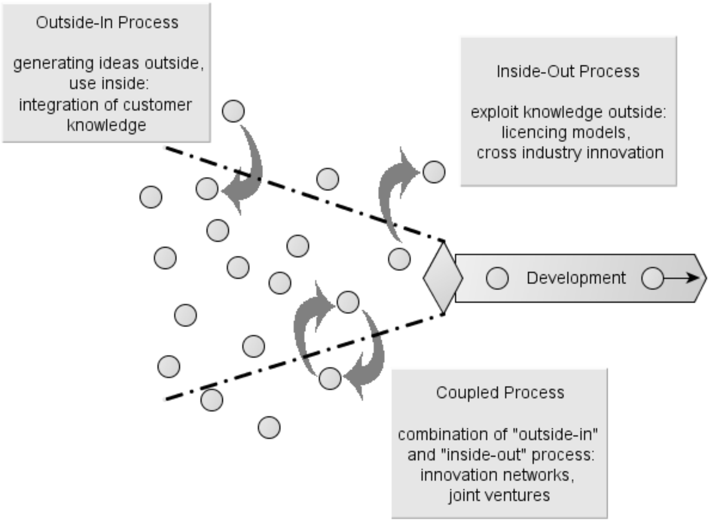

Fig. 2. Core-processes to integrate OI into the development process [16]

Sherhan, Albers and Miller [17] show outside-in and inside-out methods in the automotive industry where German Original Equipment Manufacturers (OEM) and supplier in the automotive industry are surveyed and analyzed. The study also recommended two further steps in the innovation process: An innovation impulse step for managing internal and external innovation inputs and an innovation transfer step to maximize the benefit in R&D productivity [17].

3.3 Human Factor

According to Golas [18] a company in its environment represents an open and targeted social system. Humans in the field of automotive industry are working in complex socio-technical systems. No matter how much technically dominated this operational environment is – the creative, social and individual facets of people remain very important. Working in complex systems is on the one hand characterized by routines and on the other hand by exceptional situations or crises. These situations require e.g. that people make decisions under time pressure and high risk or find new innovative solutions within very limited time. Therefore people are the highest potential in a company and have to get major support in communication and collaboration to achieve the corporate goals. They need the best possible support by a suitable environment - a well-balanced system between human factors, organization and technology [19]. In the workplace of the future access to information and technology-related knowledge will be much more open and flexible. This simultaneously increases the available range of information. In response, employees are increasingly moving into information flows and create independent and self-organized individual information as well as their own system environment. The transparency of knowledge and knowledge holders will continually rise in companies. For practitioners, it is often more important to identify the relevant knowledge holders in the companies than the explicit knowledge itself. [19]

A typical pitfall which has been observed in projects is the NIH syndrome (not invented here) coming from the co-workers within a company. A solution which was not developed inside of internal R&D is often not considered trustful and is different from solutions of the company. This often results in resistance from the people who are working for this company [20].

4 Identified Requirements for Open Innovation in PLM 2020

The perspectives of the scenarios, the statements of the experts and the analyzed challenges in the field of PLM are combined to perform a requirements catalogue for future PLM. The requirements catalogue is divided into five classes which are product, human, organization, process, and IT, taking into account that single requirements can be in one, some or all classes.

- Product: relationship between overall product and product parts (customer wish - product requirements, complexity).
- Humans/team: individuals and their relationships (team), common understanding of mission, associations and threads.
- Organization: cross-domain and global communication and collaboration
- Process: interaction of total product development process and sub-processes, transdisciplinarity.
- IT: new technology and methods for new information and communication tools (e.g. Web 2.0).

As a research result the relations of all 317 requirements and classes are shown. This paper deals with the catalogue entries that include the topic of OI. Some of them are described in detail below. At each headline, the assignment of classes is listed in parentheses.

4.1 Strong Cooperation across Domains (Human, Organization, Process, IT)

OI processes are benefited in the case that employees are independent because it forces them to contact companies and communities to share knowledge with people from different areas of interests. OI can be seen as integration of customer-knowledge into the existing one. Customers all over the world are able to take part in creation or improvement of the products. Requirements to PLM 2020 are particularly: Support interaction with the customers in the product development process; integration of analytical tools; integration of alternative procurement strategies.

4.2 Virtual Work of the Company (Human, Organization, IT)

Virtual work is one of the key trends of the future. Due to "cloud" technology, fast internet-based information exchange as well as communication channels for interaction between customers, employees and all participants of the supply chain in a product development process will become an essential part. Problems can be published to a community which provides recommendations for the problems and additionally makes changes and edits solutions. Information synchronization as a key concept of cloud technology forces interactivity and interdisciplinary working what leads to radical innovations. Creating social networks inside a company will help to share information between different departments, discuss tasks and solutions online with the required personal of the company. Trust between employees will increase.

4.3 Communication in Product Development (Product, Human, Organization, Process, IT)

Customers can take direct participation in the development of the products. All comments of the customers have to be implemented or at least labeled to be considered. Language and cultural barriers have to be solved. Power and quickness of the product development depends on the interaction between employees and customers. Quick review of the development process allows a faster development in general. The communication between two or more participants has to be structured.

4.4 Workstation of the Future (Human, Organization, IT)

Due to increasing mobility each employee needs external access to working data. Specialists in small areas of interest will be available on demand and work for one or more companies, assisted by virtual assistants. The product service system is intersected with OI as well when the customers give their feedback using different possibilities. One of them is to classify the product in a simple way, e.g. mechanisms as the "like" button on "Facebook".

5 Discussion

OI in the automotive industry is no longer an empty phrase. Sheran, Albers and Miller [17] state that in the next 10 years the way of creating and profiting from innovation will change completely in the automotive industry. They also delineate that OI is a phenomenon that has become increasingly important over the last few years in the automotive industry [17]. Gassmann [16] argues that some trends like globalization, new technologies, or new business models will foster OI concepts in industry. Gassmann´s arguments recover most of the aspects in the scenarios which were developed in the FuturePLM project, especially the mega trend globalization described in the scenario “Globalization Extreme!” [7].

The scenario “People take center stages” is formed upon the following assumptions: (1) Recognition of importance of employees (2) Mutual trust within companies increases acceptance and understanding of PLM due to deployment of new technologies, processes and organization forms (3) High cultural diversity in companies (4) Deep PLM integration, and (5) Flexible infrastructure and working conditions in complex business environments [7]. In this regard, people working from diverse locations can use social software such as wikis and blogs [13] as a modern way of disseminating information and knowledge within the company and out of company, which creates a simple form of community. Contained in the general assumption that the way companies are organized will change dramatically in future is the implication that the definition of workplaces and working time models will change as well [19]. All shifts recommended above will require equivalent changes in PLM implementation models, which will affect how goals are defined, how the system is introduced and how it is used [8].

6 Conclusion and Outlook

Being able to innovate is the key factor of success for companies in high tech branches. OI on the one hand side means customer integration rather than customer orientation. On the other hand side, OI approaches leverage the work force and creativity of the mass of smart and talented people from all around to enable new ways of idea generation to solve product development problems. Since our society heavily depends on innovative products, the new approaches of innovation processes have to be implemented in companies and have to be supported adequately by means such as PLM.

PLM is a concept of how to manage a product in terms of people, workplace and organization. The main driver will be the evolution of the concepts of employees as part of the value creation process and the growing importance of individual human potentials. To manage this successfully, a wide-ranging dialogue with the people affected will be necessary. A new culture of how information is shared needs to be developed. The technological systems development must follow the developing needs of the people and create solutions which meet the needs of both users and tasks in such a way that people can use them with enthusiasm.

The combination of concepts in the field of OI and PLM needs to change the adjustment of the company with regards of openness. New methods in research and development phases should afford an opportunity to look outside of company boundaries.

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Challenges of Model-Based Systems Engineering: A Study towards Unified Term Understanding and the State of Usage of SysML

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Abstract. Model-Based Systems Engineering is on everyone's lips as innovative approach to overcome traditional, error-prone document-based product development. The Systems Modeling Language (SysML) is the most popular tool for model-based development of multidisciplinary systems. Several research works and industrial pilot projects have applied the OMG-standardized language in the last years, but it has still not become widely accepted. Previous experiences of the authors from several research projects with industry underline this statement and have shown that engineers still have trouble in applying SysML. This paper investigates possible reasons for this issue and presents results of a survey regarding term understanding of engineers as well as acceptance of SysML.

Keywords: Term understanding, Common Engineering Language, SysML, Systems Modeling Language, Acceptance.

1 Model-Based Systems Engineering – Potentials and Challenges

Model-Based Systems Engineering (MBSE) is on everyone's lips as an innovative approach to overcome traditional, error-prone, document-based product development. The advantages of using formal models to specify a complex technical system are manifold: fewer inconsistencies, less redundancies and concurrently the basis for clear communication and sustainable documentation. Furthermore, models can help to force systemic thinking, which is often expressed as holistic and function-based thinking [1]. Over the last years, several modeling languages and approaches have been presented. They all promised to enable their users to model multidisciplinary and complex technical systems. The most popular modeling language is SysML, which is based on UML, a widely accepted, object-oriented graphical software modeling language. Observations of the authors have shown that software engineers and electronics engineers cope well with the provided diagrams for modeling several system aspects like structures, sequences or states. Emerging graphical modeling languages for embedded systems like MARTE, AUTOSAR or EAST-ADL using similar

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principles and technologies like the meta-modeling standard MOF (Meta Object Facility) seem to underline this observation. On the contrary, mechanical engineers have much more trouble dealing with such kind of modeling languages. A possible reason is that technical terminologies between disciplines differ significantly. Furthermore, there is a huge leap of abstraction from concrete discipline-specific models to abstract multi-disciplinary system models. An online survey presented in this paper was conducted in order to identify the understanding of some crucial terms in the field of MBSE and to determine the state of application of SysML. The survey was sent to selected engineers from different disciplines in industry and academia in Germany, who are familiar with Systems Engineering (i.e. members of the German Chapter of INCOSE, the GfSE). Knowing that the answers will not be representative for all engineers, it was rather intended to provide an indication about term understanding and SysML application among "Systems Engineers" as spearheads in establishing MBSE in academia and industry. 50 responses (23 from academia, 27 from industry) were evaluated. Before presenting findings from this survey, the next chapter will give an overview of adjacent research efforts and their results.

2 State of Research

Several studies and academic or industrial pilot projects aimed to gain insights about the applicability of MBSE methods and tools. The ProSTEP iViP society conducted a survey in cooperation with the Fraunhofer IPK called "PEP2015 – Challenges in modern Product Engineering Processes", which evaluated needs and visions of industry and tool vendors in terms of Systems Engineering [2]. The results showed that Systems Engineering methods are applied only occasionally within software engineering and electrics/electronics engineering. Discipline-specific tools are well-established; transdisciplinary system architecture interaction is still an unsolved issue in industrial practice. Bone and Cloutier determined from another study that especially large companies are widely aware of the benefit of MBSE and increasingly adopt corresponding programs and projects [3]. Their focus is set on architecture modeling, requirements traceability and conceptual design of products. Thus, the value for software and systems engineers is much more obvious than for hardware engineers or managers. Existing organizational structures are frequently not compatible with transdisciplinary systems engineering [1], which can be substantiated by missing methodologies for the application of existing standards or modeling languages. Therefore, Estefan conducted a survey on the most prominent MBSE methodologies in 2008, aiming to mainstream them in industrial application [4]. None of those methodologies has significantly established over the last years after this survey. Kasser discusses seven myths of Systems Engineering, due to persistent discussions about possible reasons for the lacking acceptance and application in industrial product engineering [5]. He found out, that there is neither a single broad agreement upon systems engineering processes nor on the adequate application of tools and methods to handle system complexity.

Several pilot projects have taken place in order to determine best practices or to evaluate first applications of MBSE tools and methods. Friedenthal presented several findings from the application of SysML [6]. He stated that MBSE is a cultural change and requires well-defined methodologies and handling them requires training in language, methods and tools. Karban et al. state challenges in using SysML, which have been figured out in the APE (Active Phasing Experiment) project of the SE^2 challenge team of the GfSE [7]. They propose several tasks for the advancement of SysML, which underlines that the language is still under development and will be further advanced in the future.

Other research efforts deal with the definition and understanding of frequently used terms in engineering disciplines. An example for such a term is “function”, which is for instance understood in software engineering as a piece of software code that processes input information towards a certain output. Mechanical engineers on the contrary have different connotations for “function”: it can either describe, what a system to develop is intended to do or what a system solution actually does. Moreover, a function is often distinguished between a desired function and an undesirable one. Others would name an undesired function an appearing phenomenon, an effect or a behavior. Several efforts have addressed the understanding of terms, so has Eckert et al. [8] for instance investigated the different notions of the previously mentioned example “function” in engineering design. They identified the 5-key-concept of Vermaas as the most valuable, but also differentiating definition of this term, meeting most of the previously mentioned examples [9]. Vermaas concludes that different meanings are required in different situations instead of pursuing a single definition of “function” through emphasizing that different meanings are in fact necessary to describe devices in engineering design.

Literature review has shown that the challenges in application of MBSE are manifold and leads to the awareness, that the “cultural change” from traditional document-based towards a model-based development approach has still not taken place. The aim of this paper is to identify the cause for this issue and to point out fundamental actions to be taken in order to advance MBSE tools and methods.

3 Motivation for Further Research

MBSE aims to improve communication and collaboration between engineers from different disciplines and management. Communicating efficiently means to easily gain the desired information, provided in a comprehensible and coherent manner, which is one basic goal of MBSE. Unified term understanding is crucial for establishing a coherent, formal and coincidentally intelligible modeling language for multidisciplinary systems. Considering all relevant terms and every specialized discipline would either lead to a very generic solution like SysML or to a very extensive set of specific languages. Even if the idea to apply a common language for all involved individuals is promising, none of the existing approaches has established in industrial development yet. Possible reasons are a persistent lack of common term understanding or insufficient information representation within existing modeling languages.

The approach at hand concentrates on engineers, who are familiar with Systems Engineering paradigms or concerned with Systems Engineering research. They form the basis for the harmonization of term understanding and establishing a common language in industrial product development. The aim of the survey conducted by the authors of this paper is to answer two research questions:

- What is the understanding of the basic terms "function", "behavior" and "impact chain" among Systems Engineers?
- To what extent is SysML applied, what is the perception of the added value of SysML for the daily work today and where is improvement potential?

The results of this survey shall help to harmonize term understanding by clustering consistent statements and complement previously identified definitions. Furthermore, the demand for certain modeling aspects shall be identified and the suitability of provided diagrams in SysML for describing those aspects shall be evaluated. The long-term goal of this ongoing research work is to advance MBSE languages and coevally according modeling approaches.

4 An Approach towards a Unified Term Understanding

The presented data in this chapter result from a survey, conducted among German and Austrian Systems Engineers from academia and industry. Altogether, 50 responses (23 from academia, 27 from industry) have been evaluated. The academic participants are PhD-students (14 out of 23), students or postdoctoral researchers. The industrial participants range from development engineers over trainers and consultants to product-, project- and department-managers. The spectrum of the participants' expertise is shown in Fig. 1.

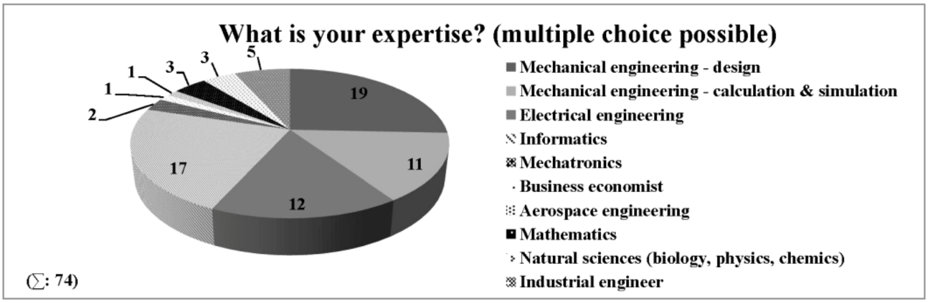

Fig. 1. Range of expertise of survey participants

The participating Systems Engineers have expertise is numerous disciplines, which helps to gain information from diverse viewpoints. However, this survey is not intended to meet representative statements with statistical evidence, but rather to point out tendencies and to collect statements from experts. The survey was divided into two sections: the first section asked for the personal understanding or definition of the three terms "function", "behavior" and "impact chain". The answers regarding term understanding were given as free statements, whereas every participant could state multiple answers per definition (i.e. to subdivide the definitions into multiple aspects). Altogether, the participants posed 78 statements for “function”, 70 for “behavior” and 58 for “impact chain”. The answers were characterized by a high degree of diversity. In the following, frequently made contradictory statements are contrasted:

Table 1. Contrasting pairs of statements towards the term “function“

Functions describe the purpose of a system	Functions realize functional requirements
Functions describe the role of persons in a company	Functions describe the transformation of matter/energy/information inputs into according outputs
Functions are solution-neutral	Functions are solution-afflicted
Functions are abstract specifications of transformations	Functions can be described in mathematical terms
Functions describe an active behavior	Function are an interaction of components to achieve a certain behavior

Concluding, the interpretation of the term “function” is very heterogeneous, even among Systems Engineers. The next question asked for the definition of “behavior” with explicit distinction to “function”. Behavior is often associated with the performance of functions, but beyond that the survey identified a very diverse understanding of this term. Many statements differentiate between static functions and dynamic behavior, regarding the latter as a time-dependent aspect. Where functions only define the desired behavior, the description of behavior itself can also comprise misconduct (i.e. system crash) or undesired functions (i.e. noise emission). Behavior is often seen as system reaction towards environmental input stimuli under certain boundary conditions and (measureable) characteristics, which are differentiated between discrete (i.e. the event “press button”) and continuous (i.e. transmit torque). Unfortunately, the opinions occasionally interfere with others and there is a lack of common understanding. For instance, one participant stated that functions are perceivable, another attributes this to behavior. Several statements contradict others regarding the question whether “behavior” describes the external view and “function” the internal view on a system or vice versa. Some participants confine behavior on the transition between system states, others acknowledge behavior to be component-afflicted; still others attest behavior to be uncontrollable. Concluding, the statements were highly diverse, but none of them embraced all mentioned aspects, which indicates a lack of unified understanding of behavior. Some statements told behavior to be a “chain of functions”. Where functions are often modeled as tree structures or using logical control flows and the input-processing-output-principle for object flows, “impact chains” intend to represent a certain sequence of functions. The resulting statements regarding the understanding of “impact chain” are discussed in the next paragraph.

In contrast to “function” and “behavior”, this term was not known to every participant. Two of them wrote that they had never heard this term before. The majority of the statements define an impact chain as a chain of functions, where input values of a function are the output values of the previous function. Some participants regarded these chains as high-level linking of systems, others as the internal progress of activities within a function which results in a system behavior. Some statements again contrasted: they described impact chains as synonym to traceability from requirements over functions towards implementation and test. Impact chains and active structure sound similar in German language (“Wirkketten” and “Wirkstrukturen”), but are fundamentally different. Impact chains deal with functions, active structures or working structures with components. The appearance of several terms in different meanings can lead to communication being confusing. This is why the next paragraph presents a graphical proposal (Fig. 2), illustrating semantic contexts of the important and frequently reoccurring term “function”. The goal of this graphical representation is to harmonize the understanding of semantic coherences between frequently reoccurring terms in Systems Engineering. The depicted aspects embrace literature research as well as own experiences made in several development projects.

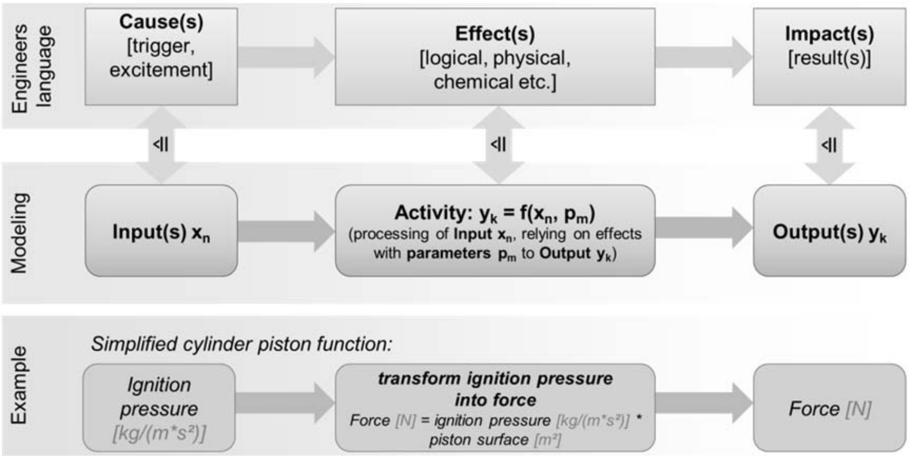

Fig. 2. Proposal for semantic context of “function”

The definition of function at hand embraces the approach to regard a function as an activity, which processes input values (information, energy, material) to output values. An input equals a cause in terms of triggering (discrete, i.e. “button pressed”) or exciting (continuous, i.e. “torque flows”) a function by certain input values. The processing of the input values in activities relies on logical (software), physical or chemical (mechanical and electrical systems) effects, which can be specified by equations, presuming a comprehensive knowledge about the system. The output flows have an impact on other functions (they can trigger or excite other functions) or result in perceivable phenomena (i.e. forces, noise or fields). Additionally, function-relevant physical parameters are factored into the processing of flows. Therefore, from the viewpoint of the authors, functions are not completely solution-neutral, but they are also not component-afflicted. The important awareness is to consider relevant properties for feasibility of functions, but not to anticipate an entire solution (i.e. component). This is one of the basic principles of the Contact & Channel – Approach (C&C²-A) for the integrated analysis and synthesis of functions and form of technical systems [10]. The graphical representation at hand was part of deriving and formalizing extending aspects for a SysML-profile in order to better meet the requirements of engineering designers towards application of MBSE [11], [12]. The simple example in Fig. 2 intends to make these theoretical coherences more tangible. A similar graphical representation was presented to the survey participants subsequently to the questions regarding term definitions in order not to influence or even to distort the respective statements. The participants were asked to rate the applicability of five statements concerning the presented figure. The results are depicted in Fig. 3 and discussed subsequently.

Statement in survey to rate:	**well applicable**	**partly applicable**	**not applicable**	**no rating**
A cause is an input and coincidentally the trigger of a processing activity.	68%	12%	8%	12%
An effect relies on mathematical, physical or logical principles and can be expressed in equations.	50%	38%	4%	8%
An impact is the result or the output of a processing activity.	76%	12%	4%	8%
A processing applies property parameters of the performing component (i.e. cylinder surface).	62%	28%	0%	10%
The description of a function comprises input -> processing -> output as well as applied property parameters of the performing component.	62%	22%	4%	12%

Fig. 3. Comprehensibility of semantic context of function

All aspects were predominantly rated as well applicable. The participants had the opportunity to make announcements or proposals for improvement of the graphic contents. Conspicuous is the second aspect, which is well comprehensible on a very deep level of detail, where mostly a few or even one equation can express this effect. However, several participants remarked that this would cause high effort on the one hand and using equations will not be possible or suffice on low levels of detail on the other hand. Therefore, the level of accuracy should be limited to the necessary minimum for the applied context. Considering this condition, a kind of relation should always be possible to be specified between input and output. For instance, the highly complex system “combustion engine” could be sufficiently modeled by a characteristic map only using load and engine speed as input values and engine torque as output value, depending on the modeling purpose. Furthermore, the first statement (cf. Fig. 3) was criticized, because not every input triggers an activity. This statement has therefore been rephrased to “processing activities are triggered or excited by one or more certain inputs”. The schematic graphic only shows one input, which is transferred into one output. The meaning behind is not that stringent: an activity can have multiple inputs and multiple outputs. Moreover, the processing of the inputs may be conducted in a variety of ways, depending on the characteristics of the input values, which will become comprehensible through further decomposition of the activity. One participant stated that processing does not only apply parameters of the performing component, but also from adjacent systems.

Concluding, the term definitions as well as the remarks contributed to the advancements of the definition of a common language and associated semantic connections. The identified inaccuracies have meanwhile been revised in the specification. The common language forms the basis for the definition of a model implementation in SysML using extending profiles. Therefore, the application of SysML as a leading MBSE tool was assessed as well, combined with the identification of relevant modeling aspects for engineering tasks as well as improvement potential regarding SysML. The results are presented in the next chapter.

5 Application State of SysML and Current Advancement Issues

Firstly, the participants were asked to rate their own SysML experience. Only two out of 50 responses had no SysML experience and have therefore not answered the questions concerning SysML. 7 participants claim their selves as SysML experts, 5 as advanced modelers and 19 as modelers with basic experience. The remaining 16 participants have no modeling experience, but know SysML diagrams from literature.

Regarding application of the provided diagram types of SysML, the participants were asked to evaluate their particular benefit in representing the desired information of a modeled system. The results are illustrated in Fig. 4. The most frequently applied diagram type is the Internal Block Diagram for modeling internal system structures. Its benefit was rated as "crucial" by 40% of all participants. The benefit of Activity Diagrams was also rated as "crucial" by 40% at a little less application ratio. The most unknown diagram type is the Constraints Diagram, which is intended to represent constraints between model entities like parameters or requirements, merely 48% know this diagram type and only 4% rate its benefit as "crucial".

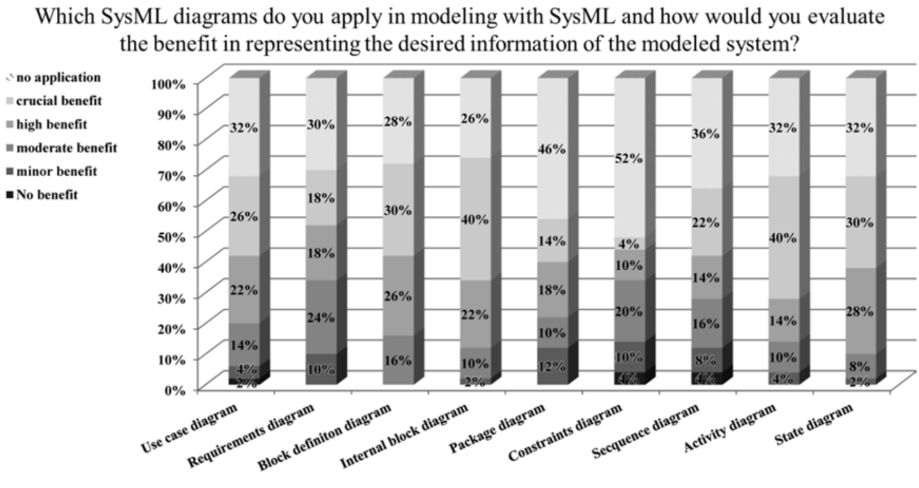

Fig. 4. Benefit of SysML diagrams for representation of particular modeling aspects

The next question demanded for the added value of SysML for modeling major tasks of discipline-crossing systems. In contrast to the provided diagram types, functional modeling has the most added value for users, which could indeed be conducted by IBD's, but would presume to apply according methods like the FAS-method (Functional Architectures for Systems, cf. [13], [14]), which applies this diagram type for enabling an additional view (containing functional blocks) in order to overcome the gap between solution-neutral modeling of activities and flows and the performing (physical) structure with interfaces in IBD's.

The following question asked for the importance of the previously mentioned aspects towards their general importance for the participant's work tasks. The comparison points out that the added value of SysML fits the user's need pretty well, but the results have shown that modeling of a system is much more demanded than data exchange between tools. Finally, the users had the opportunity to remark improvement potential regarding SysML in order to facilitate broader application of the modeling language in academic and industrial product engineering. 24 more or less detailed remarks were stated. Half of the participants remarked that not SysML itself should be improved, but rather the provided modeling tools, especially regarding usability (i.e. navigation through models, support of special views like matrices or special diagrams, handling etc.). Furthermore, six participants remarked missing modeling methods or guidelines and a high learning effort, five users missed particular aspects (i.e. decision tables, chances and risks). Insufficient Model2Model-transformation-support and variant modeling was also mentioned multiple times.

6 Conclusion and Outlook

The paper at hand has clarified that term understanding even among Systems Engineers in academia and industry is still very heterogeneous, but features tendencies towards corresponding aspects. This enables the opportunity to harmonize the understanding of basic terms like function and behavior in order to provide a basis to formalize those terms within modeling languages with according entities, attributes and relations. A graphical representation has been presented to the survey participants, which encountered predominantly positive responses. Hence, a formal specification of modeling elements can be derived incorporating minor advancements. Furthermore, the survey results have shown that SysML seems to be an adequate modeling language to cope with important modeling aspects supporting daily engineering work. Nevertheless, several advancements of SysML and in particular the modeling tools are still necessary in order to enable a wide application of Model-Based Systems Engineering in product development processes. Therefore, the IPEK conducts continuing high efforts in development of new, extending modeling aspects realizing the needs of product designers and managers (i.e. [11], [12]). Furthermore, a SysML extension for function-based modeling with derivation of dynamic structures through further implementation of the paradigms of the Contact & Channel – Approach (C&C²-A) [10] is under development in order to obtain better acceptance among model users [15]. The long-term goal is to achieve more human-centered MBSE tools and methods.

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Model Based Design with Systems Engineering Based on RFLP Using V6

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Abstract. Today, coping with the different workflows, methods and tools of this inter-disciplinary approach to product development throughout a product's life-cycle is the key challenge for a company. There is evidently a need for requirements engineering and management, as well as model-based design and engineering. More specifically, however, what is required is a unique and integrated methodology for requirements engineering and management, functional and logical design, as well as physical design in different domains for the multi-disciplinary development process based on a Systems Engineering approach early in the design process. In this paper, the RFLP approach (Requirements – Functional – Logical – Physical) will be presented as the baseline for model-based design with Systems Engineering that enable close interaction and collaboration between the different engineering disciplines render resources and processes more efficient, enhance quality, and ensure that the target system ultimately meets the requirements, while reducing design cycle time and engineering lead time.

Keywords: Systems Engineering, RFLP, Requirements Engineering and Management, Functional & Logical Design, Mechanical Design, V6.

1 Introduction

In recent times, the term Systems Engineering has increasingly cropped up in the context of developing, testing and validating technical systems [1-3]. The "Gesellschaft für Systems Engineering" (GfSE) describes it as a comprehensive engineering activity necessary for the development of complex products [4]. Besides the traditional fields of application (the aerospace industry), the method is becoming increasingly important in other areas such as the automobile industry and medical technology. Here, Systems Engineering serves as a construct for solving complex problems at system level. This procedural model incorporates methods, procedures and resources for developing and implementing technically complex systems, from requirements definition, system analysis and system development all the way to integration of the finished system. Systems Engineering focuses on the process of problem solving, which comprises the two components of system design and project management; its fundamental criterion is "systems thinking". Hierarchization, in other words the

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process of moving from the general to the particular, is just as fundamental a feature as the application and creation of models as structuring aids [5]. The model-based abstracting of complex systems often enables the latter to be broken down into their component parts and the minimized complexity of the real system to be depicted [6]. Emerging from this development, the systems thinking approach has taken center stage in product development with the intention of producing innovative and globally competitive products that meet customer requirements in full [7]. Thanks to the multitude of disciplines (mechanics, electrics/electronics, software) involved in today's innovative products in particular, a command of Systems Engineering is increasingly becoming a genuine competitive advantage for companies which develop and manufacture products. For example, implementing a competitive system for developing mechatronic products would be difficult to achieve with any degree of success without first introducing a method of Systems Engineering and model-based development techniques. It is for this reason that VDI Guideline 2206 was modeled on the Systems Engineering methodology with the aim of ensuring methodical support for the cross-domain development of mechatronic systems while proposing an end-to-end development environment for mechatronic systems [8].

2 The RFLP Approach

When it comes to designing and developing complex, multi-disciplinary products, it is essential that the manifold customer requirements, system functions and operating principles of the various disciplines are described and integrated within a common product model. In virtual product development, the various disciplines such as mechanical engineering, electrical/electronic engineering and information technology have access to specific methods and CAx systems which, as a rule, are employed only at certain stages of the product development cycle (e.g. in design, computation and simulation). For this reason, integrated development environments are needed to maintain a holistic view and provide end-to-end support for all systems [9].

2.1 The Systems Engineering Procedural Model

In mechatronic product development, Systems Engineering is divided into three main phases: system analysis, system development and system integration. In system analysis, the product being developed is described theoretically in the worksteps requirements definition, functional analysis, logical architecture design and component specification, and specified further via the resulting product models. The system development phase creates product development data (including e.g. 3D CAD models, behavior models). In the system integration phase, the developed components are simulated and tested, integrated in the system, and subjected to continuous verification and validation. In Figure 1, the so-called V model is used to illustrate this procedure.

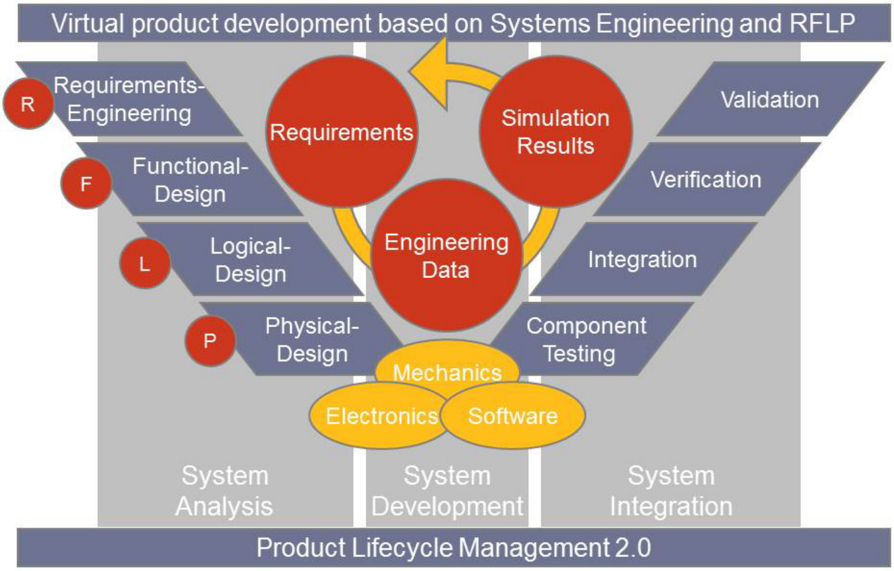

Fig. 1. Virtual product development based on Systems Engineering and RFLP

2.2 General Description of the RFLP Approach

Previous IT systems used in product development offered only limited support of Systems Engineering methods and data of the kind detailed e.g. in ISO Standard 10303 AP 233 "Systems Engineering". This was due to the absence of an integrated information model spanning all product development phases and disciplines, and because many of the IT tools used were geared to specific application areas and consequently were unable to be integrated adequately [9]. For the first time, the so-called RFLP approach for developing mechatronic products could succeed in providing the called-for holistic support for design and development projects based on Systems Engineering . The acronym RFLP stands for Requirements engineering, Functional design, Logical design and Physical design (the 3D CAD model), and describes the process of systematic product development from system analysis to system development, comprising the descending branch of the aforementioned V model based on VDI Guideline 2206 "Development methodology for mechatronic systems" (VDI2206).

The RFLP approach was first implemented as a basis for Systems Engineering in the conventional V6 PLM environment of Dassault Systemes. This approach was tested with the ENOVIA and CATIA systems, taking this solution as an example. Figure 1 shows the artifacts R-F-L-P, along with the development phases system analysis, system development and system integration as supported by the CATIA V6 CAx system and the PLM platform ENOVIA V6 for Systems Engineering.

2.3 Requirements Engineering and Management

The first phase of the RFLP approach is called requirements engineering and comprises requirements engineering and management of all specified requirements. In line with VDI Guidelines 2206 and 2221, client requirements with regard to the product in question are recorded and managed [8, 10]. First, a requirements model is created in the V6 environment in close synchronicity with ENOVIA V6. The requirements can be imported directly into ENOVIA from Microsoft Word, for example. Once in the ENOVIA environment, the requirements are managed and made simultaneously available to the CATIA CAx platform based on the V6 integrated information model. Any changes to these specifications are automatically synchronized between system components and are therefore always up-to-date and globally available within the V6 environment. Figure 2 demonstrates the support of and interaction between Word, ENOVIA V6 and CATIA V6 systems during requirements engineering.

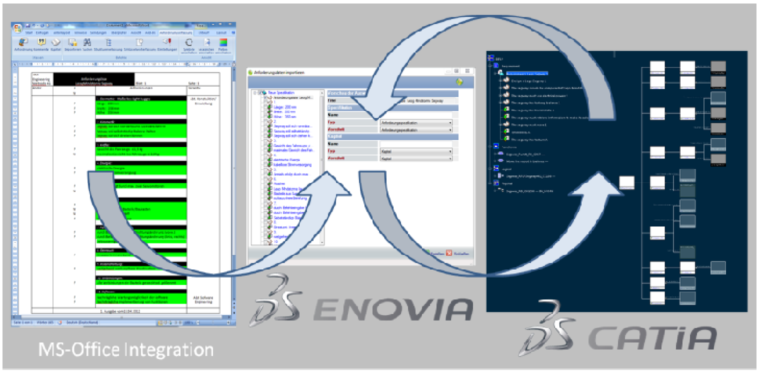

Fig. 2. Requirements engineering and management using Word, ENOVIA and CATIA systems

2.4 Functional Design

At the Functional design stage, the VPM Functional Logical Editor workbench is used to link the requirements structure to the functional structure and the logical system structure. The main and sub-functions, and the logical components of the system can be displayed and structured graphically. The functions are derived from requirements in terms of specification and design, and thus expand the requirements model. The main and sub-functions form a basic framework with which to create a functional structure, whereby sub-functions are linked to form main or general functions. A sub-function (or part function) is a transaction broken down into its individual elements; in CATIA V6, these are represented in blocks. Links between individual functions can comprise one of two types: according to engineering design [11], "data flow" connections are defined as a flow of energy, materials or signals. In addition, "control flow" connections can be modeled as so-called activation flows.

2.5 Logical Design

By integrating the *Dymola* IT solution in CATIA V6, it is possible to create the logical model and then generate a dynamic behavior description using the open Modelica modeling language. Model-based design first involves defining a logical system model as a 2D graph in CATIA V6, connecting the relationships between the various components used. On this basis, an architecture concept is created for the system that describes operating principles as solutions for the defined logical components. With the aid of what is known as *Dynamic Behavior Modeling* in V6, a specific system behavior modeled with Modelica is stored for each logical component, thus gradually forming a complete, simulation-ready system. Figure 3 shows a sample logical model resulting from behavior modeling in V6.

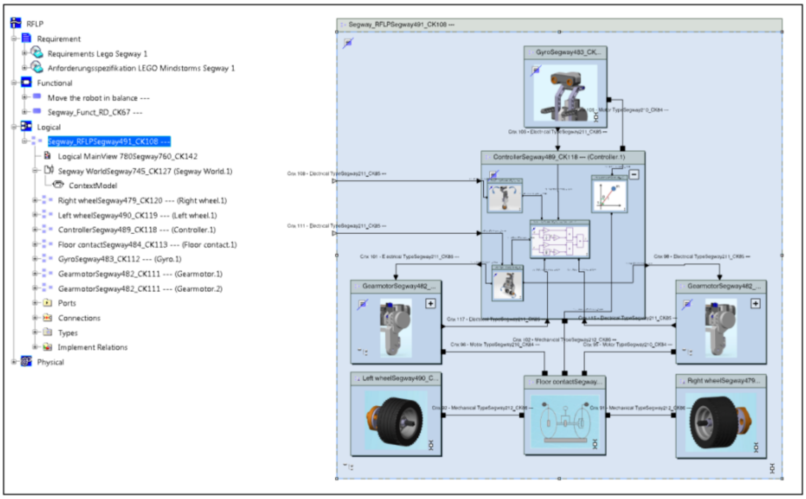

Fig. 3. Functional design and schematic diagram for electronic scales

2.6 Physical Design

With RFLP-based design and development, full simulation of a virtual prototype is facilitated with the aid of a 3D CAD design model (*Physical* view). To this end, a 3D CAD model is created using the design tools already available in CATIA V5. The 3D parts and assemblies generated via the CATIA/Modelica integration process are now incorporated into the Dymola simulation environment, where they supplement the logical model – now equipped with the behavior description – with the physical characteristics set out in the 3D CAD model. Thus, alterations made to the CAD model directly affect the simulation model and are fully linked to the logical system behavior description in the integrated information model.

2.7 Sample Application for Evaluating the RFLP Approach in V6

The RFLP approach in V6 was evaluated using the example of a LEGO Mindstorm NXT 2.0 robot, and this is discussed below. Modeled on a Segway personal transporter, the robot in question was a two-wheeled, single-axle, electrically driven vehicle, able to maintain balance during forward motion with the aid of an electronic drive control. Management of the robot's forward motion and rotation about its own axis for the purpose of turning right or left was by remote control. A LEGO Mindstorm NXT 2.0 kit comprising two servo-motors with integrated rotary sensor, a gyro sensor for determining position, data communication lines and a set of LEGO modules were available to build the robot. The behavior of the NXT robot with CATIA V6 system was modeled, simulated and optimized, starting with an analysis of the requirements and creation of a requirements list, followed by the design of the functional structure and system architecture.

A list of requirements for the sample application was compiled in MS Word, so that it could be imported into ENOVIA V6 using Microsoft Office Requirements Management Integration. For this purpose, certain passages in the requirements list were defined as *requirements*, *comments* or *chapters* and marked in color in the document. It was possible to configure these definitions individually during the import process. In this step, the list of requirements was declared e.g. as a set of system requirement specifications, and a distinction drawn between client/user requirements, and functional/non-functional requirements. On completion of the import process, the requirements specifications have been integrated into the ENOVIA platform and are depicted both as a requirements model in the RFLP structure tree (*Requirements* view) and in the form of a 2D graph in CATIA V6 systems (see Figure 4).

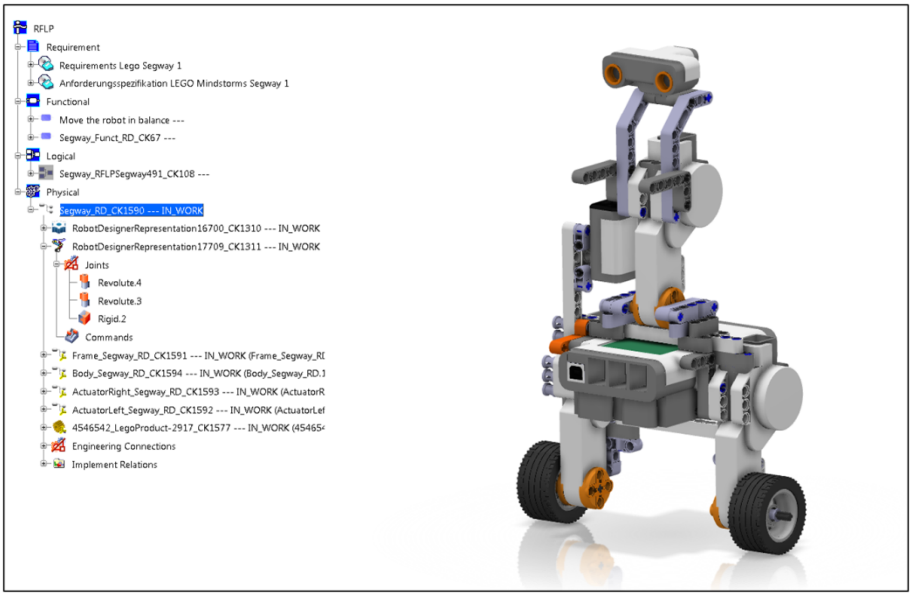

Fig. 4. Physical design of the LEGO Mindstorm NXT 2.0 robot

In the *VPM Functional Logical Editor* of V6 Systems Workbench, the functional model was then extrapolated from the requirements model and stored in the RFLP structure tree (*Functional* view). The functions of the NXT robot are displayed in the form of a block diagram, differentiated by main and sub-function and linked together by means of functional flows .

Fig. 5 shows the robot's general mode of operation. The robot's general task of "maintaining balance while moving" is formulated in the main function and divided into the three sub-functions "Maintain balance", "Manage movement" and "Generate electrical energy". These sub-functions are detailed further into sub-functions of lesser complexity, extending all the way to functions such as "Transform electrical energy into mechanical energy", "Query motion specification" and "Adapt mechanical energy". Connecting the individual sub-functions together produces a functional design, i.e. the robot's general mode of operation.

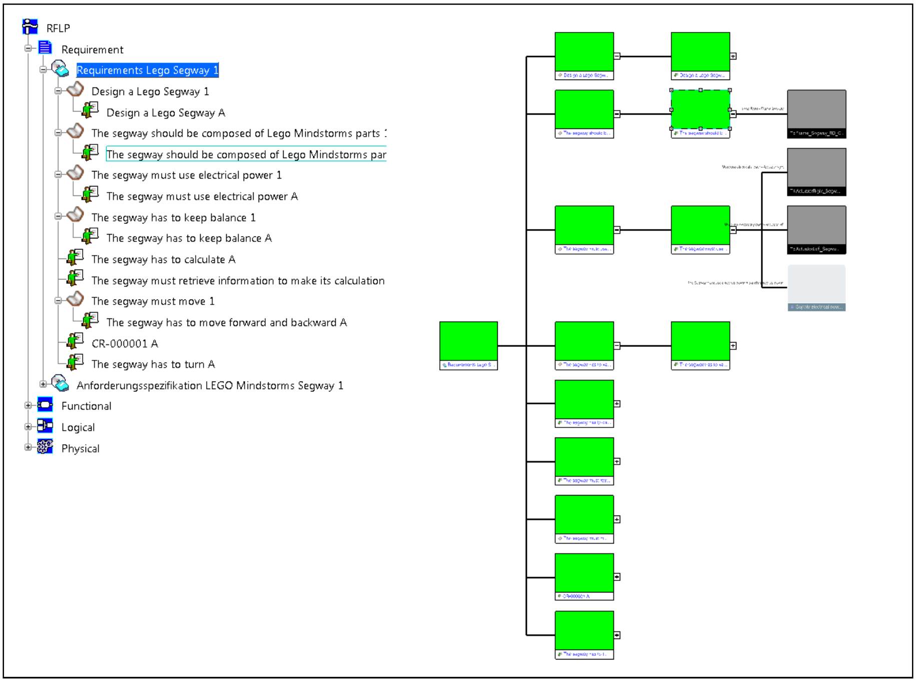

Fig. 5. Requirements for LEGO Mindstorm NXT 2.0 robot

The logical design details the functional architecture via the model-based development of a simulation-ready behavior model for the robot based on defined operating principles and selected technology solutions.

The robot's logical architecture comprises the elements sensor, controller, actuator and control loop. For the sensor, a gyro sensor was adapted to measure the robot's angle (tilt) and position. Mechanical energy is converted into electrical power (actuator) by two electrical servo-motors, which transmit parameters of the gearbox setting to the controller via an integrated rotary sensor. The controller (a 32-bit microprocessor) evaluates and calculates all recorded signals and commands. The control loop is interpreted as an inverted pendulum that establishes contact with the ground via two wheels and a single axle, and is governed by a PID regulator integrated in the controller.

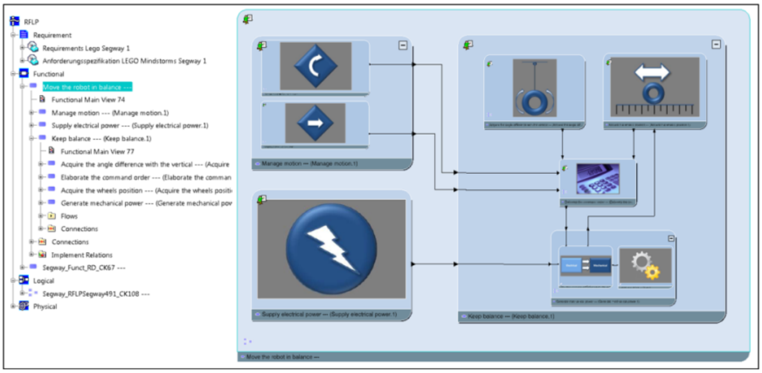

Fig. 6. Functional design of the LEGO Mindstorm NXT 2.0 robot

With the aid of the Dynamic Behavior Modeling workbench and Modelica, behavior descriptions are stored for the functions and logical modules and these are then calculated and simulated on the basis of Dymola in CATIA V6 systems. Figure 7 shows the Lego Mindstorm NXT 2.0 robot's electrical drive system created using Modelica.

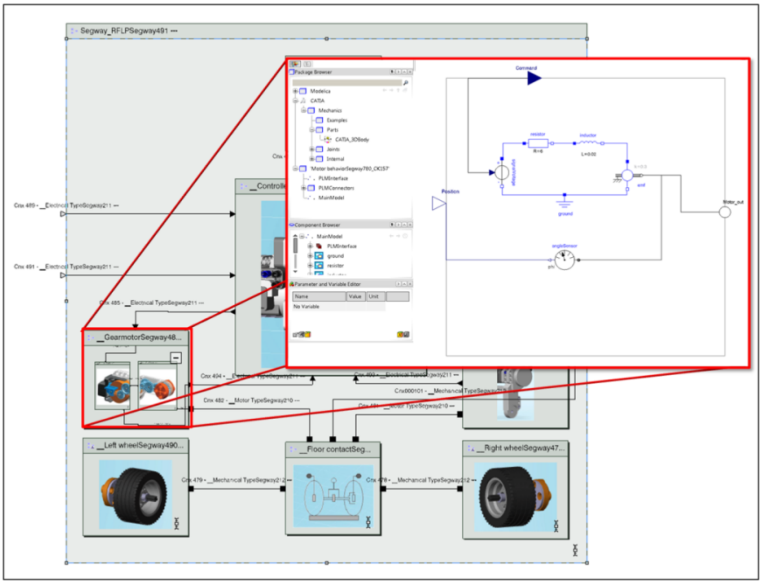

Fig. 7. Dynamic behavioral modeling of the LEGO Mindstorm NXT 2.0 robot

CAD-based modeling of individual components and assemblies in CATIA, and the associated definition of a system's form and mechanical properties have been around for years. But the integrated *CATIA 3D Body* Modelica Library now allows the CAD model to exert a direct influence on the simulation behavior, merging the physical model with the behavior model. This Modelica library allows parameters such as mass, inertia and density to be transferred to the simulation environment directly from the geometry or 3D CAD model. After calculation, the system behavior is described with the aid of the simulation in the form of diagrams, and the movement of the 3D model visualized in an animated sequence. The simulation run is recorded via live plots, which are also used for evaluation and optimization purposes.

3 Systems Engineering and the RFLP Approach in Practice

The development of complex technical products calls for comprehensive, multi-disciplinary engineering and a holistic approach in the early phases of development. The RFLP approach facilitates multi-disciplinary, model-based development and supports the early analysis, evaluation and optimization of the technical system. This approach was tested using the V6 PLM platform and, specifically, CATIA systems.

The special feature of CATIA V6 systems is that the items of RFLP information are represented on the basis of an integrated data model, so that links between individual development phases and models can be established as and when required. RFLP partial models are linked to each other via so-called implement relations and allow the user e.g. to jump from an individual function – whether main or sub-function – to the implemented requirement or the logical design. In addition, the transparency and traceability of development steps and results are secured by means of informative representations (e.g. the traceability report). The links between the individual RFLP representations mean that data can be validated and verified on a continuous basis.

With V6, the V model can be used to develop technical products in a process that extends from requirements engineering and management via the functional analysis and logical architecture all the way to the physical design of the product in question. The engineer can therefore see at a glance which requirements led to the implementation of a certain logical behavior and the effect this had on the 3D geometry. The V6 PLM platform thus provides an end-to-end Systems Engineering solution along with options for generating and managing the objects that are created during product development. To this end, all modeling results and product information, as well as simulation data and results, are stored in the central ENOVIA PLM environment, where they are available on the database server in an object-oriented, structured format. Which means that a common product model spanning all disciplines and featuring neither interfaces nor breaks in the media chain can be used for Systems Engineering.

The model-based development of technical systems requires engineers to have knowledge of model-based development techniques and of appropriate modeling languages. Model-based development in an interdisciplinary team of several engineers calls for appropriate modeling methods and techniques (e.g. modeling rules and conventions) in order to craft models that are at once transparent, robust and maintainable [1]. V6 currently offers a proprietary modeling language for use in the functional and logical design stages of a project. In practice, however, SysML appears to be prevailing as the standard language. Support for and integration of SysML and other standards for system development, e.g. AUTOSAR, in the automobile industry are necessary for enterprise-wide, model-based development.

Today we are seeing other technologies and trends already playing a certain role or coming to the fore in practical terms – and thereby complementing Systems Engineering in general and model-based development based on RFLP in particular (e.g. model-based testing, automatic code generation, co-simulation).

Systems Engineering is a general, procedure-based model that is not geared to specific development challenges and which provides multi-disciplinary development teams with a common means of communication [12]. In addition, the RFLP approach is a successful means of supporting model-based development. The methods and procedures presented here have been tried and tested successfully in practice in a sample V6 application. While the selection and implementation of appropriate integrated IT development tools is necessary when introducing Systems Engineering and the RFLP method, this is not sufficient by itself. The necessary development and support processes must be established, and the project team members involved in Systems Engineering must be well qualified and motivated in order to implement this comprehensive methodology successfully in practice.

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Consolidating Product and Process Information of Connections – A System-Theoretical Approach

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Abstract. The selection of the optimal connection is one of the most crucial parts in product development as it determines both, product properties and production processes. In multi-variant series production, functionality presumed, process cost is more and more in the focus of the selection. Designers face a big challenge in evaluating the feasible connections and surveying them holistically. Main challenge is the consideration of both, product and process related characteristics as they are documented according to different methodologies and in different sources. Therefore, a system-theoretical approach for consolidating product and process information is developed enabling designers effective designing and surveying the possible connections for given parts to be assembled. A case study evaluates impact on design time and connection quality.

Keywords: product and process documentation, mechanical connection, DFA, process selection, systems-theory.

1 Connections in Multi-variant Series Production

Mechanical connections strongly influence product properties and production processes. Studies for the metal working industry indicate that connections determine up to 50% of the labor time [1] and 70 – 80% of the manufacturing costs [2].

Selecting the connection during concept design determines product characteristics that occur either in production, during times of product utilization or at the end of the lifecycle. Influencing those characteristics at a later point in development is either not possible at all or only with high effort. For this reason, selection of the most appropriate connection is one of the most crucial tasks in product development.

From an OEM perspective two major trends will increase the significance of these figures: individualization and sustainability. Due to individualization the number of feature options and consequently the number of different parts to be assembled will rise further [3]. Each new assembly requires an individual connection that needs to be designed separately. The second relevant trend - sustainability - currently is fulfilled in product development either through new sustainable materials (e.g. natural fiber) or

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via lightweight materials (e.g. magnesium, titanium, carbon fiber). Both approaches depend on new connection techniques as the conventional techniques cannot, or respectively not optimal be applied to the new materials and material mixes.

Described tendencies increase the complexity of the task of selecting the optimal connection further, as variety (number of different connection techniques to be considered) and changes (number of different connections to be designed) increase.

In reference to the product, designers need to keep various requirements in mind while selecting the connection. These are functional requirements like forces, tightness or positioning accuracy but also process-related aspects like assembly cost. The result is a multi-criteria problem that needs to be applied to an extensive solution space, defined by the number of connections, type of connections and specification of those.

According to an application-oriented approach the context of discovery is described (Section 2), existing approaches are surveyed and requirements are derived (Section 3) before a new approach is developed (Section 4) that is finally evaluated in a case study of bolted connections in the automotive industry (Section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

2 Challenges in the Selection of Connections

The solution space is defined by three dimensions: the number of connection points, the type of connection used and the dimension of the connections. In order to quantify the number of solutions, which are part of the solution space and thereby evaluate the challenge of selecting the optimal connection, a standard assembly (see Fig. 1) is surveyed: the assembly of a control unit (Fig. 1a) to a metal hold (Fig. 1b).

(a) control unit

(b) metal hold

Fig. 1. Assembly control unit

To estimate the number of different connections, part of the solution space of the surveyed assembly, each of the solution space's dimensions is analyzed individually. An internal study of 3214 bolted connections in a modern medium-class car is the database for the results described in the following.

The number of connection points theoretical possible is defined by the size of the part to be assembled and the minimal distance between the connection points. Even when smaller than the theoretical possible number of connection points, for further calculation 15 connection points per part assembled are taken as a reference corresponding to the study (see Fig. 2).

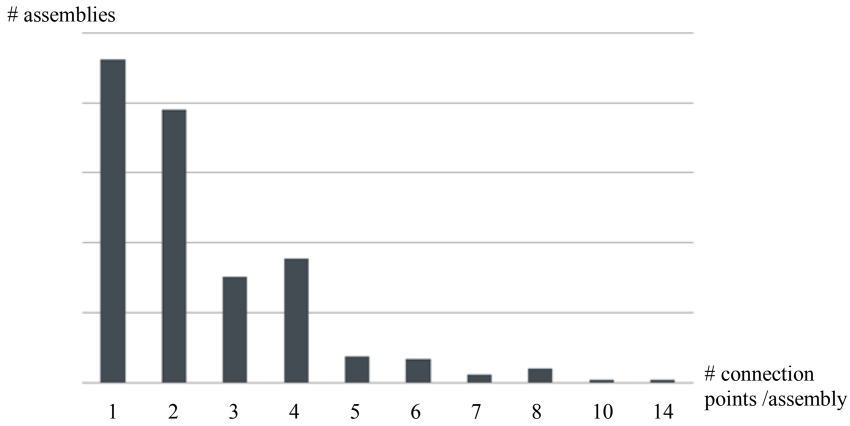
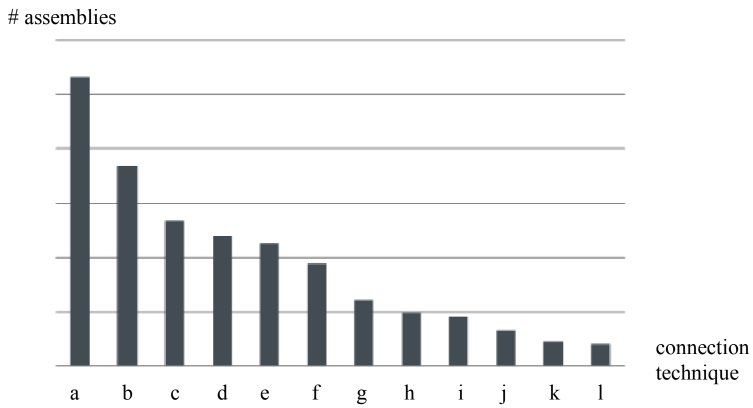


Fig. 2. Number of connection points (authors own study)

For the second dimension of the solutions space, the different connection types are surveyed. The study describes ten different kinds of bolted connections (see Fig. 3).



a: bolt and weld nut
b: nut and weld stud (metric thread)
c: bolt and through hole (metric thread)
d: bolt and snap nut
e: bolt and blind hole (coarse thread)
f: bolt and blind hole (metric thread)
g: bolt and straddling dowel
h: bolt and through hole (coarse thread)
i: bolt and nut and through hole
j: nut and integrated bolt (coarse thread)
k: bolt and blind rivet nut
l: bolt and punched nut (metric thread)

Fig. 3. Bolted connections (authors own study)

The variation in dimension of the connection types as third dimension of the solution spaces is even more versatile than connection points and connection types. The combination of five different diameters, three different thread types and thirty different lengths lead to more than 100 different dimensions - differences in the characteristic of bolt and nut as head geometry not considered.

Combination of the described dimensions demonstrates for the comparatively simple assembly of a control unit more than ten thousand possible solutions. Necessary condition for the identification of the optimal connection, due to a given set of requirements, is the derivation of all connections part of the solution space and the ability to assess those methodologically corresponding to the set of requirements.

Due to the proven large number of theoretical possible connections, designers depend on methodic support and computational help for this task. As the different connections need to be evaluated holistically [4] according to described functional and nonfunctional criteria like process cost, the derivation of the different connections needs to include not only product, but also process information.

That calls for a general description of the connection between parts of an assembly, the ability to variegate the configuration of the connection and the consideration of both, product and process information. Following existing approaches of product and process information structure are surveyed towards their ability to solve described challenges.

3 Approaches towards Product and Process Documentation

Existing approaches towards the integration of product and process information (Section 3.1) are analyzed for their applicability to the described challenge of connection selection (Section 3.1).

3.1 Integrated Product and Process Documentation of Connections

Beside the broad work on product and on process documentation few approaches towards the integration of the two fields can be found in literature. The most relevant approaches will be detailed in the following.

Grabowski95. With the integrated product and production data model Grabowski [6] offers a approach towards the improvement of data management in product development. For this purpose a object oriented data model was developed, that describes information about the entire lifecycle of a product or production tool. With the description of manufacturing processes, individuals and workplaces linked to the product, the integration of process information into the product model is achieved.

Munoz06. Munoz [7] describes an approach for the identification of inconsistencies in connections and supports thereby design for assembly with a model for the evaluation and analyze of connections. The model consists of a functional and a structural part. The structural part allows the description of geometrical and physical characteristics of the assembly, the functional part describes a method for the analysis of the connections.

Therefore, elementary attributes (PLUG attributes) are defined for the description of the parts. Besides geometrical information like the position and characteristics of the contact surface of the parts to be assembled, also information about the connection element is documented in the structural model. With the help of multi agent systems PLUG attributes of the parts to be assembled are compared and analyzed in order to identify inconsistencies. From this, an expert can determine the according production processes.

Groll08. Groll [8] offers with interconnection based product and process documentation a method for the customers related series manufacturers aiming for the optimization of data structure and management through an alternative to the existing methods of hierarchically oriented product structures. Products are therefore configured as a web of parts and interconnections. An interconnection describes the connection between two specific parts and holds process specific information like capabilities, time, instructions, procedures, utilities and tooling.

3.2 Conclusion

Described state of the art presents a broad base in the fields of product and process information, as well as several approaches towards the integration of those. Especially the work of Groll [8] offers an important approach towards the described research question. Even though, as the motivation of the approaches is either the documentation of product and process [6, 8], or the analyze and checking of the connection [7], none of the described approaches offers the required level of detail in order to enable the assisted design of connections regarding economic criteria.

3.3 Requirements to the Consolidation of Product and Process Documentation

To attain the assisted design of connections, following requirements towards the documentation of product and process of connection need to be fulfilled:

1. Solution independent description of the assembly (parts to be assembled and connection)
2. Different degrees of detail and different views (manufacturing, assembly)
3. Holistic description of all processes
4. Evaluation of resulting changes due to modification of the parts to be assembled

The requirements result from a survey among a group of 15 persons, involved in the process of designing, planning and assembling connections in the automotive industry.

4 Product and Process Information of Connections – A System-Theoretical Approach

In order to fulfill above defined requirements (Section **Fehler! Verweisquelle konnte nicht gefunden werden.**) towards the consolidation of product and process information of connections, a system-theoretical approach was developed that describes a connection not longer as the relation between the assembled parts (see Fig. 4), but as an independent element in the system of the assembly.

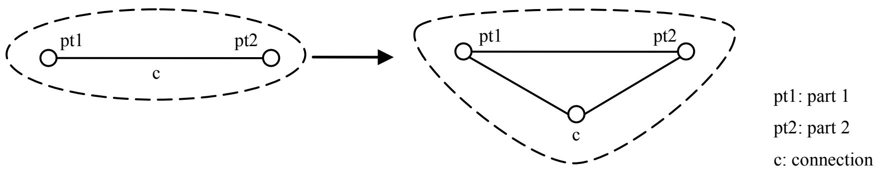


Fig. 4. Connection as element of the system assembly

Thereby, the connection element defines an independent subsystem consisting out of the individual joints. Each of the joints itself defines an individual subsystem, consisting of joining elements and joining process (see Fig. 5). These three layers allow for the documentation of all information about the connection, including assembly and manufacturing processes. As of this closed description, the connection can be evaluated and compared holistically to others.

Following the different layers (4.1) and elements of the models (4.2) are described in detail.

4.1 Layers of the Connection Model

Corresponding to the systems-theory the system consists of elements and relations between them. These have functional and structural relations. As the elements can define (sub-) systems themselves, they can inhere also hierarchical relations:

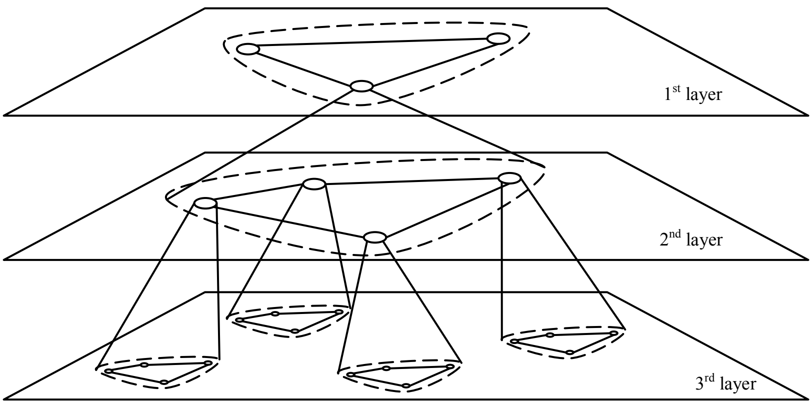


Fig. 5. System-theoretical three layer description of a connection

1st layer. General description of the assembly, consisting of two or more parts and the connection. The first level defines the parts to be assembled (pt1, pt2), the connection system (c) as well as the requirements towards the assembly.

2nd layer. Subsystem of the connection of the 1st level constitutes from the individual connection points c1,…,i and their configuration.

3rd layer. Subsystems of the connection points c1,…,i constitutes from the connection elements and production processes.

4.2 Elements of the Connection Model

While 1st and 2nd layer represent the structural and hierarchical relations, product and process information is represented in the 3rd layer. Therefore, a detailed description of the 3rd layer's subsystems:

Each of the systems contains connection elements and related processes. Assumption is the assembly of a product by starting with one part and then successively adding parts until the completion of the product. Thereby, the part closer to the core of the product (mount) carries index 1, while the part fixed carries index 2 (when connecting the door hinge to the a-pillar of car, the a-pillar is closer to the core, takes the function of a mount and carries index 1, the hinge accordingly index 2. But when connecting the door to the hinge, the hinge is closer to the core and carries index 1, the door accordingly index 2). In order to define the single elements, above described assembly of a control unit, using a bolted connection is surveyed. Each of the bolted connections is a single 3rd layer subsystem, consisting of four individual elements (see Fig. 6).

- *Connection Element (ce)* defines the part of the mechanical connection added to the assembly in the production process
- *Function Element (fe)* defines the part of the mechanical connection that is part of the assembly (mount)
- *Assisting Element (ae1)* defines the modification of part 1 necessary to enable the application of the connection technique
- *Assisting Element (ae2)* defines the modification of part 2 necessary to enable the application of the connection technique

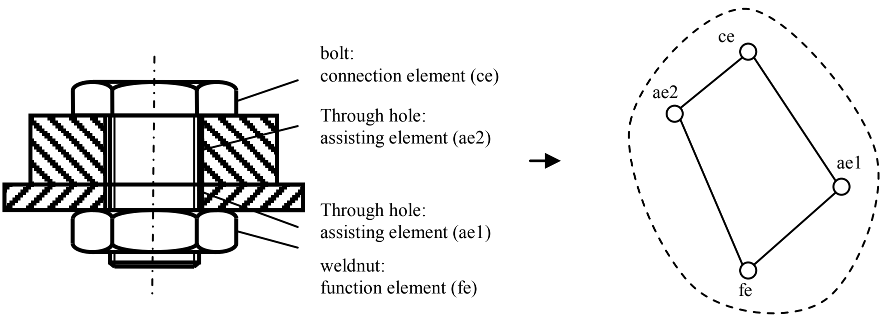


Fig. 6. System-theoretical description of a bolted connection with connection elements

The described elements represent the physical parts of the connection as shown in Fig. 6 and define the connection sufficient. This representation is completed by the assignment of the related processes. Therefore, five different processes are defined and linked to the corresponding elements of the 3rd layer (see Fig. 7). Furthermore, the related processes are described:

- *Production Process Connection (ppc)* defines the interaction of connection element and function element – screwing bolt in weldnut
- *Production Process Connection Element (ppce)* defines the interaction between the connection element and part1 – inserting bolt in through hole
- *Production Process Function Element (ppfe)* defines the interaction between the function element and part 2 – welding the weldnut to part 2
- *Production Process Assisting Element1 (ppae1)* defines the preparation of part 1 – adding the through hole into part 1
- *Production Process Assisting Element2 (ppae2)* defines the preparation of part 2 – adding the through hole into part 2

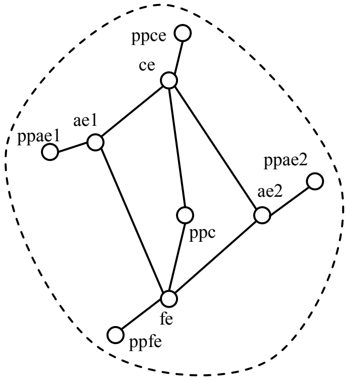


Fig. 7. Sufficient description of a connection with all corresponding processes

Each of the processes can be further detailed into assembly processes, tools, logistic processes and informational processes. The production processes can be derived automatically or manually by the designer, due to the related elements.

For evaluation the initially described assembly of the control unit is redesigned using the system-theoretical approach towards consolidation of product and process information.

5 Evaluation

In order to evaluate the developed system-theoretical approach towards the integration of product and process information, the surveyed connection of the control unit (Section 2) was redesigned. Therefore in the first step the characteristics (weight, size, material, etc.) of the parts to be assembled (part1, part2) and requirements towards the connection (c) (forces, tightness, position accuracy, etc.) were defined (1st layer). Based on this information, different connection scenarios were created by the variation of the number of connection points and their orientation (2nd layer). For the scenarios, the load on every connection point was calculated and the connection points were dimensioned according to the requirements (3rd layer). By the allocation of the production processes to the elements, the connection models were completed, allowing for the derivation of the assembly expenditures using a methodology described in [5]. Corresponding to this derivation the functional and economic optimal connection was selected.

With the support of the system-theoretical approach towards the integration of product and process information a new connection was designed, that offers the same functionality as the known design but is characterized by less and smaller connection points. Thus the assembly causes 40 percent less expenditures than the actual connection.

6 Summary and Further Work

Current methods of product description like variant parts list, open/closed variant parts list, rule based parts list etc., only focus on the parts to be assembled, while methods of process description like assembling planning, variant work plans etc., only focus on the process of joining the parts. None of the existing methods is capable to join and structure product and process information sufficiently.

The approach allows the representation of the assembly and production processes as well as the relations and dependencies between those in a structured model and expands thereby the state of the art.

Designers and planners benefit from the approach by the ability to survey all suitable connections of a given solution space corresponding to a given set of requirements quick and comprehensible. Via the application on different automotive assemblies the approach is evaluated, demonstrating the definition of the entire solution space, assessment of all resulting connections and selection of the optima, demonstrating significant improvement during the design process and in the quality of the solution. Described system-theoretical approach towards the consolidation of product and process information of connections is a contribution to the field of information and knowledge management in product development. The approach is limited to production processes that are characterized by fixed and standardized manual work cycles as they can be found in multi variant series production.

Further studies could focus on either the survey of different joining processes or on the implementation of the approach in a software tool.

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A Structured Approach for Function Based Decomposition of Complex Multi-disciplinary Systems

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Abstract. The aim of this paper is to introduce the Systems State Flow Diagram as a structured approach to high level solution-independent function based decomposition of a complex multi-disciplinary system. The approach is discussed in the context of existing function modelling frameworks and in relation to current practice in industry. A generic case study is used to introduce the approach and to highlight the salient features, followed by an illustration on its application to the analysis of an electric vehicle powertrain. Experience with the practical application of the approach with engineering teams is discussed.

Keywords: Systems engineering, function decomposition, system state, function flows, product development.

1 Introduction

The complexity of automotive systems has increased dramatically over the past couple of decades driven by the accelerated pace of innovation and introduction of new technologies to enhance customer satisfaction and to mitigate environmental and safety concerns in a highly competitive marketplace. This escalation in complexity has brought significant technical challenges, compounded by the increase in sophistication of the control systems employed to manage the integration of the new technologies within the system. Managing multi-disciplinary system integration is recognized as being a very difficult task [1-3], which is not well supported by the existing frameworks and tools for function decomposition of complex systems [1]. The particular difficulty with the analysis of multi-disciplinary (i.e. electro-mechanical, electronic, control, software) complex systems is that system to system interactions are very difficult to assess or predict early in the systems engineering design process.

Observation of current systems engineering design practice in industry has highlighted the prevalence of a structural based decomposition of systems, generally underpinned by clustering analysis on a design structure matrix (DSM) [4-5]. Allocation of design responsibilities to engineering design teams mirrors the system decomposition, which means that design teams have responsibility for design units or chunks, and not for functions, which often means that "system integration" functions are left to chance. For illustration, taking the example of an exhaust system (based on

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the authors' observations across a number of OEMs), the design responsibility is typically split between 4 teams on the basis of the disciplinary grouping of the sub-systems involved: exhaust pipework, after treatment components, sensors, and control software. There is no overall responsibility for the integration of the system on the basis of its main function (to transport and condition exhaust gas), which is ultimately the root cause for common field issues, e.g. associated with the regeneration of the exhaust particulate traps (a well-known cross-industry issue). This illustrates that the conventional approach of structure - function decomposition works well for the integration of reasonably small electro-mechanical systems, but it does not provide a good approach for complex mechatronic systems, which is a conclusion similar to literature findings [1-2].

The aim of this paper is to introduce the Systems State Flow Diagram (SSFD) as a simple but effective tool to support the high level analysis and function based decomposition of a complex system. The method will be explained with a generic case study, followed by an illustration of an industry-based example of an electric vehicle powertrain, and a discussion of the experience with the application of the method on a broader basis for complex automotive systems. The organization of the paper is as follows: section 2 gives an overview of common methods for functional decomposition of complex systems; section 3 outlines the proposed method, followed by discussion and conclusions in section 4.

2 Overview of Function Modeling Approaches

The function of an engineered system is commonly defined in relation to the transformation of the inputs to the outputs; the inputs and outputs are usually considered in terms of types of energy (E), material (M) and information (I) [6-7]. Design decomposition is based on mapping the flows of energy, material and information through the system [7]; sub-functions are defined as successive operations on flows, with output from one sub-function providing the input to the next. Several graphical diagrammatic representations have been developed to visualize the system's functional structure and to facilitate the analysis by teams of engineers, e.g. Function Trees, System Block Diagrams, System Boundary Diagrams, Function Flow Block Diagram, FAST Diagrams, Integrated Definition for Function Modeling (IDEF0) [8-9].

The description of the function commonly follows a verb – noun structure [9]. The "functional basis" approach by Stone and Wood [10] provides a consistent framework including a taxonomy for functions and a coherent representation of the overall function in terms of interconnected sub-functions, defined as operations on flows (of E, M, I). Design development is carried out through successive decompositions of functions and sub-functions into lower level sub-functions. This is usually done iteratively within the design synthesis, i.e. an iterative decomposition in the functional and the design solution domains, referred to as zigzagging in the context of axiomatic design [11]. At any level, system integration is supported through interface analysis, facilitated by a design structure matrix (DSM) type approach [4-5], which aims to identify the relationships or linkages [12] between components. Clustering analysis on the DSM is used to group components into structure-function units [4].

Several other methods for defining functions have been proposed (see for example [13] for a review), aiming to support different phases of the design process, in particular by enhancing the understanding of the relationship between function (defined in relation to the utility to the user or customer) and the intended behavior and structure of the system. The Function – Behavior – State (FBS) [14] framework suggests that functions are defined in relation to states of the structures (design objects), which are represented by entities, their attributes, and relations between entities. Within FBS the functions are defined by the combination of verb-object which relate to the designer intentions, and behaviors expressed through adjectives, which can instantiate the function, thus embedding the time dimension into the function definition. While providing a strong framework for functional modeling which lends itself to useful software implementation and automation, the FBS framework has been found rather difficult to implement in engineering practice [15].

The Object-Attribute-Function framework [16] proposes a similar approach, with the input and output defined as generic objects thought of as tangible entities that have attributes (such as mass), or information (expressed as signals that can be detected). Within the OAF framework, the input and output objects are described by their measurable attributes, with a clear taxonomy developed to describe both.

A generic issue with all frameworks is that they do not support the high level functional analysis / decomposition of a complex system in a solution independent manner. At any level, decomposition tends to be based on brainstorming, i.e. by asking the question "how is this function achieved". The Contact and Channel (CC) framework [17-18] addresses this issue by providing a coherent structure for functional decomposition based on identification of working surface pairs (WSPs) at the system input and output, as well as the channel that connects the WSPs within the engineered system. A working surface is described in terms of a state characterized by measurable attributes, and the system function defined as "transfer of one state into another" [19]. The functional decomposition is carried out by defining surface pairs with the channel, which correspond to design subsystems. While this framework is structured and powerful, it uses a taxonomy which is not always conducive to the analysis of multidisciplinary systems (e.g. control or software systems engineers are unlikely to adopt the language of working surface pairs).

3 System State Flow Diagram

A review of current frameworks for function modeling pointed out the need for a more structured tool to support high level solution-independent function analysis and decomposition for complex multi-disciplinary systems. Analysis of current methods and practices in industry, discussed in [20], has also highlighted the need for a structured tool to address the heavy reliance on less structured approaches (largely based on brainstorming) in carrying out practical function decomposition analysis. The requirements for such a tool can be summarized as follows:

- To be integrated with other tools commonly used in industry – such as Boundary Diagrams and Interface Matrices [8], to encourage broad take-up of the tool;
- To have a graphical (diagram based) representation to facilitate the development of shared mental models [21] within the engineering team carrying out the analysis;
- To be portable across disciplines (electro-mechanical, control and software) and domains (design / process);
- To promote axiomatic design principles of domain separation and primacy of function and solution-neutral thinking in systems engineering design analysis.

The System State Flow Diagram (SSFD) was first outlined in [22], and further discussed in [20] with a comprehensive example of application to the analysis of an electric vehicle powertrain. The SSFD has been further applied to the analysis of automotive systems, giving a rich experience and feedback from many teams of engineers.

This paper will explain the principle of the approach on the basis of a generic example – design analysis of a generic Bread Toasting System (BTS), followed by an illustration of the application in an industry based context.

3.1 Principles of a State Flow Diagram

Block Diagrams are commonly used to represent an engineered system. At high level, a system (conceptually thought of in terms of its function and physical structure / design solution) is represented as a black box, showing the inputs and the outputs to the system, as shown in Figure 1. Coherent with FBS [14] and OAF [16] function modeling frameworks, the *input* and the *output* can be thought of as generic *objects* described by a set of measurable attributes. For the BTS example, the sliced bread (input) and toast (output) can be thought of as objects characterized by physical and chemical attributes (e.g. density, humidity, porosity) and geometry (e.g. thickness).

As discussed, a generic system function definition is "the transferring of one state into another" [19]. The SSFD embeds this definition of the system function in a graphical representation, shown in Figure 2. The SSFD follows the general principles of state diagrams (such as state transition diagram or reliability state diagram [23]), in that by convention the boxes denote the *states* of the objects and the arrows denote the *functions* required to achieve the transfer from one state to another. The important feature of this representation is that it divorces the consideration of function from the consideration of the design solution. In the SSFD framework the functions can be thought and articulated purely in terms of transformation between states of objects, as

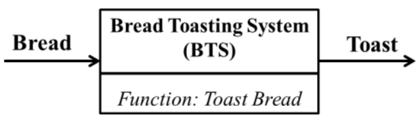

Fig. 1. BTS System Block Diagram

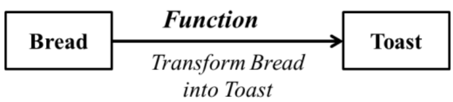

Fig. 2. BTS High level SSFD

described by their observable and measurable attributes. So the function of the BTS to "toast bread" can be more clearly expressed as "transform bread into toast", which can be defined and assessed in terms of the change in the physical (e.g. humidity, density, thickness, weight), chemical (e.g. oxidation) and geometrical attributes.

3.2 Function Decomposition Based on State Flow Diagram

The function decomposition using the SSFD is based on identifying intermediate states between the input state and the output state. The definition of the intermediate states should follow the same logic and structure as the one used for the input and output; i.e. consistent with the OAF framework, we need to think of observable states characterized by the measurable attributes of the objects they relate to. The SSFD maps the *flow* of the states through the system and the functions required to achieve the transitions between the states. Figure 3 illustrates the development of the SSFD for the BTS system, showing only the *main flow* through the system, which in this case is that of bread. The functions defined can be mapped in terms of the object attribute changes required to transition between states. For example:

- "F1 – load bread" and "F3 – remove toast" are associated with changes in the attributes relating to spatial location and orientation;
- "F2 – Toast Bread" relates to the change in physical and chemical attributes of the bread when it is converted into toast.

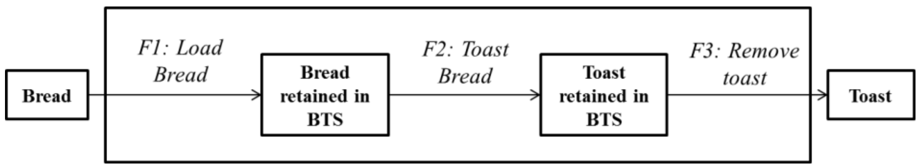

Fig. 3. SSFD for the Main Flow in BTS

The box around the system defines the "system boundary", i.e. the limits of the scope for responsibility for the design team. Once the main flow is depicted, the engineering design analysis and synthesis can be carried out to identify the best way in which the functions can be delivered through the engineered system. Based on the understanding of the science of toasting, the "working principle" of a BTS can summarized as "reduce bread moisture content and oxidize the surface of the bread". The BTS engineering design task associated with function F2 is to find a way of delivering the function; in this case this relates to the delivery of heat energy from a given source to the "Bread retained in BTS". Figure 4 shows an updated SSFD which maps the energy states flow through the BTS system. This shows an "Energy Source" as another input to the system, an intermediate state of "Heat", and a function F4 to "Convert Energy into Heat". Given that the SSFD delivered a solution independent analysis, the BTS engineer has the freedom to consider a variety of sources of energy (electrical, gas, chemical, sunlight), and a range of *design concepts* as ways of converting this energy into heat to achieve the F2- "toast bread" function. Therefore, the attributes of the 2 new states shown in Figure 4 (i.e. "Energy Source" and "Heat") cannot be fully defined until technology and system design decisions have been made.

Function F2 – "Toast Bread" is achieved directly by "Applying Heat to the Bread retained in the BTS", i.e. heat will change the physical and chemical attributes of bread, transforming it into toast. In general, coherent with the OAF framework, an engineered function is completely defined in terms of the ***triad*** of (1) input object state, (2) output object state and (3) transforming energy or process. The functional decomposition is complete when functions are fully defined, i.e. specified in terms of the triad defined above, typically requiring several function decomposition iterations.

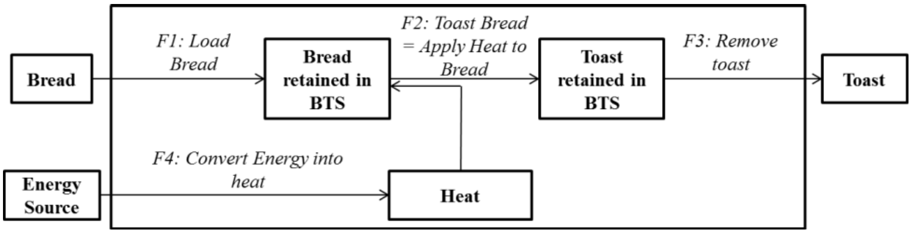

Fig. 4. SSFD for the Bread Toasting System (BTS)

The key feature of the functional representation in Figure 4 is that it is fully in the functional domain and solution-independent. As such, the SSFD in Figure 4 could provide an adequate representation for a range of BTS designs, e.g. a common household electric bread toaster (which holds the bread in a case), a hotel type bread toaster which uses a conveyor belt, or an ecological bread toaster where focused sunlight heat is used to toast the bread. The SSFD diagram in Figure 4 could equally represent a *process* of toasting bread under a gas grill or over a barbeque, if all the transportation functions on the main flow are performed by the user.

From this SSFD representation we can directly extract a high level BTS Function Tree, Figure 5. This has been derived from a structured decomposition of the system in a solution neutral way, and not based on directed brainstorming (How-Why) which is the typical approach in practice [9].

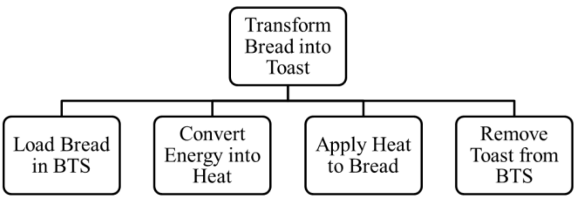

Fig. 5. High Level Function Tree for the BTS

3.3 Design Analysis of System Control Features Using SSFD

Most modern systems are required to have a control system in place to support the robust achievement of the consumer requirements. Consumer requirements are generally directed at the attributes of the output object state. For example, the "browning" level of the toast is a critical attribute that can be related to the customer requirement of "consistent good toast". The browning level as an attribute of the output state, depends on the attributes of the input state and the functions (transformations) in the system. Figure 6 illustrates an *attribute transformation matrix* for the BTS system that supports the identification of the functions which can influence the browning level of bread. As discussed, functions F1 and F3 are associated with a change in the location and orientation attributes, and do not affect the browning level. However, the input state (in terms of the physical and chemical properties of the bread – such as moisture content, density, structure, chemical composition), and function F2 (in terms of the heat rate and overall heat exchanged) have a clear influence onto the browning level. The designer has little control over the attributes of the input state (arbitrary choice by the user), hence the control strategy must be directed at function F2, i.e. control the heat rate and the overall heat applied to the bread. The way in which a control feature is designed and implemented depends on the design solution adopted and the required level of control. For example, on a common domestic toaster the heat control can be based on time or heat rate setting, whereas for a hotel type bread toasting system the control is based on the belt speed and / or heat rate settings. The BTS control system

Critical output state attribute	Input State	F1: Load Bread in BTS	F2: Apply Heat to Bread in BTS	F3: Remove Toast
Browning level	X		X	

Fig. 6. Attribute Transformation Matrix

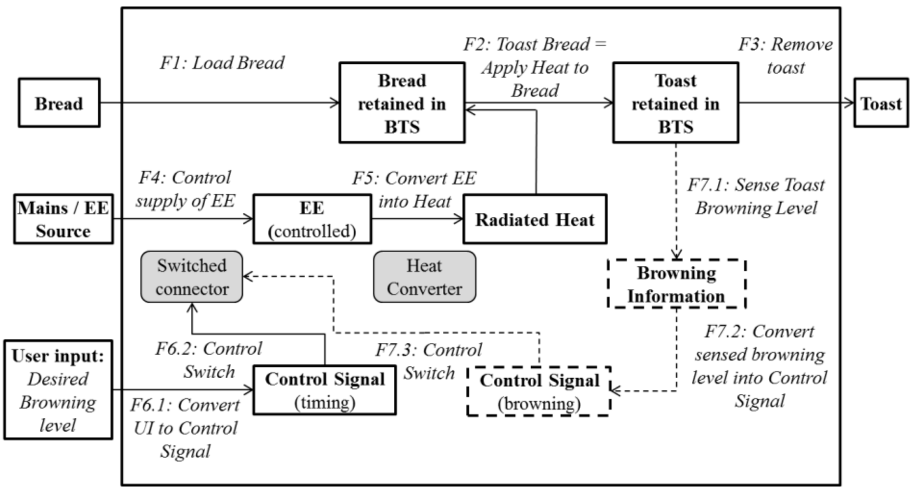

Fig. 7. SSFD for a BTS with Control System

can be manual (i.e. adjusted by the user), or automated if based on in process measurements (e.g. sensing the "browning" level). For illustration, Figure 7 shows a SSFD "customized" for a common household electric bread toaster, showing two options of control system.

The function "Convert energy into heat" has been further decomposed into "F4: Control supply of EE " and "F5: Convert EE into Heat", reflecting the design choices made – i.e. to use mains electrical energy (EE) as energy source, which is converted into radiated heat (applied to the bread, function F2) through a heat converter. The design elements that achieve functions F4 and F5 (i.e. the switched connector and the heat converter) have also been indicated on the SSFD. Figure 7 illustrates 2 control strategies:

(1) Manual control based on timing, where the user selected setting for the browning level is converted to a timing control signal (F6.1), which controls the switch connector (F6.2);
(2) Automatic control, based on sensing the toast browning level (F7.1), the conversion of the sensed browning level into a control signal (F7.2), which controls the switch connector (F7.3).

It is important to note that the control functions are still solution independent; e.g. sensing the toast browning level can be achieved in a number of different ways which can be considered by the design engineers. Fundamentally, the only design decisions that have been made relate to the use of mains electric energy to power the BTS. The function tree can be updated to include the control functions derived from the SSFD, as sub-functions to "convert energy into heat" function on the high level BTS function tree shown in Figure 5.

3.4 SSFD Illustration for an Electric Vehicle Powertrain System

Figure 8 illustrates the application of the SSFD to the analysis of an electric vehicle powertrain (EVP) for a small truck application [20]. In an EVP system there are 3 main flows, i.e. (i) to charge and store energy; (ii) to deliver controlled torque to the rear axle; (iii) to provide power for vehicle consumer units. The SSFD analysis shown in Figure 8 integrates these 3 flows into a compact functional representation of the

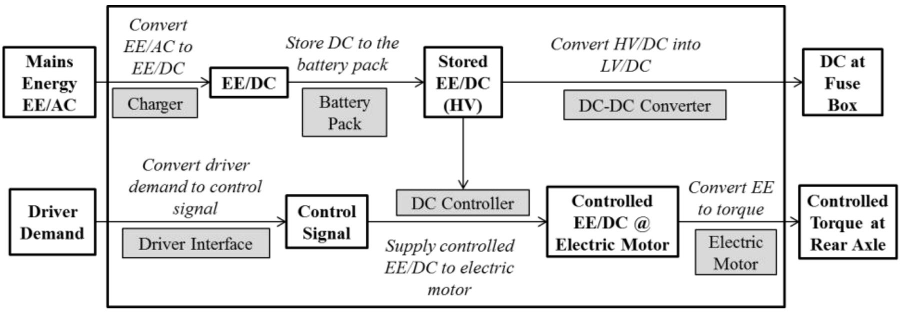

Fig. 8. SSFD for an Electric Vehicle Powertrain

EVP system. This analysis was conducted by a multi-disciplinary team of engineers, and used to define the functional breakdown of the system and the allocation of associated design responsibilities on a functional basis. The subsequent analysis of the functional integration of the EVP system, at the system level, was developed through an enhanced interface analysis, described in [20].

4 Discussion and Conclusions

The main aim of this paper was to introduce the Systems State Flow Diagram as a structured approach to high level solution-independent function based decomposition of a complex multi-disciplinary system. The review of current frameworks and tools for functional modelling as well as the discussion of current industrial practice pointed out the need for the development of such a tool. The SSFD draws on the FBS and OAF frameworks for function modelling, and introduces a state transition based graphical representation, which is intuitive to use, yet powerful in terms of maintaining the discipline of solution-independent thinking in the analysis of system decomposition on a function basis. The reasoning structure underpinning SSFD is similar in principle with the Contact and Channel framework [17-19], but it has the advantage that it offers a more straightforward graphical representation, it is more portable across multiple engineering disciplines (including mechatronics and control systems), and easier to integrate with other tools commonly used in industrial practice.

The Bread Toasting System case study illustrated the development of the SSFD and showed that the requirements outlined in section 3 are met. The integration with other tools was illustrated in terms of the development of the Function Tree (Figure 5) – which is a common basis for engineering design deployment and analysis. The broader integration with other engineering tools (including interface analysis and Failure Modes and Effects Analysis) was discussed in [20]. The SSFD provides a system representation that is easy to understand, thus supporting the achievement within an engineering team of a common understanding of the functional decomposition of the system in a fundamental, solution independent way. Figure 7 clearly illustrates the ability of the SSFD to support multi-disciplinary analysis, by showing that control features can be accommodated in a seamless way within a SSFD.

The SSFD has been rolled out with two major automotive OEMs, and feedback from the engineering teams has been extremely positive, in that it is a clear and easy to use tool, supporting a thorough and objective analysis of the system. It supports a better understanding of the functions that need to be delivered by the engineered system, and the way in which engineering design tasks can be allocated to teams to ensure a better integration of the system, focused on the customer required functions. A strong feature of the SSFD is that it improves communication between disciplines in the sense that it is a tool that can be equally used by engine component design engineers and engine calibration engineers, responsible for control feature development. The SSFD can be applied at all levels of the systems engineering cascade, and promotes a seamless integration between product and process engineering design on the basis that the SSFD is a similar representation to a process flow map.

The authors' experience of using the SSFD discussed in this paper has been mainly in conjunction with complex automotive systems. However, the SSFD framework and tool can be applied to any complex system.

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Methodology for Identification of Adaptive Reusable Modules in Automated Production Systems

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Abstract. The development and design of mechatronic systems require detailed knowledge in mechanical, electrical and software engineering. In order to face challenges, like reduced time-to-market, reduced costs and increased variability, complex systems should be modularized and the identified mechatronic modules reused for the development of new variants or versions. This paper focuses on the identification of adaptive reusable modules with an appropriate level of granularity and the representation of the deduced modules to support the development. Based on the collection of deduced modules, with defined functions and structure, new systems can be designed through a combination of the appropriate modules.In this contribution, the methodology will be presented through a use case. This example shows how appropriate modules are identified in a first step. In the second step, the impact on the engineering process is shown by the support of the selection and design of the modules.

Keywords: Modularization, Development and Design, Automated Production Systems, Engineering tool.

1 Introduction

Automated production systems nowadays are complex mechatronic systems and demand engineering solutions tailored to the customers' needs and commissioned within a restricted time. In order to stay competitive the innovation cycle, the time-to-market, and the costs have to be decreased, while the quality has to stay on a high level.

Interviews with companies in the machine and plant manufacturing industry showed that modularization is an important innovation factor to face the described challenges, while missing solutions for module management act as an innovation inhibitor. However, the benefits of a reuse of modules are not capitalized, because the reuse of the modules is limited to discipline specific tools, module searching mechanisms are not developed efficiently, and interdisciplinary modules are not clearly

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defined [1]. A literature study on the integration of knowledge in the engineering process has shown that the automatic combination of components and modules to complex production systems is a recent development trend [2]. A prerequisite for an automatic combination is identifying adaptable reusable modules. This contribution focuses on interdisciplinary modules in the field of automated production systems. The researched aspects comprise the modularization of existing systems, the identification of the right module-granularity, and the modeling of the identified modules.

2 State of the Art

Despite ongoing efforts in the field of research and in industry to implement reuses systematically, there are still many aspects which are strongly dependent on the experience of the particular developer. One such aspect is determining the appropriate granularity of a reusable module in order to reuse it successfully [3,4]. The difficulty is to decide which level of granularity the module must have in order to function appropriately in a future project. The term granularity stands for the number of subsets of an element. In software architecture granularity differentiates between fine, medium and coarse-grained levels. In the case of reusable modules we speak of fine-grained, medium-grained and coarse-grained modules [5]. A fine-grained module is mostly passive and has a short processing time. In contrast, a medium-grained module is mostly active or interactive. Finally, coarse-grained modules are active units which check and control processes units and have a longer processing time as well. Fine-grained modules can be reused in many projects. Additionally, fine-grained modules show greater flexibility because only those modules which match a project-specific application are chosen. However, many adjustments are necessary and mistakes are possible during integration so that the stability of the whole system can be at risk [6]. On the other hand, if the reusable modules are coarse grained, a major part of the functionality or structure of the automated systems will be covered. Only few adaptations are then required in order to construct the model of the entire automated system. However, this greater efficiency comes at the cost of flexibility and the amount of reusability. The reason for this is the reduced probability that the modeled features at the coarse-grained level will be appropriate for further automated systems. A module-based engineering method of automated production systems has been described by Weyrich et al. [7]. The blue print that results from this method can be verified by simulation tools with regard to the function, performance or energy consumption [8]. Various approaches have been analyzed to increase the reusability of the identified modules [9]. Other approaches are pursuing the issue of reuse of very small, mechatronic units [10]. The demand for the adaptability of the modules results primarily from the aim to modularize production systems, not products. The production volume and the degree of standardization are benefits that can be used in the design of product architectures [11], while automated production systems are manufactured for specific applications in small number. Therefore, the adaptability and reusability are requirements for the configuration of production systems in contrast to the configuration of products [12]. The modular design of automated manufacturing systems is comparable to a modularization in the process industry [13]. The aim of the module identification for configuration systems is to increase the reusability of the modules with high complexity. In contrast, the modularization for configuration of products aims at improving the manufacturability or suitability of service [14]. The reusability of artifacts is an aspect of the systematic improvement of the engineering process described by Fay et al. [15]. Especially the comprehensive reuse of modules in different engineering phases requires adaptability of the modules. The reuse of adaptive, mechatronic modules should be implemented as part of integrated engineering tools. An evaluation of the possibility of cooperation of such tools has been presented in [16]. The development of a new system for conceptual design of mechatronic systems has been presented in [17]. This tool allows specifying systems by reuse of mechatronic modules. In contrast to the adaptation of mechatronic modules the adaptation of software components has been already analyzed [18]. For an efficient development through the reuse of modules, the derived modules of existing systems have to be modeled with defined inputs and outputs. In this way an analysis of dependencies of the elements within a module and between different modules is possible. In order to show discipline-specific as well as interdisciplinary dependencies of the elements in a module a port based approach for the modeling of mechatronic modules and their functions is proposed in [19]. Each component is defined through its input and output-ports, containing either a flow of a physical quantity or an information flow. A prerequisite for an application of reusable modules in industry is the compatibility to engineering tools. Maga et al. [20] identified that currently available engineering tools cannot deal with the dependencies between software and hardware components. Bassi et al. [21] propose a hierarchical SysML (Systems Modeling Language) [22] framework for the machine and plant manufacturing industry. The system is modeled with different levels of granularity and each level can be mapped onto the other levels. However, modularity was not the focus.

3 Methodology for Modularization

3.1 Modularization

Existing automated production systems are analyzed for the identification of reusable, adaptive modules, which consist of several components. The dependence of the components of these production systems to one another can be shown in a design structure matrix (DSM) (Fig. 1).

	1	2	3	4	5	6
component 1	x	x				
component 2	x	x				x
component 3			x			
component 4				x	x	
component 5					x	
component 6	x	x				x

	3	1	6	2	4	5
component 3	x					
component 1		x		x		
component 6		x	x	x		
component 2		x	x	x		
component 4					x	x
component 5						x

Fig. 1. Design Structure Matrix (left unstructured, right structured)

The illustrated relationships between the components emphasize that a component depends on another component, in order to fulfill its function. The representation in the DSM allows analyzing the relationships between the components. The components which have strong dependencies among each other, can be summarized by sorting of rows and columns. This allows the clustering of components into modules (marked red in Fig. 1). The resulting modules are assigned to functions in order to systematize them. This enables the identification and selection of appropriate modules based on a functional description of the automated production system. This systematization also allows the interchangeability of modules. Optimization within the engineering and a conceptual revision of existing systems are further outputs. A performance evaluation of the modules enables selecting not only modules which perform a function, but modules that perform the function under certain criteria best. The reusability of the modules is improved by various adaptations e.g. adapting the granularity.

3.2 Adequate Granularity

Reusable modules include structure and performance or take into account overlapping aspects in regard to automated systems. In this way requirements, software components, electrical circuit plans, reference architecture, test cases or processes can be conceived and modeled in a reusable way [23]. However, this requires that the modules feature an appropriate granularity. Following this approach the creation of reusable modules takes place independently of a project. These modules can be implemented during the actual realization of a project. The method offers the instruction on how to determine the level of granularity of the module as well as how to raise the quality of the reutilization [24]. Thereby the following points should be taken into account:

A1: *Conflicting Requirement*
In most cases the domain requirements are competing, since they intend to fulfill a broad field of different functionalities. The reusable modules should be created as detailed as possible, in order to offer concrete support during application engineering [25]. In order to deal with competing requirements, it is necessary to build reusable modules in a modular manner. The modules should have a similar level of granularity, in order to be interchangeable.

A2: *Different Levels of Granularity necessary for Reuse in separate Disciplines*
The different disciplines imply different levels of granularity. Even within one discipline, different project phases require different levels of granularity. It is very difficult to propose a certain level of granularity for a reusable module if this changes depending on the project phase in which it is instantiated. Therefore, it is reasonable to provide modules that cover different levels of granularity. This can be achieved by designing reusable modules in a hierarchical manner. The top-level of such a reusable module should be coarse-grained, with many configuration and parameterization possibilities. The bottom-level of a nested module should be fine-grained. This should be detailed, specific and easy to change. However, it is crucial to ensure consistency

between nested modules. In addition, the used tool chain should support the stepwise creation of nested reusable modules [26].

A3: Different Levels of Granularity in Domain and in project development
In advance, it is sometimes unclear which level of granularity is required for a certain module. In order to mitigate this problem, we propose carefully analyzing the application development process. Which modules are required, depends on the concrete process. Next, the granularity-level necessary for the created reusable modules is analyzed. Then it should be mentioned whether a reusable module created can provide the required level of granularity. Combining lower level components and higher level template guides for the integration of the components is essential for successful reuse.

A4: Mismatch between Reusable Modules
Structure, behavior and crosscutting aspects should be bundled to large blocks, attached to the same module in the reference architecture and finally reused together. If these aspects are modeled at different levels of granularity, it is very difficult to group them to a bundle and to reuse them together. The systematic development of reusable modules could solve this problem. In this case, the different disciplines are obliged to work together from the very beginning. This increases understanding for adjacent disciplines. In regard to the granularity level of the modules, it is necessary to enable connections between reusable modules which have the same level of granularity.

A5: Thorough documentation
Reusable modules should be well documented, in order to be found in the domain repository, recognized as appropriate for the specific project and finally to be reused. Reusable modules should contain the description of their functionality and the description of how to be reused. Behavior, structure, origin and quality of reusable modules should be included in the documentation of the model. In the case of coarse-grained modules, providing a concrete description of configuration and parameterization possibilities is indispensable. It should be clear which variants are covered by the module and where changes are necessary, in order to obtain the variant required by a specific project. In case of fine-grained modules, a description of functionality and interfaces should be provided. Also, a mechanism to find reusable modules with an appropriate level of granularity for a concrete project phase or discipline has to be realized and links to required, recommended or optional modules should be offered.

3.3 Adaptability

The reusability of modules in the development of new machines or plants requires a modular structure of the system's model. The SysML framework offers the possibility to decompose a system into sub-systems, or modules, which can be modeled separately. Included in the models are the requirements, the behavior, and the structure of the system or module. For a representation of the models the SysML offers nine diagram-types as shown (Fig. 2). The diagrams, which are the most useful to model adaptive reusable modules, are highlighted in Fig. 2.

The requirement diagram is used to show the requirements which have to be fulfilled by the specific module and their relationships. The modeling of requirements for the reuse of modules is necessary, as the functions executed by the module and the used components derive from the requirements. The activity diagram represents the functions or the 'workflow' of the module. This diagram is especially important as the modularization of the system in this methodology is based on the functional dependencies of the elements (see section 3.1). The block definition diagram (bdd) and the internal block diagram (ibd) show the structure of the system. While the bdd is used to show which modules form the required system, the ibd illustrates how the different elements are deployed within a module and which logical relationships exist between the different elements. An important prerequisite for the reuse of modules is their adaptability. New requirements as well as forced innovations, e.g. the withdrawal of a component, make changes in modules necessary. These can affect the development of a new system, but also can have an influence on existing systems. The identification of change influences is important, as the exchange of an element can result in a multitude of required changes of other elements, leading to unexpected costs and time delays. As the influences of an element on others often are interdisciplinary, we propose to form interdisciplinary modules, including mechanics, electronics, and software and to integrate all views into the model.

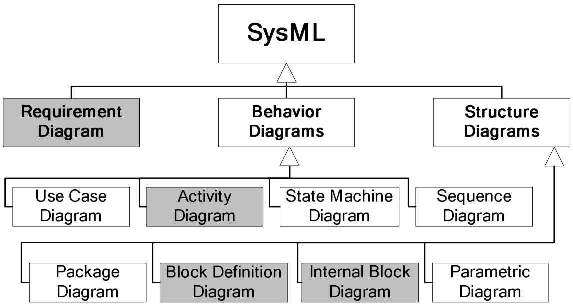

Fig. 2. SysML diagrams [22]. Diagrams, necessary for reusable modules, are highlighted.

4 Use Case

For the described methodology a bench-scale model of a stamping and sorting plant serves as a use case. It consists of a stack depot, a crane, a stamp module and a sorting belt and executes typical steps of a manufacturing process.

4.1 Modularization

The described system is modularized by the method described in section 3.1. An extract of the DSM and some resulting modules are shown in Fig 3. If they include at least four relationships, the components are clustered into modules. The relationships are expressed by numbers in the following. A one indicates that a relationship exists. Central components such as control are split for modularization. Therefore, it is assumed that the production systems are distributed and decentralized. In this case, the sorting of the rows and columns and the definition of the modules was done manually. The matrix, in which the relationships between the components of the system are shown, is not symmetrical. Consequently, a component in a row can affect the component in a column, but not necessarily vice versa. Thirteen modules result from the modularization of the exemplary system described. The example shows that the resulting modules map the functions of the example system. These functions are storing, passing, stamping, passing and sorting. Exemplarily the functions of passing are described which are realized by a crane. The functions of the crane are the material transfer from the storage and from the stamp to the conveyor belt. Both functions are represented by appropriate modules. In addition, control modules have been identified for these function modules. Other modules are for communication and for data input.

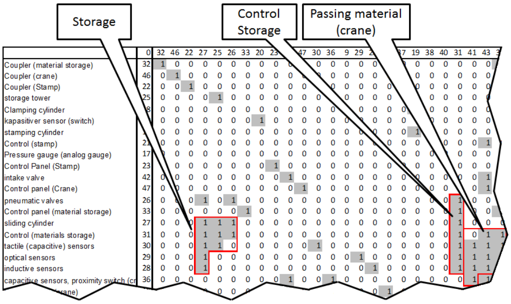

Fig. 3. Extract of the structured Design Structure Matrix

4.2 Granularity

The adaptive reusable approach mentioned above has been concretely deployed in the case study for the domain of stamping and sorting plants. We created reusable modules of physical structure and of the behavior of the stamping and sorting plant and stored them in a repository. Subsequently, we executed the activities of engineering, in order to simulate the construction of a customer-specific stamping and sorting plant. The goal of the case study was twofold: first, to evaluate the approach and identify necessary refinements, changes or completions. Second, to investigate the granularity levels appropriate for the reusable modules. In order to provide an optimal support for application engineering, adaptive reusable modules shall be created as detailed as possible. Templates, customizable CAD-drawings, and customizable wiring diagrams shall be created independent of a certain customer order. They should contain all basic information necessary to accomplish a well-defined engineering step. This implies first, appropriate activities should be included in engineering to prepare templates. Second, information regarding required forms of reusable artifacts and their level of granularity shall be fed back to engineering process. It is difficult to find the appropriate levels of granularity for adaptive reusable modules. For this purpose we should consider both the domain requirements and the intended reuse of the concerned modules. As general recommendation, we suggest to use well-documented, hierarchical and nested modules, which provide different levels of granularity depending on the required functionality [27].

4.3 Modeling

A modularization of the stamping and sorting plant through a DSM (see section 4.1) has shown that the system consists of the interdisciplinary modules storage, crane, stamp, and sorting system. In a first step the system is divided into this structure in a bdd (Fig 4). The different modules contain a list of the used parts, however the internal structure is not depicted. Thus, this representation has a very coarse granularity, and is used to give an overview of the entire production system and its modules.

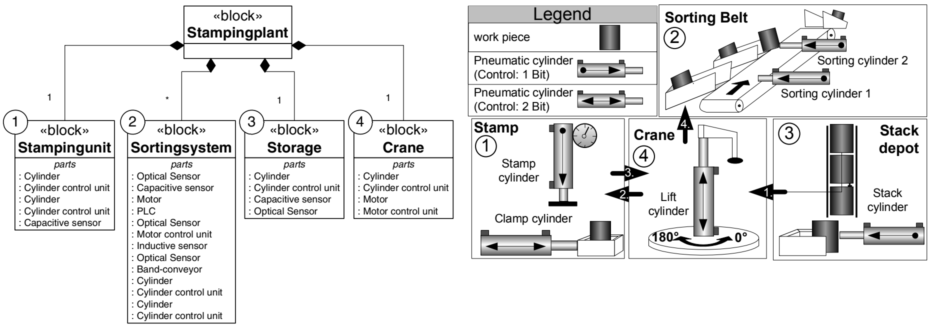

Fig. 4. Extract of the bdd of the stamping and sorting plant

In the next step the modules are modeled in detail. Each module executes certain activities within the system. The main activity is detailed to sub-activities in an activity diagram. The sub-activities conducted by the sorting-system would be for example: Notice workpiece (WP), Move WP (Pos. 0-1), Identify metal WP, Sort out metal WP, Move plastic WP (Pos. 1-2), Identify white plastic WP, Sort out white plastic WP, Move black plastic WP (Pos. 2-3). The described activities are conducted through components of the respective module, whose structure is modeled in the ibd. It includes mechanical components, e.g. band-conveyors, and electrical/electronic components, e.g. sensors. The software steps are excluded to keep the diagram clear. However, the interfaces between software and other components are included in the ibd through the integration of input and output ports of the PLC. In this way the output port (e.g of a sensor) can be connected to an input port of the PLC. The software steps can be modeled in a separate view (as sub diagram). The modules contain next to the ports of the elements also global ports (ports on the border of the ibd), which constitute the interfaces to other modules. By modeling the identified modules in the described way they can be reused in the development of a new production system. As the influences of each component on other components, discipline-specific as well as interdisciplinary, are shown through the connections of the respective input and output ports, the modules stay adaptable and change influences can be analyzed.

5 Results of the Use Case

The employment of the methodology on the use case has shown that adaptive modules with an appropriate level of granularity can be identified in existing systems and modeled for a reuse in new systems. However it is difficult to develop detailed artifacts, because they have to cover more requirements than a specific product has to. Many requirements contradict each other, so that they cannot be integrated in one module. If coarse-grained modules are developed, they can cover the requirements of an entire production line. Unfortunately, they cannot be utilized/applied for specific problems. On the other hand, fine-grained modules, although they can be applied for specific problems, don't have a high quality level of reusability. The case study has shown that the modules that cover a wide range in a domain are coarse-grained. However, for the specific realization of a requirement fine-grained modules are needed.

6 Conclusions and Outlook

In this paper a methodology for the identification and the modeling of adaptive reusable modules for automated production systems was presented. The methodology is based on three steps: First an existing system is analyzed on functional dependencies between its components and is clustered accordingly. Second, the right level of granularity has to be identified. Thereby a tradeoff between reusability and number of included components has to be made. In the third step the identified modules are modeled in the SysML framework, to make an effective reuse in new projects possible. The modules for automated production systems hereby are interdisciplinary (mechanics, electric/electronic, software) as many dependencies exist between the different domains. The methodology was applied to a bench-scale model of a stamping and sorting plant. The steps were carried out thereby manually. Thus, in future research a suitable tool will be developed, which makes an automatic component clustering to modules with an appropriate level of granularity possible. This tool should have an interface to common modeling tools, to import the identified modules directly. The long-term goal is the support of the design of modularized plants. Therefor the interdisciplinary modules should be stored in a library. Based on the collection of modules, new machines or plants can be designed by combining different modules.

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Reverse Engineering for Manufacturing Approach: Based on the Combination of 3D and Knowledge Information

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Abstract. Today industrial companies are still trying to optimize in terms of time and cost the re-manufacturing of mechanical components. They need to directly define a new process planning from 3D information (points cloud, drawings…). This paper proposes an approach called Reverse Engineering For Manufacturing (REFM) which allows to directly obtain a CAPP (Computer Aided Process Planning) model from 3D and knowledge information. Routine tasks will also be taken into account. In this paper, RE is considered as a specific domain and concerns parts where no information is available on them. The system management is based on Design For Manufacturing (DFM) approach and enables to manage manufacturing information (the number of fixtures, the kind of milling operations...). Additionally, the future REFM system will have to propose alternatives for CAPP models. Therefore the main innovative point of REFM is to develop “manufacturing knowledge extraction” phase which is the aim of this paper.

Keywords: reverse engineering, manufacturing, knowledge extraction, process planning, Design For manufacturing.

1 Introduction

Reverse Engineering (RE) is the process that is used in several domains like mechanical engineering, electrical engineering, computer sciences and so on… In this paper, we focus on reverse engineering of mechanical parts. In this context, RE is used to create a CAPP model of an existing physical part from 3D information. The 3D information like 3D points cloud is obtained using 3D scanning technologies. In this study, the following context is considered: there is no information on the part (no plan or scheme); only the physical part is available. So to remanufacture this kind of parts, we propose an approach called Reverse Engineering For Manufacturing (REFM). REFM will allow to define a method of RE of mechanical parts, supported by a software demonstrator. One hypothesis of this research is to consider that the methodology developed will be based on DFM approach. Indeed, the re-engineering of a part

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needs to be done through a systematic process that integrates the work of the designer and the product development team from identification of the problem until the final design of the product, offering a greater chance of success. REFM consists in providing a Computer Aided Process Planning (CAPP) model including a new manufacturing tree. This tree must be selected by optimizing the manufacturing sequence and define alternatives operations which aim to facilitate and optimize the re-manufacturing. REFM aims to integrate databases that contain all the necessary information for the construction of the CAPP model. In this context, the system of Ashby et al. [1] CES4.5 is adapted. The major advantage of this method is to integrate at the earliest the manufacturing constraints in the product's lifecycle. In addition, RE can also be a recursive process; routine tasks will also be taken into account. Nowadays, RE approaches including routine tasks begin to be supported by Knowledge Base Engineering Systems (KBS) [2]. These systems are efficient to quickly obtain CAD models based on functional features. These CAD models are successful for re-designing activities and then for defining a process planning. So, these systems are not adopted to obtain directly a CAPP model in a routine RE context. The main problematic of this paper is to explore how to adapt DFM to the RE context. The contribution of the paper is limited here to propose a prospective approach in a milling process context. This paper is structured as follow: section 2 presents a state of the art of knowledge based system for RE in order to highlight the way to support routine context, and a state of the art of DFM for RE context; next, section 3 proposes a prospective approach in a milling process context. A top of reducer is considered in this paper in order to illustrate our system. This case study will provide the basis of analysis of the system REFM.

2 The State of the Art

2.1 Knowledge Based System for Reverse Engineering

RE methodologies are able to duplicate complex parts; however they can capture a very low level semantics. Or, a CAD model is not only a geometrical model. Additionally in design, functional aspects are often attached to geometric shapes. So today, it is necessary to integrate in a RE process these semantics to the geometry. Actually, many researches are discussed the importance of knowledge management of RE. For example, Mohaghegh et al. [3] propose to involve a pre-knowledge on the part before performing the reverse engineering activities. The works of Fisher [4] explore the possibility to extract features even in very noisy data and that by using "knowledge based" techniques. To select surface types and manufacturing actions, he exploits engineering knowledge and functional constraints with some user assistance. Or in their works, the knowledge is implicit and is not driven by a methodology. Thompson et al. [5] describe a classical geometric features-based reverse engineering system (Reverse Engineering Feature Based - REFAB). The developed prototype creates interactively the CAD model of a part where the user selects predefined features in a list and chooses where these features are located in the 3D points cloud. So, manufacturing knowledge extraction is achieved implicitly by the user. Only five manufacturing features (such as types of pockets and holes) are performed and 2.5 is considered.

Certain types of knowledge allow extraction of geometrical primitives. As an example, the VPERI [6] (Virtual Parts Engineering Research Initiative) project was created by the US Army Research Office in order to provide the vision, strategy, and methodology to help solving problems of long life cycle product maintenance. The knowledge of the geometric shape is necessary but not sufficient to reproduce the part. Re-engineering and re-design need functional specifications. A design interface is used to allow the additional of knowledge in the form of algebraic equations that represent engineering knowledge such as the functional behavior of the components, the physical laws that govern the behavior, etc.

The KBE for reverse engineering context is a good solution to reverse a part and obtain a CAD part. It is often based on functional knowledge to reverse the part. So, the manufacturing knowledge is not really integrated. In the scientific literature, CAD model is obtained from points cloud. Then, process planning is redefined from this CAD model. In this case, feature extraction/recognition based approaches are used and often characterized as knowledge based. For instance, Zhou et al. [7] use feature recognition/extraction and feature based design to integrate CAD and CAPP systems. Or, our approach REFM consists in identifying directly the CAPP model from the points cloud. Hence, KBE is used to extract knowledge on manufacturing. This knowledge explores the possibility to adapt the concept of DFM to the RE context.

2.2 Design For Manufacturing for RE Context

As mentioned above, REFM is a RE methodology that aims to directly define a new process planning of a mechanical part. This approach is based on the combination of 3D and knowledge information. These knowledge should be manage and should be integrate in the re-design stage to reach an optimal CAPP model and then to achieve a successful RE process. It is for these reasons that DFM methodologies are more appropriated. In the literature, Kerbrat et al. [8] bring a new DFM approach to multi-process manufacturing. This research considers that the choice of the manufacturing processes is based on the determination of the manufacturability complexity and the time/cost estimation at the design stage. Zhao and Shah [9] proposed a DFM shell for aid to manufacturing analysis in taking into account technics and economics data. Other work aims to reduce the manufacturing cost and time, so it turns to optimize the product form, material selection, and resource selection [10]. Gupta et al. [11] proposed an approach to select processes and materials during embodiment design based on the cost estimation. CES4.5 (Cambridge Engineering Selector) system of Ashby et al. [1] includes a database oriented on the triple characteristics: Process, Material and Geometry. In this database, all numbered characteristics are limited by intervals which show the manufacturability. For this paper, the DFM approach is limited to the context where a designer has to define a product in the point of view of manufacturing process. The manufacturing process view in REFM has to be in the technical data with accurate details such the fixtures, kind of machines, kind of tools and so on…

REFM has to integrate databases which include all these information according to the manufacturing resources of the company. In this context, we utilize a database which combines the system of Ashby et al. [1] with other information from handbooks such as [12]. In the following section of this paper, the REFM method will be revealed and the prospective interfaces will be proposed through a case of study.

3 REFM Methodology

REFM is a methodology which concerns components that are get out of the product lifecycle. The inputs points of REFM method are the digitized part and the manufactured part. To recall, all precedent capitalizations of the original product lifecycle are lost. So, Manufacturing knowledge extraction phase will be based on user's suppositions. The aim of REFM could be considered such as the combination of geometrical approaches (segmentation) and aided process planning methodologies (manufacturing knowledge extraction) of design context. The main innovative point of REFM is to develop "manufacturing knowledge extraction" and to define how it is possible to adapt to RE context in this contribution. Figure 1 shows the REFM methodology in details where Manufacturing knowledge extraction phase is developed. The different modules used in our methodology are described in the following sections.

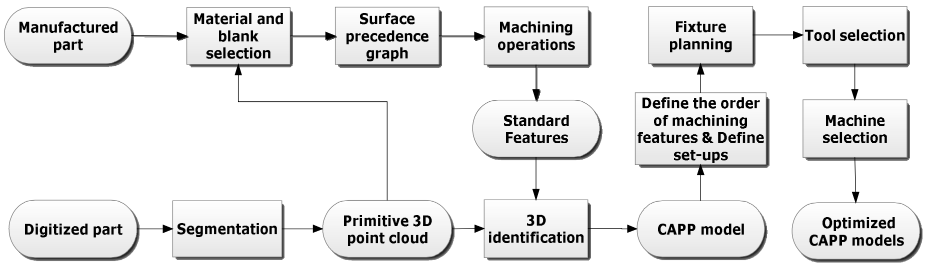

Fig. 1. REFM methodology in details

3.1 Segmentation

To start, according to related works on RE, REFM should import RE files such as 3D points cloud or STL (STéréo Lithographie) file. As a supposition REFM starts when treatment operations of cleaning STL or points cloud are previously executed. The segmentation phase is used here in order to detect surfaces (plan, cylinder, spherical, and conical surfaces) without geometric parameters. It consists in the division of the 3D points cloud of a given part into a set of n points clouds representing the n surfaces that compose this part. In the RE process, this phase can be performed by one of the following three segmentation techniques: Region-based technique [13], Edge-based technique, and Hybrid technique.

If we apply the first technique on the top of reducer, the 3D points cloud will be divided into 36 surfaces (figure 2). Note that if some surfaces are not recognized, the user can enter the data for unrecognized surfaces. This aspect of the software enables the handling of any complicated part. This paper does not deal with the segmentation phase. It is mainly focusing on Manufacturing knowledge extraction phase.

3.2 Manufacturing Knowledge Extraction

a. Material and blank selection
After the segmentation phase, the DFM process can start. To select the material of the part to be re-engineered, REFM asks the user to enter its mass. Then, the system calculates the volume of the part from the 3D points cloud file and that to obtain the density. Once REFM has the density, the system CES4.5 of Ashby et al. [1] is to be used. The system proposes some materials and according to their needs and their experiences; the user chooses the material that he finds the most appropriate. If the user did not find the suitable material, he can add additional material.

The following step of DFM analysis is to determine the original blank of the part. To recall, REFM concerns milled parts. So, the blank comes from a precedent process step of the part. REFM can propose an original blank from primary processes: the extraction process of raw (rolling, extrusion…) or the process of shaping (casting, forging…).

b. Surface precedence graph
The surface precedence graph connects machining surfaces between them by starting from raw surfaces (figure2). Each surface is represented by a circle containing the type of the surface (B: raw surface, F or A: machined surface). The arrow starts from a reference surface and ends at a referenced surface. Geometric and dimensional tolerances help the user to draw this graph. Hence, references surfaces are to be machined prior to the machining of the referenced surfaces, or the reference and the referenced surfaces should be machined in one set-up. So, based on the combination of the Ashby database and using a manufacturing method of analysis: REFM asks the user to select a machined surface and its reference one, then REFM proposes one or more tolerances and the user can chooses the tolerances that he finds the most appropriate, as we show in figure 2. After that, the user enters by supposition the tolerance class and the roughness of the surface (the user can measure the roughness by a roughness meter).

c. Machining operations
Using the above data and based on a cutting tools database [14], the user searches for a logical grouping of machined surfaces. Indeed, the accessible surfaces by the same tool should be grouped to be machined at the same time. For example, selected surfaces (F3 and F6i; i = 1 to 8) in figure 3 are combined in a group called GF. In addition, REFM can propose groups of surfaces in the case of routine tasks.

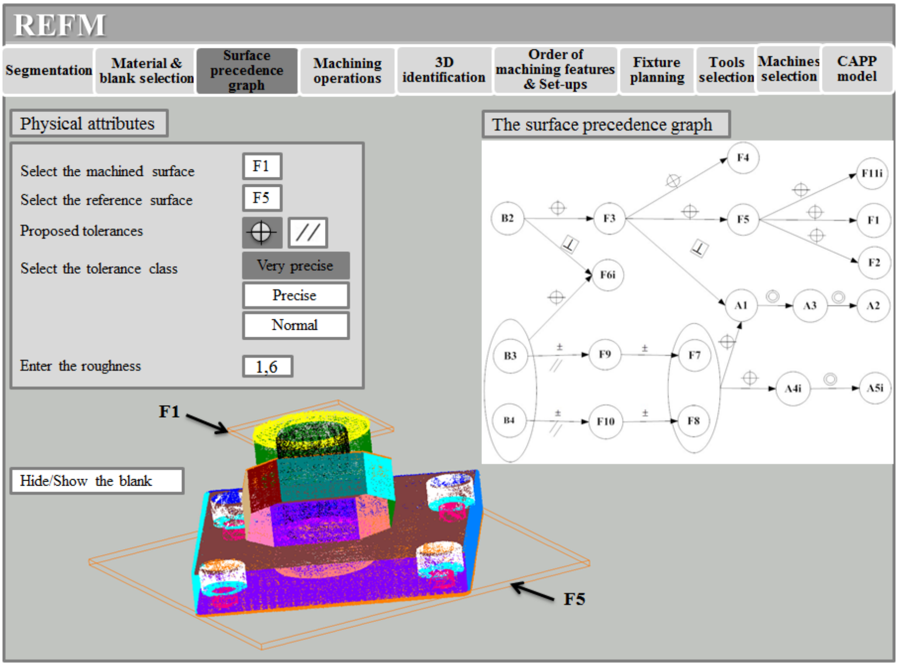

Fig. 2. Interface of the surface precedence graph in REFM

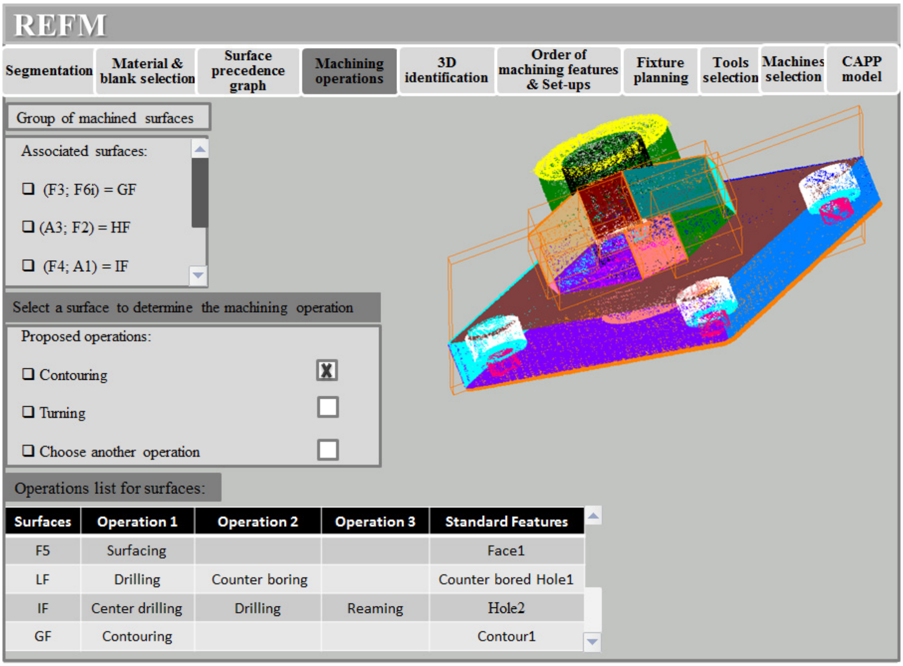

Fig. 3. The selection of machining operations in REFM

Many details affect the selection of machining operations such as: the shape, accuracy and surface finish requirement of the surface, the overall structure of the part, and the workpiece material. In fact, Ashby et al. [1] explain that the best solution of design for manufacturing is retained if decisions of materials, geometry and processes are taken into account simultaneously. And based on the surface roughness, the system determines the number of operations to reach the final surface finish requirement (rough, semi-finish, finish). REFM tries to select alternatives routes to machine each surface or group of surfaces. And thus, the user has the option to choose its appropriate route. Note that the user can change the machining operations according to requirements. After that, standard features can be generated. Indeed, a feature is the combination of surfaces coupled to an operation.

d. 3D identification

The previous steps allow the user to obtain machining operations, standard features and so on. Each operation, for example, the contouring of the feature selected in the figure 4 should be linked to geometry. This geometry will start from the blank and will decompose to the final part. 3D identification serves to translate operation steps of manufacturing process in geometry. To make this modeling, REFM uses Skin and Skeleton concept. In fact, for each skin and Skeleton element [15], an included script in the database performs an algorithm based on the least squares approximation. This step is extremely important in our approach; it is already addressed in our previous work [16]. The output of this module is a primitive CAPP model including machining operations that are not yet defined in order (figure 4).

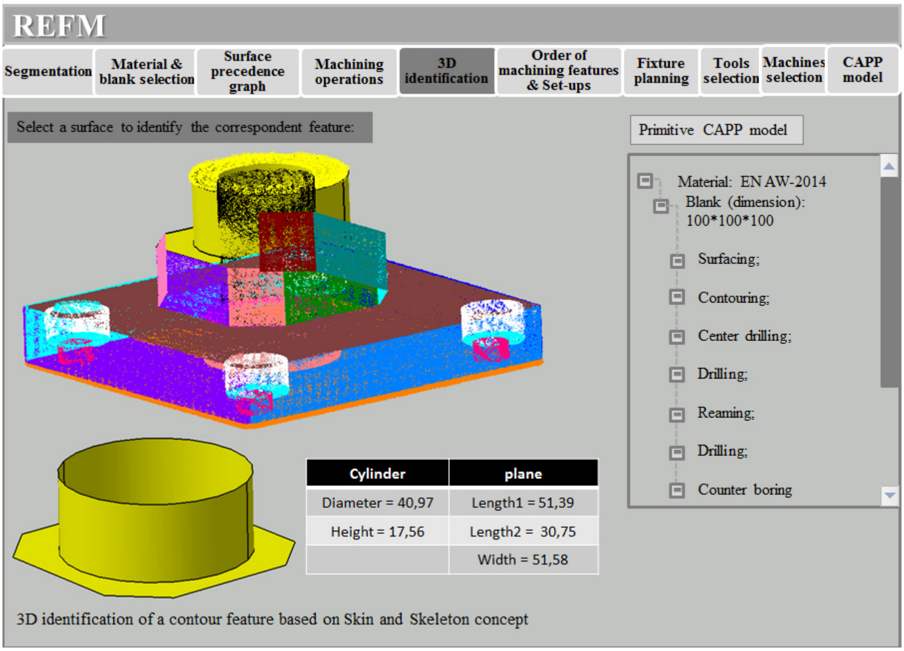

Fig. 4. 3D identification module in REFM

e. Define the order of machining features & Define set-ups
The order of machining features of the re-engineered part depends on non-geometric information such as geometric dimensions and tolerances. So to reach feature sequencing, REFM returns to the data mentioned in the Surface precedence graph module. In addition, REFM will integrate simple rules taken from Handbooks such as [12] which include constraints on the optimization of cutting conditions to perfect the order of machining features. For instance, if the part to re-engineer contains a hole on an inclined surface, so it is optimal to machine the hole before the inclined surface since holes cannot be machined accurately on an inclined surface. Or, if the part contains a hole on a flat and smooth surface, so we start by the milling operation and that to not plug the hole as in our case. After that, REFM groups the features into set-ups. Set-up design should be such that a maximum number of features can be machined with a minimum number of set-ups. Before proceeding to the next step, REFM asks the user if he is satisfied with the proposed sequence. If not, he is allowed to change the order, based on his own experience and knowledge.

Next, fixture planning module will to be achieved. According to 3-2-1 method (locating method for prismatic parts), the user can select the surfaces of fixtures. Then, REFM selects for each feature, from the cutting tools database of Sandvik (www.sandvik.com), 2 or 3 cutting tools based on geometric parameters and surface finish requirements of the correspondent feature. And then the user can choose the suitable one according to him. Finally, REFM selects for each operation one or more machines. To choose the best one, it considers a set of criteria. For example, the most suitable machine among those that are previously candidate, is the machine that

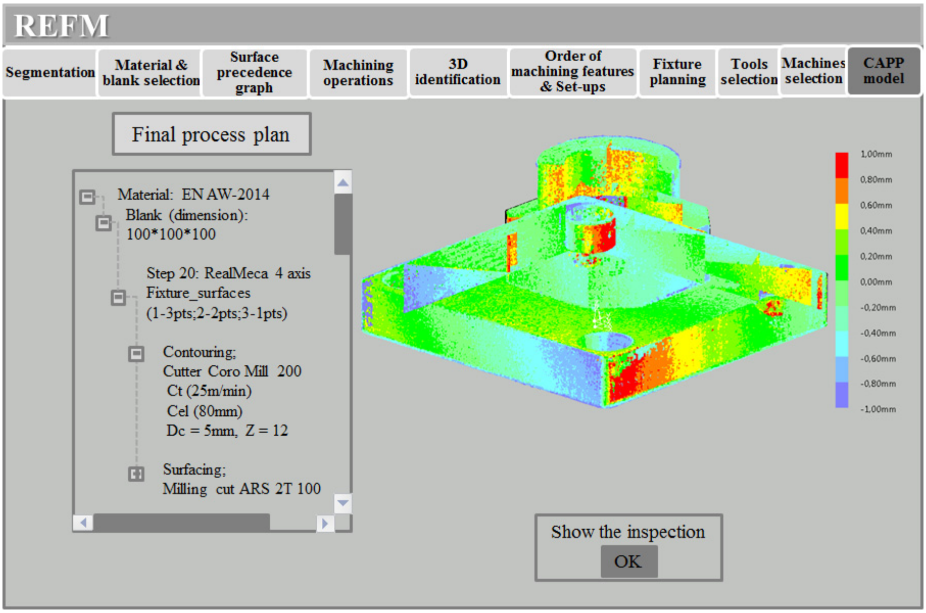

Fig. 5. The final CAPP tree and the inspection with the RE files

realizes the maximum number of operations with the maximum number of set-ups. Note that the user can enter information on the means of production available in his enterprise, which allows constraining the suggestions provided by the system.

Thereby, the process plan is generated by REFM system (figure 5). In addition, the user can show by inspection, the distances between the RE files and the CAPP model decomposed in machining operation steps.

4 Conclusion

This paper proposes a new method for re-manufacturing mechanical components. Indeed, industrial companies of the cluster NOGENTECH have to define a new process planning from 3D information (points cloud, drawings, etc). Or, late commercial solutions, such as GeomagicTM, RapidFormTM and CATIATM are more efficient to obtain a CAD model. Nevertheless, the industrial who needs to define a CAPP model redefines the process planning from this CAD model. REFM is a methodology based on DFM approaches and focuses on the milling process. According to the related works, the Ashby et al. [1] classification seems to be a way of resolution. The future REFM system provides a Computer Aided Process Planning (CAPP) model including new manufacturing tree. This tree must be selected by optimizing the manufacturing sequence and define alternatives operations which aim to facilitate and optimize the re-manufacturing. Each milling operation is a Skin and Skelton feature which is fitted in the 3D information. The aim of REFM system is really to propose a prototype software which can be coupled in CATIA V5 and Solidworks. It means that REFM system is independent but could use the geometrical resources of commercial softwares. A final version is planned based on PYTHONOCC (OpencasCadeTM) resources in order to propose a complete independent software. After that, a next way will to be adding in the future created database: the cost aspect (evaluating the cost milling), the time consuming (the time of the process milling) and the sustainable aspect (to produce milling part in respect of environment).

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A Kinematic Approach for 6-DOF Part Positioning

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Abstract. This article proposes a fixturing system consists of a cuboid baseplate located through a 3-2-1 configuration of locators. The locators are mounted on machine table/pallet and posses one axial DOF. The workpiece is mounted on the baseplate and all the elements are assumed to be rigid with zero friction. The positioning error of the workpiece is calculated and the compensation is performed by the axial movement of the locators. The proposed analytical model is verified by the simulation performed in the CAD model.

Keywords: Analytical model, Fixturing system, Part positioning, kinematic model.

1 Introduction

There is a competition in the manufacturing industry to design and deliver a variety of high quality products to their customers in the shortest time. Due to rapid change in production technology and customer demand, the manufacturers need to develop flexible manufacturing practices to achieve a rapid turnaround in product development [1]. Among other factors, the use of feasible fixtures is one of the factors influencing the final part's quality. Fixtures are devices used to support, locate and hold a workpiece at a desired position and orientation in machine's workspace during manufacturing. The final part's quality is influenced by the capability of the fixture to precisely hold and locate it on the machine considering different functional conditions during fabrication. About 10-20% of total manufacturing cost is associated with the fixtures in traditional FMS systems [2]. The design of fixtures is important to precisely hold the workpiece and compensate the errors that the workpiece can encounter during machining or assembling operation, so that higher product's quality can be ensured [3].

The need of high quality production, at lower cost, has accelerated the research efforts in fixture design. To cope with current market demand, Ryll et al. [4] emphasize on the need of "intelligent" fixtures which should be capable of self-configuring; reducing and compensating dimensional errors; providing stability and adapting

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clamping forces to guarantee optimum performances. This fixture should be generic and should be able to adapt to different workpiece configurations.

2 Positioning Errors

Dimensional errors of the parts from a part family cause the initial misplacement between the workpiece and machine tool affecting the final product quality. The possible causes of the positioning errors between the machine tool and the workpiece are shown in Figure 1, which are:

- Error due to the placement of locators [5–8]
- Geometric/form defects of the workpiece [9–12]
- Errors due to deformation of locators [13–18]
- Kinematic defects/ machine tool errors [19–26]
- Misc. errors due to tool wear, heat, NC codes, etc…

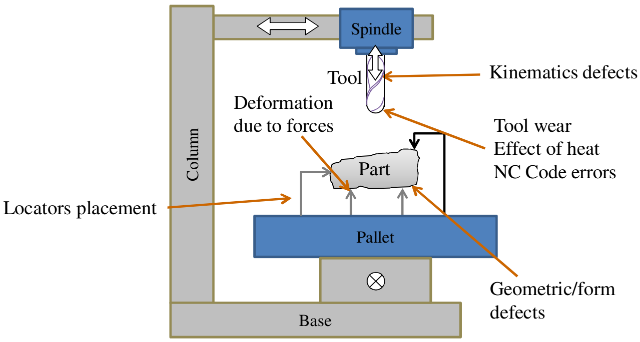


Fig. 1. Errors between the machine tool and the workpiece

Rough workpiece's dimensions are varied from one part to another, so the machining allowances have to be added. Even after the addition of allowances, the rough workpiece may not be completely included in required position, which causes the wastage of the workpiece due to incomplete machining. To avoid the loss of time and material, it is necessary to precisely place each new part relative to machine tool. But this placement needs a mobilization mechanism on the machine. This mechanism should assure the kinematic transformation to place the workpiece at an optimal position by compensating the positioning error between the workpiece and the machine-tool. A high number of degrees of freedom (DOF) machine would be an easy way to perform this compensation.

In an existing serial production environment, the global choice of 5-axis machines in the whole production line is not an economically feasible choice. So a new fixturing system is proposed. This fixturing system is able to perform a 6 DOF workpiece's repositioning on a low DOF production machine through the axial motion of 6 supporting locators placed at 3-2-1 configuration. The initial and final positions of the workpiece are given as the input data and an algorithm calculates the positioning error and the axial displacement of each locator required to compensate this positioning error.

The proposed system can be used on the existing machines as well as on automatic production lines where the number of axis is limited for each station. The proposed system allows better positioning of the workpiece on the fixture and hence limiting the required allowances. It also insures a prepositioning of complex parts for precise machining operations. The necessary geometric and kinematic models of the proposed fixturing system are presented in this article.

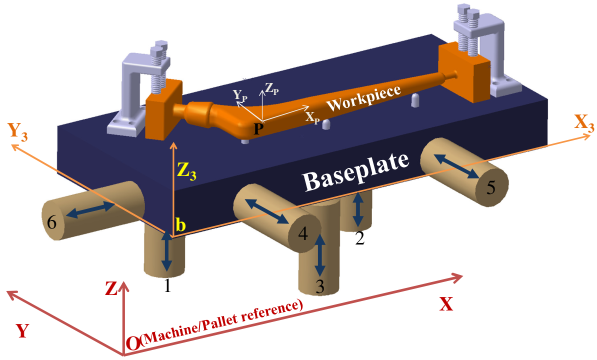


Fig. 2. Proposed fixturing system principle

3 Proposed Fixturing System

This article proposes a fixturing system consists of a set of six locators whose positions and orientations are defined through locating holes of the machine table/pallet, a cuboid baseplate, and a workpiece fixed on the baseplate as shown in Fig. 2. Hip prosthesis is chosen as the demonstrated workpiece because it requires repetitive machining operation on expensive material and the dimensions of part change according to patient need. The baseplate is introduced because when the locators are directly in contact with the rough workpiece surfaces, it is impossible to attain the precise positioning of the workpiece through the axial displacement of 6 locators due to uncertainty of the contacting points caused by the local geometrical defect at rough contacts. The positioning surfaces of the baseplate are considered to be perfectly plane and orthogonal. This assumption causes the surface normals to always remain parallel to the contacts' normals, which enables us to predict the exact location of the workpiece by the locators' positions. Thus the addition of intermediate baseplate avoids this positioning uncertainty: kinematic model will be independent of part geometry.

The locators are assumed to be in a 3-2-1r configuration [27] and possess only one axial DOF. The lateral position of each locator is chosen by considering the constraints of accessibility, stability of the workpiece and manufacturing knowledge. It is also assumed that the workpiece is mounted rigidly on the baseplate and no additional deformation occurs between workpiece and baseplate except those caused during clamping the workpiece.

3.1 Analytical Formulation

For kinematic analysis, all the elements of the fixturing system are assumed to be rigid. It is assumed that the positioning error of the baseplate is negligible as compared to the positioning error of the workpiece. Also the unknown initial position of the workpiece could imply large displacements (LD) during correction phase; the kinematic model is built using homogeneous transformation matrices (HTM) and LD formulation. The initial position of the workpiece can be measured through CMM while its final position is the position according to which the machine tool is programmed. This position is known by the part program. These positions are compared and if the difference is more than the allowed tolerance, the algorithm calculates the unique relative axial position of each locator to relocate the workpiece at the required position.

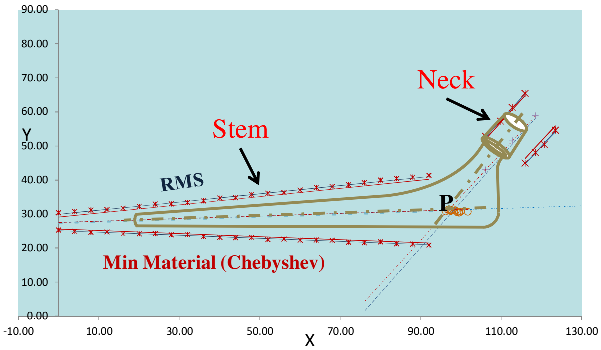


Fig. 3. 2D Demonstration of measurement though CMM

The measurement principle of the hip prosthesis though CMM (in 2D) is shown in Fig. 3. Rough part dimensions are larger than the final product. Random measured points are generated in MS Excel for stem and neck of the hip prosthesis. RMS and Chebyshevs' surface association criteria are presented [28], [29], and theoretical centerlines (for neck and stem) are then deduced. The angle between these centerlines should be under the tolerance range. Point P denotes the intersection of centerlines. In 3D space, the definition of point P, in machine reference, cancels 3 DOF; the definition of the XY plane cancels two more DOFs and the last DOF is canceled by defining the angle of stem axis with XZ plane, completing workpiece placement in the machine space. Some position variations among the parts of the same part family will remain. Random measuring points are generated and the point P is calculated for each set of measuring points. The generated distribution of P is also presented in Fig. 3.

The HTM of cuboid baseplate position is the function of its surface normals calculated from the positions of the six locators [12]. This HTM is shown in Eq. (1) where a, b and c are the unit vector components; 1, 2 and 3 are the unit vectors in Z, Y and X directions while x_b, y_b and z_b are the coordinates of baseplate origin.

$$[P_{Ob}] = \begin{bmatrix} a_3 & a_2 & a_1 & x_b \\ b_3 & b_2 & b_1 & y_b \\ c_3 & c_2 & c_1 & z_b \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Similarly, the HTM of the workpiece position in machine coordinates is defined considering YPR transformation as shown in Eq. (2) with α, β and γ being the rotations along Z, X and Y axes respectively.

$$[P_{OP}] = \begin{bmatrix} \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & -\sin\alpha\cos\beta & \cos\alpha\sin\gamma + \sin\alpha\sin\beta\cos\gamma & x_P \\ \sin\alpha\cos\gamma + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta & \sin\alpha\sin\gamma - \cos\alpha\sin\beta\cos\gamma & y_P \\ -\cos\beta\sin\gamma & \sin\beta & \cos\beta\cos\gamma & z_P \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Positioning transformation scheme of the proposed fixturing system is shown in Fig. 4 where X_i represents the position vector of reference i while $[P_{ij}]$ represents the transformation matrix from position i to j. The HTM of the baseplate with respect to machine reference ($[P_{Ob}]$) is calculated from the locators' initial positions. The transformation of the workpiece relative to the machine ($[P_{OP}]$) can be measured through CMM. Thus the required transformation of workpiece with respect to baseplate ($[P_{bP}]$) is deduced and HTM of the error compensation ($[P_{Ob'}]$) is calculated as shown in Eq. (**3**). Final absolute positions of all the six locators, required to compensate the workpiece positioning error, are shown in Eq. (4).

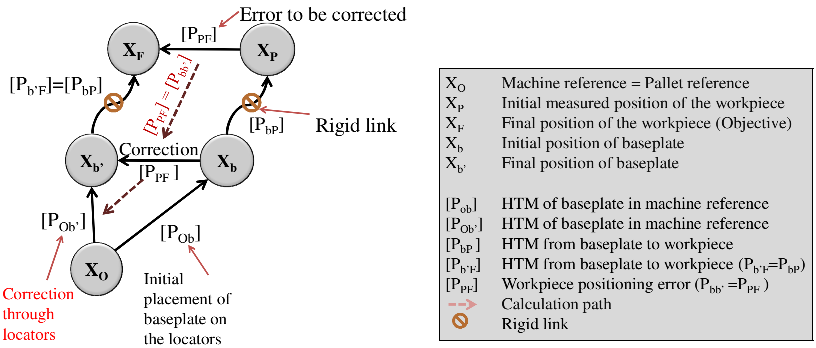


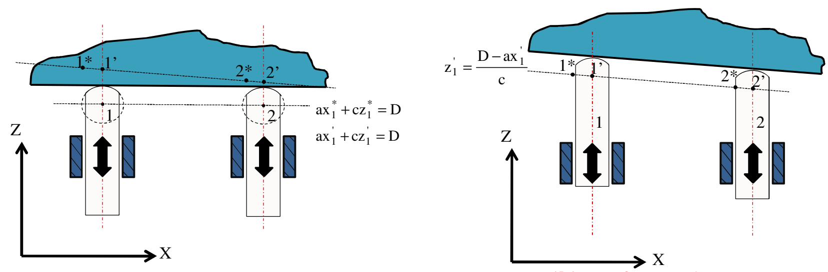
Fig. 4. Fixturing system reference transformation

$$\begin{aligned} [P_{bP}] &= [P_{Ob}]^{-1}[P_{OP}] \\ [P_{Ob'}] &= [P_{OF}][P_{bP}]^{-1} \end{aligned} \quad (3)$$

$$[P_{Ob'}] = \begin{bmatrix} a_3' & a_2' & a_1' & x_b' \\ b_3' & b_2' & b_1' & y_b' \\ c_3' & c_2' & c_1' & z_b' \\ 0 & 0 & 0 & 1 \end{bmatrix} = [P_{OF}]\left([P_{Ob}]^{-1}[P_{Ob'}]\right)^{-1} \quad (4)$$

The resolution of the above equations give the positions of locators which are impossible to attain because the contacting points of locators on the baseplate change as a result of rigid body motion of the baseplate on locators. This is shown with a 2D example in Fig. 5, where the final calculated positions of the arc centers of locators are shown by 1* and 2*. Due to the constraint of uniaxial motion, the locators cannot be advanced to these positions. To overcome this mathematical issue, a line is drawn between the points 1* and 2* (plane in our case of 3D), and the points of intersections of this line with the locators' axes are calculated. Moving the locators at these calculated positions will enable us to perform the required workpiece transformation. In the same manner, axial advancements of all the six locators are calculated through the contacting points of all three contacting surfaces. The final axial position of locator 1 is shown in Eq. (5) with a_1', b_1' and c_1' being the unit vector components of the baseplate surface. The advancements of the rest of the locators are deduced similarly.

$$z_1' = \frac{D_1 - a_1' x_1 - b_1' y_1}{c_1'} \quad (5)$$



(a) drawing line and calculating new axial positions (b) perform advancement

Fig. 5. Calculating the axial advancements of locators

3.2 Case Study

In order to validate the kinematic model, a case study is performed on a hip prosthesis repositioning through CATIA® simulation. A CPT® 12/14 Hip Prosthesis by Zimmer [30] is chosen as a demonstrative workpiece. The part is created in CATIA® with slightly larger dimensions and supports are added. It is supposed that this workpiece is clamped rigidly on the baseplate which is further located through six rigid locators. An inverse impression of the workpiece (like a half die) is created with the original hip prosthesis dimensions and is placed on a fixed position with reference to the machine origin. This position represents the tool path on the machine as the tool moves with reference to machine and not with reference to workpiece. Boolean operation is performed to simulate the machining operation by subtracting the common material from the workpiece. Two slots are made in the supports during machining of the first half part which will help to place the workpiece on two well positioned blocks after inverting.

The analytical model is implemented in a worksheet directly linked to CATIA® model which furnishes the initial position ($[P_{OP}]$) of the workpiece as shown in table 1(a). This position should be obtained by CMM in real environment. The initial position of the baseplate ($[P_{Ob}]$) is a function of locators' positions shown in Table 1(b). The machining performed on this initially roughly placed workpiece is shown in Fig. 6. The workpiece should be repositioned at the required position ($[P_{OF}]$) to perform a precise machining operation. This final position is known by the part program and is shown in the Table 2.

Table 1. Initial positions of locators and the workpiece

(a) Initial locators' positions (Axial positions are highlighted)

Locator no	x (mm)	y (mm)	z (mm)
1	70	100	15.00
2	180	100	15.00
3	120	40	15.00
4	70	10.00	40
5	180	10.00	40
6	8.00	60	40

(b) Initial workpiece position

Plane Angle	Degree	Point P	mm
α_i	0.75	x_P	102.62
β_i	-0.06	y_P	57.23
γ_i	0.45	z_P	70.19

Table 2. Required position of the workpiece (Objective)

Plane Angle	Degree	Point P	mm
α_f	0	x_F	100
β_f	0	y_F	60
γ_f	0	z_F	70

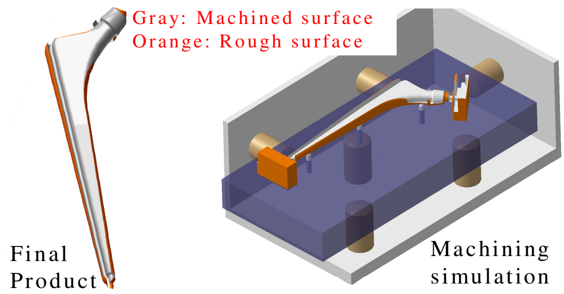


Fig. 6. Machining simulation on the workpiece at initial position

The algorithm calculates the final axial positions of all the six locators (Table 3) to compensate the workpiece positioning error. The locators are moved to these new positions and the machining simulation is re-performed. This time the material removal was uniform throughout the workpiece as shown in Figure 7.

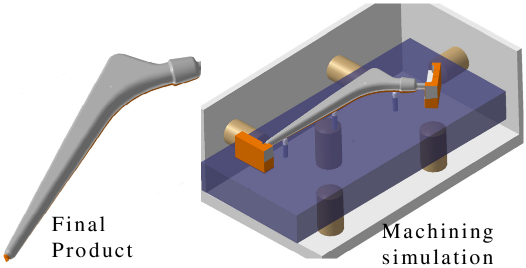


Fig. 7. Machining simulation on the workpiece after repositioning

Table 3. Calculated final position of the six locators (Axial positions are highlighted)

Locator no	x (mm)	y (mm)	z (mm)
1	70	100	14.62
2	180	100	15.48
3	120	40	14.95
4	70	13.20	40
5	180	11.75	40
6	5.61	60	40

Simple investigation reveals that the workpiece was not at the exact required position. The 6 DOF repositioning error of the workpiece is shown in Table 4(a) while the same for the second side is shown in Table 4(b). This positioning uncertainty is due to the limited advancement precision (10 µm) of locators. This positioning uncertainty can be expressed as robustness of the proposed model.

Table 4. Workpiece positioning error due to locators' precision

(a) First side of the workpiece

Plane Angle	Degree	Point P	mm
α_i	0.002	x_P	0.006
β_i	0.008	y_P	-0.004
γ_i	-0.002	z_P	0.001

(a) Second side of the workpiece

Plane Angle	Degree	Point P	mm
α_i	0.00	x_P	0.002
β_i	0.00	y_P	0.00
γ_i	0.00	z_P	0.00

3.3 Robustness of the Model

The workpiece position uncertainty is calculated from the Plucker coordinates[31] as the function of precision of locators' advancements. In our case, using the locators' input positions (Table 1. Initial positions of locators and the workpiece(a)), the uncertainty at reference point P (Table 2) is deduced as a function of six advancements,

$$\left\{ \begin{array}{c} \delta x_P \\ \delta y_P \\ \delta z_P \\ \delta\alpha \\ \delta\beta \\ \delta\gamma \end{array} \right\} = \left\{ \begin{array}{c} dx_6 - \frac{6dy_4}{11} + \frac{6dy_5}{11} - \frac{4dz_1}{11} + \frac{4dz_2}{11} \\ \frac{18dy_4}{11} - \frac{7dy_5}{11} + \frac{4dz_1}{11} + \frac{10dz_2}{33} - \frac{2dz_3}{3} \\ \frac{8dz_1}{11} - \frac{46dz_2}{33} + \frac{5dz_3}{3} \\ \frac{dz_1}{110} + \frac{dz_2}{132} - \frac{dz_3}{60} \\ \frac{dz_1}{110} - \frac{dz_2}{110} \\ -\frac{dy_4}{110} + \frac{dy_5}{110} \end{array} \right\} = \left\{ \begin{array}{c} 31/11 \\ 128/33 \\ 125/33 \\ 1/30 \\ 1/55 \\ 1/55 \end{array} \right\} \times \xi \tag{6}$$

where, dz_1, dz_2, dz_3, dy_4, dy_5 and dx_6 are uncertainties of the locators' advancements. In order to calculate the maximum positioning error, all the term are arranged so that their effect is added to the positioning error. The right most vector in Eq. (6) is the maximum positioning error as the function of precision of locators' advancements ξ, in our case, assumed to 10μm.

4 Conclusion

A fixturing system has been proposed which is capable of performing the compensation of the positioning error of the workpiece through the advancement of six locators. To allow a repetitive repositioning of irregular parts, a baseplate has been placed in between the machine table and the workpiece. The baseplate has been located through a 3-2-1 locating configuration and all the fixturing elements were considered to be rigid. The kinematic model calculated the locators' advancements which enabled us to relocate the workpiece indirectly by baseplate relocation. The kinematic model has been simulated in CATIA and the results verified the analytical model.

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Control Architecture for Plug-and-Play Intelligent Axes within Fast Reconfigurable Manufacturing Equipments

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Abstract. A new perspective on a control architecture, capable to increase the overall performance of the manufacturing equipment by endowing it with distributed intelligence, thus providing short ramp-up times, plug-and-play capability, great integrability and scalability, together with cost reduction, is presented in this paper. The architecture concept, based on the outcome of applying specific problem solving methods, shows an intelligent axis equipped with a network of smart sensors and units controlled and supervised by a master control unit. The proposed solution is based on both electronic and software designs in order to expand equipment performances and take a step forward in supporting manufacturing systems towards reconfigurability. An experimental testing bench has been constructed around a mechanical axis for exploring control architecture performances and intelligent axis concept feasibility. Results have shown that the proposed control architecture is functional, highly reconfigurable, cost effective, and the concept of intelligent axis is feasible.

Keywords: intelligent axis, reconfigurable system, control architecture, smart units, distributed intelligence.

1 Introduction

Starting over a decade ago, manufacturing environment and thus manufacturing systems became subject to continuous changes due to increased customer needs and rapid technological developments.

A manufacturing concept called reconfigurable manufacturing system meant to quickly respond to the forthcoming manufacturing needs is introduced by Koren and Mehrabi in the late 90s [1-2]. This concept comes with some advantages to the dynamically changing product varieties and batches, including lower costs, shorter ramp-up time and time to the market, easier to debug, reduced risk of becoming obsolete, etc. [3].

Modularity, integrability, customization, convertibility and diagnosability are the core functions of reconfigurable manufacturing systems (RMS). Among enabling

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technologies, modular machine tools and software, open control architecture, plug-and-play equipments and heterogeneous platforms have been identified [3].

Even if RMS concept it's not new, its core functions and enabling technologies are considered actual research directions in the Factories-of-the-Future (FoF) initiative roadmaps [4-5]; some of the research directions to which this paperwork is related are: open-control architecture, adaptability, reconfigurability, embedded intelligence, smart and Plug-and-Produce equipments.

This initiative is meant to help European Union (EU) small to medium sized enterprises (SMEs) to achieve sustainability and competitiveness in the turbulent global market [6]. One question that comes up is: What are the costs of implementing such technological developments that have to be supported by manufacturing SMEs?

Most of the current manufacturing systems of SMEs are characterized by traditional control architectures, built around programmable logic controllers (PLCs), which are still not able to provide the desired level of reconfigurability, as well as the background for implementing required functionalities on the go and thus they might not represent reliable solutions to the future control architectures for manufacturing systems.

This paperwork introduces the authors' view of an enhanced control architecture capable to increase the overall performance of manufacturing equipments by endowing it with distributed intelligence, thus providing short ramp-up times, plug-and-play capability, great integrability and scalability, extended configurability and control options, rapid customization, real-time assistance for system building and maintenance, still being cost effective, easy to build and develop.

The proposed solution is based on both electronic and software designs in order to expand equipment performances and take a step forward in supporting manufacturing systems towards reconfigurability. Equipment prioritization, system expandability, self-integration, communication options, short control loops, reporting of events, analog and digital data processing with respect to chosen configuration options and decision taking are investigated.

2 The Problem

Considering the current world economic crisis, when the EU manufacturing sector has experienced the biggest decline in the number of SMEs from all sectors [6], the global market instability and customer continuous changing requirements, strengthening manufacturing SMEs with sustainability and competitiveness is a must-target.

Lack of reconfigurability, modular structure of both software and hardware, interoperability between equipments, advanced diagnosability and limited functionalities of which traditional manufacturing systems are characterized, together with the desirable level of technological progress to be brought by implementing the FoF concept, represent a big step forward for manufacturing SMEs but also generate inevitable challenges: lifecycle cost management and effective development of the required infrastructure.

This paperwork presents a simpler concept of control architecture for plug-and-play intelligent axes that can be used within RMS, which might be less expensive if it is integrated and developed from the perspective of open-source philosophy.

3 Background

A smart sensor or unit is an embedded solution, built from the sensor or unit itself and a microcontroller [7-8]. In the microcontroller, distributed intelligence is implemented by software means. In this configuration, increasing the performance of the embedded system is a matter of creativity and innovation with respect to sensor capabilities and embedded hardware design constraints.

Also a similar concept to the one of smart sensors, to which the paper will refer from now on as smart units (e.g. smart motors, smart circuit breakers, smart contacts), is going to be introduced in this paperwork. An experimental bench, where an embedded design is employed to boost up the functionalities and control options of an electro-mechanical axis, is also considered.

The link between the control architecture, smart sensors, smart units and the human machine interface (HMI) will be done over the I2C communication protocol developed by Phillips [9]. The major facts that led to this communication protocol are presented by Murar and Brad in [7]; however, the communication protocol should be selected in order to better suit the served process.

4 Guidelines towards Innovation

In order to achieve the proposed objectives, innovative problem solving tools have been considered. The use of CSDT method [10] in combination with TRIZ method [11] have been used to approach two conflicting generic design problems: increased capacity of the system from the perspective of reconfiguration while keeping low costs for development and integration; and increased versatility/adaptability of the system while keeping low costs for development and integration.

For the first design challenge, the vector towards innovation is to change the concentration of functions and modularity. For the second design challenge, three vectors of innovation have to be integrated: change the concentration of functions, development of non-uniform structures and make some characteristics of the system's components to change. The most impacting generic module of the control architecture is the information management software, followed by the algorithms for equipment control and the interface with process information. For the smart sensors, the most impacting module is the interface between the configuration options and the operating rules, followed by the operating algorithms and the interface with the communication protocol. The same impacts are reflected in the case of other smart units (e.g. smart motors). Thus, the focus was on developing sensors, motors, etc. that are independent in terms of intelligence (building them as self-intelligent units, able to carry their own past events), ensuring that these intelligent units can change some of their operational functions (using software means for resetting), and making them capable to communicate immediately with other intelligent units for self-reconfiguration in new operational systems. In-process configuration without losing information is another issue that should be solved by means of special buffers.

5 Application Example

A simplified conceptual schematic of the control architecture, based on the design vectors from the previous section, is illustrated in figure 1. The characteristics and functionality of its components are briefly described below.

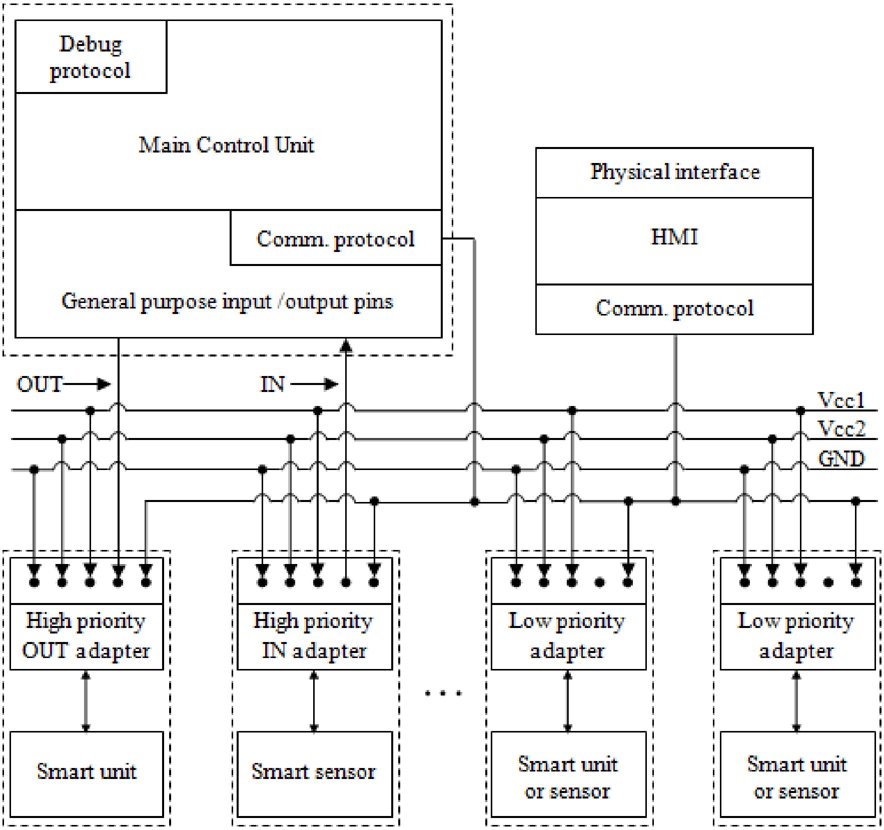

Fig. 1. Simplified conceptual schematic of control architecture

The control unit is an embedded solution built on such hardware and software platforms that allow monitoring and management of information together with the control of smart equipments that are part of the served process. It is characterized by:

- *Scalability*: the number of high priority equipments that can be connected is limited by the number of general purpose input output pins (GPIOs) available on the used microcontroller; in this case study, up to twenty five equipments. Theoretically, for the low priority equipments there is no limit, but process constraints and communication protocol parameters have to be considered.
- *Configurability*: is considered with respect to the direction (input or output) of the direct connection between control unit GPIOs and high priority equipments, which are not predefined, thus resulting in the ability of having connected either only inputs or outputs or both, as well as replacing an output with an input equipment at any time. This depends of the process needs.
- *Plug-and-play*: the control unit offers software support for automatic detection and integration of connected equipments, providing the operator with real-time assistance together with all the information and configuration options that the connected equipments have. The operator just has to select the desired level of functionality, in a friendly manner, thus eliminating the need of specialized personnel.
- *Diagnosability*: checking and identifying of problems or incompatibilities between equipments or cascade-connected equipments are supported by the information management algorithms and by the distributed intelligence enclosed in smart equipments, resulting in a high control level with direct impact on system fitness, functionality and stability.

Since smart sensors and their characteristics are already presented in [7], still it makes worth to mention that they have been enhanced in this research work in order to achieve an extended orientation towards modularity and scalability, the electronic design allowing to quickly creating new smart sensors solutions for accommodating more sensors with different or special requirements.

Smart units represent intelligent output manufacturing equipments which make use of embedded systems, software creativity and microcontrollers in order to boost up the performances and functionalities of normal output equipments.

Employing both hardware and software designs it was possible to implement the concept from figure 1 on a electro-mechanical axis driven by a 24 VDC 5 phases stepper motor with windings in a pentagon connection, resulting in an intelligent electro-mechanical axis with the following functionalities:

- *Distributed intelligence:* it was implemented by placing relevant information about the electro-mechanical axis, controlling algorithms, available functionalities and options inside microcontrollers' memories.
- *Plug-and-play*: it is achieved by exchanging important information about the intelligent axis with the control unit using a communication protocol that makes the integration and configuration processes of the intelligent axis simpler and quicker.
- *Controlling*: a broad range of motor control options have been implemented (but they are not limited to this range): half step, full step, forward, backward, speed control and all are accessible by software.
- *Remote control* and *learning*: once the intelligent axis is integrated, the user has the full control upon its functionalities and can decide how and where to drive the axis

and what moves to be learned and introduced in its working sequences in relation with other connected equipments, if any.

- *Short control loops* and *independent decision taking:* they have been obtained via the level of distributed intelligence implemented inside the microcontroller and via the information provided from data management algorithms and logic from this equipment or from others that can influence its functionalities, as specified in the configuration process by the operator.
- *Parameters monitoring*: the electronic part is designed such as to allow electric parameters monitoring and, together with data management algorithms, to identify possible malfunctions situations, stop the control algorithms on equipment level and let the control unit and user knowing about these situations.
- *Preventive maintenance*: simple algorithms are implemented to keep track of working hours and conditions in order to alert the user when processes similar to: equipment inspection, greasing, adjustments and re-calibration are needed in order to prevent faults to occur. Even more advance features could be implemented if linked with the information from the monitored parameters.

Adapters are additional hardware parts in the system. They are used to prioritize smart equipments and they can be of two types: high or low priority. By prioritizing the control unit, special procedures can be quickly triggered on the smart units' side. As well, smart sensors can quickly trigger special procedures on the control unit side. A secondary role of the high priority equipments is to adjust voltage logic levels of the direct connection between smart equipments 24 VDC and control unit 3.3 VDC.

Human machine interface (HMI) is the connection of the user to the control unit or smart equipments and it is used for selecting between configuration options, remote control of smart units and other specific issues or to monitor process parameters.

6 Tests and Results

An experimental testing bench has been constructed in order to test the feasibility of the developed control architecture and the related intelligent axis concept, as it can be seen in figure 2.

It consists of one master control unit (1), one power and signal distribution unit (2), three smart sensor units (one Smart Temperature Measurement Unit (5) for measuring temperature that can accommodate up to four LM35 or equivalent temperature sensors, one Smart Magnetic Field Measurement Unit (6) for measuring magnetic field that can accommodate up to four SS49 Honeywell Hall effect sensors or equivalent, one Smart IR Barriers Unit (7) capable to accommodate up to three pairs of IR emitter and receptor for realizing IR barriers), one High Priority Smart Axis Unit (4) for mechanical-axis control, one human machine interface unit (3) used for configuring the connected smart equipments, high and low priority adapters (12).

Each smart-equipment has its own microcontroller, where distributed intelligence and specific test control algorithms have been developed and implemented by software means for concept testing purposes.

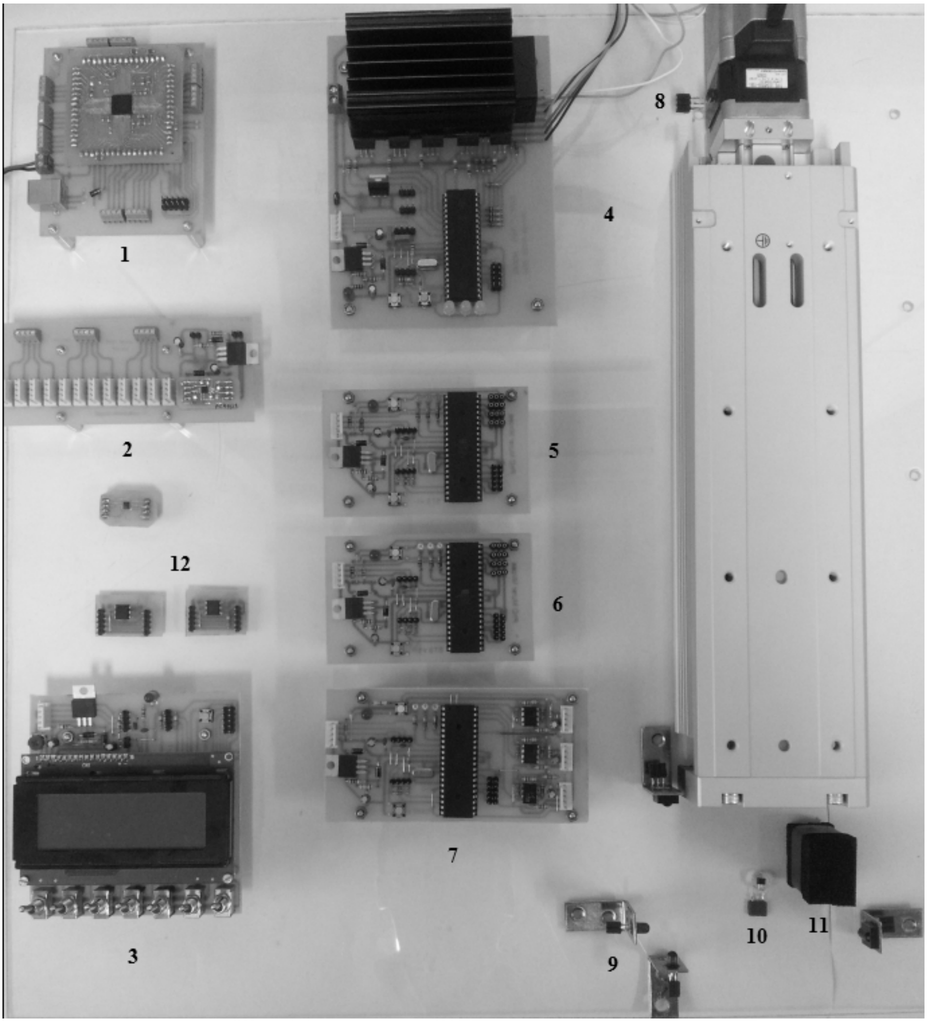

Fig. 2. Experimental test bench (without connecting wires)

Current equipment configuration that can be seen in figure 2 could represent a process in which an electromechanical axis (4) is used to move a part (11), the actual smart sensors configuration can be interpreted as follows: one smart IR barrier (9) is used to detect if the part has been pushed over a point so that another equipment to process it, the second IR barrier is used to detect if the part has exceeded the operating range of the electro-mechanical axis, the Hall effect smart sensor (10) is used to detect when the sliding part of the electro-mechanical axis (4) has been brought back to home position (a small magnet is placed on the bottom of the sliding part), the smart temperature sensor (8) is placed on the stator of the electromechanical axis' (4) motor and can be used to keep temperature data logging, to detect if high temperature are experienced and to prevent axis deterioration by shutting down the control.

If sensors are repositioned and additional software is developed, different configurations and functionalities can be achieved for the overall system.

For a better understanding of the concept, the paperwork dives into one smart sensor and smart unit from software point of view and exemplifies the implemented functionalities. The functionalities of the other smart sensors used in this experimental test bench are left to reader creativity to deal with. Bellow, in figure 3, a list of functionalities that can be implemented into specific equipments is introduced.

High Priority Smart IR Barriers	High Priority Intelligent Axis
Configuration options	
1. Specify number of used sensors.	1. Select working environment. 2. Keep track of working hors? 3. Monitor electric parameters?
Configuration of functionality	
1. Detect object presence? 2. Identify direction of movement? 3. Calculate speed of movement part? 4. Count parts?	1. Select default stepping mode. 2. Select default working speed. 3.Drive the device if monitored parameters are out of specification?
Configuration of functionality	
1. Trigger alarm if trespassing barrier? 2. Report information.	1. Trigger specific control routine? 2. Listen to communication port for information from control unit?
Additional options	**Maintenance options**
Reserved for additional options to be implemented.	1. Use mathematic models to identify equipment aging. 2. Alert operator when maintenance due dates are close?

Fig. 3. Example of functionalities that can be implemented into smart units

Available Units	Actions	Characteristics	Operators	Condition and specific condition options
Intelligent Axis . Move	Forward .	Full Stepping .	WHILE	Smart IR Barrier . Barrier 1 . Detect presence = TRUE
	Move Backward	Half Stepping	IF	
	Direct Connection	n Steps	AND	
			OR	
Intelligent Axis . Move	Backward .	n Steps = 10	IF	Smart IR Barrier . Barrier 2 . Object count = 3

Fig. 4. Process programming example related to specified equipments

After connecting and auto-integrating the equipment, specifying the control algorithm of a unit by the operator using HMI physical interface is inspired from object oriented programming (OOP) since it is very intuitive. The HMI will real-time actualize and populate the list of available options, based on equipment configuration options, other connected equipments and their configuration options, operators, specific actions and options. Thus, a small fracture of the control architecture is presented in figure 4. Reduced representation regarding the list of available options and what they imply can be viewed in figure 4, representing a line of the control algorithm.

7 Discussions

Intensive testing on the case study for recognizing specific characteristics has shown that the proposed control architecture is functional, highly reconfigurable, cost-effective, and the concept of intelligent axis is feasible. Some of the features of great importance in dealing with future manufacturing system problems and market needs can be also found in our experimental test bench: *reconfigurability*, master control unit has the capacity to configure on-the-go and at any time the direction of its pins (i.e. the connection to the external world) with respect to the connected device; the operator can ask a specific connected equipment to provide its configurability options and choose between these options a desired way of how an equipment will act with respect to the implemented software and hardware configuration; *plug-and-play*, master control unit detects when an equipment is disconnected or connected on the communication bus and takes care to integrate and configure the connected part without corrupting data transfer on the communication bus; *real-time assistance*, all information about a device is inside the memory of the attached microcontroller, thus connecting two or more incompatible devices will result in alerting the operator and blocking any attempt of driving or controlling that device; *scalability*, has been obtained by conferring a priority level to equipments: high or low priority (note: the number of high priority equipments is restricted to the number of available pins on the master control unit, thus having a direct connectivity to master control unit for quick triggering of actions; the number of low priority equipments is restricted by the time constraints of the deserved process and the bus electric capacitance); *independent decision taking*, like preventive actions, in the case of smart units it is based on process information and data statistics regarding process values. The level of *decentralization* is another important feature identified in our design. It is obtained from the symbiosis between the given equipment and a microcontroller connected by a communication network to other equipments and to the higher management level.

Test performed on a communication protocol's speed of 400 kbit/s has shown that a time period under 5 seconds is needed by the main control unit to detect and auto-integrate any connected equipment. Also, an average of 5 minutes is needed by a skilled operator to configure the connected equipment.

8 Conclusions

This research introduces a control architecture that enables building up intelligent axes for fast integration within technical systems. Tests have shown that the proposed control architecture is suitable for supporting the development of small scale, highly reconfigurable systems using smart equipments at affordable costs. In comparison with control architectures build around programmable logic controllers, the proposed architecture takes a step closer to what reconfigurable manufacturing systems concept is based on.

One noticeable limitation of the proposed solution is related to the communication protocol performances where significant propagation delays are experienced over 100 meters at high data rates, as stated by the producers. In has to be considered that this communication protocol was employed to emphasize the concept of the control architecture, if data transmissions over larger distances have to be covered, protocols like CAN and LAN could be used together with the set of hardware and software framework that they require.

The obtained results encourage to further work on this concept for reaching its full potential. The first envisaged research direction would be on increasing the simplicity of equipment and process configuration by developing an enhanced HMI that considers a PC-software together with the USB support of the main control unit microcontroller. The second research direction is about developing an online open-source data base with information, control algorithms, drivers, etc. about different smart equipments.

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Product Development Process Modeling: State of the Art and Classification

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Abstract. Process modeling is a set of activities to be followed to create one or more models of a process for a certain purpose. Some modeling methods are more suitable for a given purpose than others, an essential fact to remember when choosing a modeling method. Some literature reviews about product development process modeling and their purposes are available on the literature; however, none of them intend to deplete the subject. Therefore, this research aims to provide a state of the art about product development process modeling methods and propose a detailed and comprehensive classification of them based on their purposes. To this end, a systematic literature review is conducted, followed by the elaboration of a matrix that relates modeling methods to their purposes. The resulting matrix can serve as a starting point for the elaboration of a framework for modeling method selection.

Keywords: product development, process models, process modeling, process representation, process visualization, models purposes.

1 Introduction

Among basic organizational capabilities, the ability to innovate by developing new products provides the greatest competitive advantage [1, 2]. Product development (PD) is the process by which an organization transforms market opportunities and technical possibilities into valuable information for commercial production [3]. Unlike business processes designed to produce predictable results, PD is intended to create something new. A business process with distinct characteristics, PD involves creativity and innovation, is non-linear, and iterative [4, 5].

Process modeling is an activity set to be followed to create one or more models of a process for a certain purpose, usually the representation, explanation, design, specification, analysis, or control of a given process [6]. It is essential to choose a model appropriate to its purpose [5–7]; some process modeling methods are more suitable for a given purpose than others. For example, a design structured matrix will show process activity dependencies more clearly than a simple flowchart and will not

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highlight process improvements opportunities as efficiently as a value stream map can.

As well as other processes, it is possible and useful to build models for product development processes [8]. For example, process models can help a development team focus on value-adding activities, provide current situation transparency and visibility to a workforce, indicate process-related best practices, provide a baseline for process management, allow process change analyses, and assist the comprehension of complex processes, among others [5].

The business process modeling literature is extensive. Literature reviews on both general modeling methods [2, 7, 9] and specific PD process modeling [5, 8, 10–12] have been conducted. Although these authors do not agree on the definition of the term "modeling methods" (but instead use terms like "frameworks," "approach," techniques," "languages," and "views"), they discuss with varying abstraction levels and foci a similar set of PD process modeling methods (e.g., event process chain, design structure matrix, flowcharts).

Some of these reviews describe modeling method types and their typical purposes [5, 10], group modeling methods in categories regarding their purposes [8], or analyze the fitness of modeling methods for various purposes [12]. However, none of these reviews intend to deplete the subject. Methods described in one review are sometimes not cited in others, and none of the reviews aggregates all of the extant methods. The current classification based on process purposes is largely generic (as it refers to modeling method purposes collectively rather than to each method's individual purpose) and is often partial. For example, Browning [12] examines the attributes that a model view is able to represent and that are useful to a given purpose to elaborate a matrix showing the alignment between model views and their purposes. The matrix is a very interesting contribution, but, as it relies only on information about attributes, does not consider other aspects important to a model's fitness for its purpose, like intuitiveness and ease of use.

Therefore, this research aims to aggregate, complement, and update the extant literature reviews in order to provide a current overview of PD process modeling methods, and propose a more detailed and comprehensive classification of them based on their purposes.

2 Research Method

2.1 Systematic Literature Review

The following systematic literature review was based on the roadmap proposed by Conforto et al. [13], adapted from other knowledge areas [14, 15] to guide systematic literature reviews on operations management. This roadmap's main characteristics are its research strings tests and refinements, the iterative processing of its results, and its references by references search. The roadmap phases will be described, detailing the methodology employed.

Phase 1: Inputs. In this phase, the systematic literature review was planned and its inputs defined. The resulting plan as the inputs defined are shown below.

1. Objective definition: identify the modeling methods used in PD process modeling.
2. Database definition: qualified experts, and ISI Web of Science (Thomson Reuters) and SciVerse Scopus (Elsevier) authoritative sources. Articles and conference proceedings available in English, free of charge, and authenticated by the researchers' institutions should be considered. Searches should be conducted using the "title," "abstract," and "keywords" fields.
3. Strings definition: the keywords were selected from the list of articles identified by the experts. Three iterations were then carried out for strings refinement.
4. Inclusion criteria definition: the established criteria for articles including was "proposition, description or application of modeling frameworks, methods, techniques or approaches to PD process modeling" and "proposition, description or application of new PD process models".
5. Searching: searching the selected databases, eliminating duplicates, and exporting results to a table for filters application
6. Filters with inclusion criteria application: 1st iteration with article's title, keywords and abstract reading; 2nd iteration with article's introduction, results and conclusion reading; 3rd iteration with article's full reading.
7. References by references search: should be performed using the references of the selected articles.
8. Data extracting to synthesis table, obtained from deep reading of selected articles.
9. Articles cataloging and storing in bibliographic reference manager software.

Phase 2: Processing. A systematic literature review search, results analysis, and documentation were performed. Searching using the chosen string produced 5646 articles (counting both databases). Of this total, 1394 articles were duplicates across the two databases (a 33% overlap). Thus, 4252 articles were iteratively subjected to the filters defined in the previous phase. During articles' full reading, it is normal to find citations to other relevant articles that did not appear in the references by references search. In our systematic literature review, 36 articles were found through the references by references search. Finally, 101 articles were analyzed, 65 from the filters selection and 36 from the references by references search. Data extraction from the selected articles to a synthesis table then occurred, listing all the modeling methods found and their purposes. The only information considered was what could be retrieved from the analyzed set of articles; no critical analysis occurred at this point.

Phase 3: Outputs. The literature review's main output was the synthesis table (reflecting 52 modeling methods) and the identification of the main authors and journals about the subject. Most of the selected articles were drawn from the engineering and computing fields.

2.2 Elaboration of the Modeling Methods x Purposes Matrix

The raw data collected into the synthesis table after the systematic literature review enabled the elaboration of the modeling methods x purposes matrix. This data were submitted to a refining critical analysis consisting of two phases. In the first, the modeling methods were analyzed; in the second, their purposes were examined. The critical analysis of the first phase occurred in two steps: duplicates were eliminated (some authors referred to a single modeling method using different names), and the selected modeling methods were confirmed to lie within the scope of this research. In the second phase, the examination of the modeling methods' purposes was refined in two steps. First, the purposes assigned to each method according to what could be found in the literature were examined for duplicates and discrepancies and were then rewritten in standard format (i.e., using a verb followed by a substantive). These steps were repeated in three iterations in order to produce a refined set of purposes (see Figure 1). Finally, a matrix was elaborated based on the refined set of modeling methods and purposes.

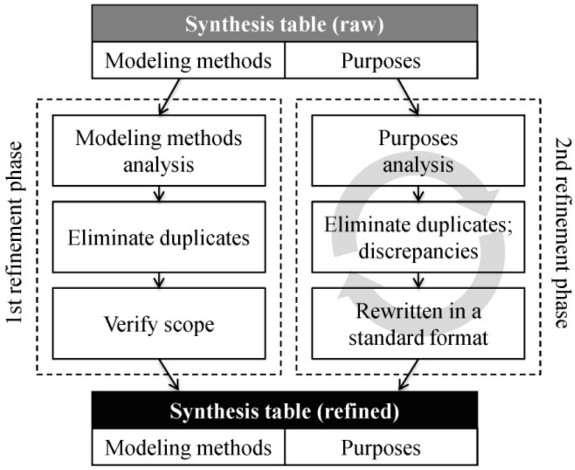

Fig. 1. Method for synthesis table refinement

3 Results

The main result is a matrix relating the modeling methods to their purposes (see Table 1). The modeling methods, along with their main references, occur in the rows, which include descriptions and more detail.[1] The purposes, represented by an ID, occur in the columns and are further explained in Table 2, which also shows the respective matrix ID.

[1] Due to the page restriction, only a small subset of the consulted articles is referenced in the matrix. Please contact the authors for additional references.

Table 1. Matrix relating modeling methods to purposes

Purposes	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	
Modelling Method [main references] A[1]	7	7	12	21	4	6	40	6	20	3	29	8	33	15	5	2	27	16	5	9	9	17	9	28	11	4	13	34	B[2]
Event process chain diagram (EPC)[11, 16]		X			X		X	X			X		X	X	X			X	X	X		X	X	X			X	X	**16**
Business process modeling notation (BPMN)[5, 17]	X				X		X				X			X		X	X	X	X	X			X	X			X	X	**14**
New modelling framework [18]			X	X					X	X	X		X		X		X	X			X	X		X				X	**13**
Signposting [5, 10, 19, 20]	X		X	X			X			X	X	X	X				X						X	X			X	X	**13**
Design structure matrix (DSM)[5, 10, 18, 21–23]			X	X			X				X		X				X	X		X	X	X		X				X	**12**
Work transformation matrix (WTM)[5, 8, 18, 24, 25]				X			X		X		X		X	X			X	X			X	X		X				X	**12**
Design roadmap [18, 21]							X				X	X	X					X	X	X	X		X	X			X		**11**
Q-GERT model [5, 8, 26]	X			X			X		X		X		X				X		X			X		X			X		**11**
Fuzzy DSM [5, 27]			X	X			X				X		X	X			X					X		X			X	X	**11**
Graphical evaluate review technique (GERT)[5, 11, 18, 28]	X			X			X		X		X		X				X		X			X		X			X		**11**
Activity-on-arc diagram [5, 11, 29]	X			X		X	X		X				X					X							X	X		X	**10**
Gantt chart [7, 11, 18]				X		X	X	X	X		X		X					X				X			X				**10**
D-critical path method [5, 30]				X			X		X		X		X	X			X					X		X					**9**
Sequential iteration model [5, 8, 25]				X		X	X						X	X			X					X					X	X	**9**
Markov models [5, 25, 31]				X			X		X		X						X	X						X			X	X	**9**
Value stream mapping [5, 11, 32]	X	X					X					X	X	X									X			X		X	**9**
Integration definition for function modeling (IDEF3)[5, 7, 10, 11, 18, 21, 33]			X				X						X				X	X					X	X				X	**8**
Activity module decomposition model[5, 8, 34]							X				X		X	X			X				X	X						X	**8**
Function block diagram [21]							X				X	X	X				X				X		X	X					**8**
High-level "life cycle" models [11, 35]							X				X				X					X	X			X	X			X	**8**
Modeling the release time of a single uncertain iterative activity [36]							X		X			X	X				X				X			X				X	**8**
Iterative cycle time estimation[5, 8]							X		X		X		X				X	X				X						X	**8**
Entry-task-validation-exit (ETVX) diagram [5, 11, 38]							X	X			X		X				X			X				X				X	**8**

[1] A: Total of modeling methods that fulfill this purpose.
[2] B: Total of purposes that are fulfilled by this modeling method.

Instructions for authors, p. 2, 2013.

Table 1. (*continued*)

Purposes	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	
Modelling Method [main references] A²	7	7	12	21	4	6	40	6	20	3	29	8	33	15	5	2	27	16	5	9	9	17	9	28	11	4	13	34	B³
Structured analysis and design technique (SADT)[5, 21, 33, 37]			X				X					X	X	X									X	X				X	8
Integration definition for function modeling (IDEF0)[5, 7, 10, 11, 18, 21, 33, 39]			X				X					X	X	X									X	X				X	8
Petri net [5, 7, 10, 18, 21, 40]		X			X		X						X				X	X						X			X		8
Feedbacks and crossovers [5, 8]				X			X										X				X	X		X			X	X	8
Activity-on-node task graph [5, 29]				X		X	X		X				X	X														X	7
Project evaluation and review technique (PERT)[5, 10, 18, 21, 36]				X		X	X		X													X			X			X	7
Colored petri nets [5, 7, 18, 41]		X					X				X		X	X													X	X	7
Activity-activity incidence matrix [18, 33, 42, 43]			X				X						X	X			X					X						X	7
Data flow diagram [7, 12]											X			X				X		X				X		X		X	7
Critical path method (CPM)[5, 10, 18, 36]				X		X	X		X													X			X			X	7
Flow chart [5, 7, 11]					X		X									X	X	X						X				X	7
Module scheduling [5, 8]			X	X			X	X	X		X																	X	7
Stage overlapping [5, 8, 44]		X		X			X		X				X				X							X					7
Digraph [18, 21, 27]							X		X				X				X	X										X	6
Stage targeting [5, 8]			X	X			X	X			X																	X	6
Queuing network model [5, 8]							X		X		X	X	X									X							6
Network of commitments [5]							X				X		X	X										X				X	6
Strategic information flows [23]											X						X							X	X			X	5
Product release [8]		X		X					X																X		X		5
SIPOC diagram [5, 11]											X		X							X					X			X	5
Textual narrative [11, 12]							X								X					X				X				X	5
Analysis of interconnected decision areas (AIDA)[8, 45]	X									X			X		X														4
Block diagrams [5, 24]			X						X		X						X												4
Parallel scheduling [5, 8, 46]				X			X						X											X					4
Signal flow graph [18, 47]			X						X		X						X												4
Stock-and-flow diagram [11, 12]		X																X							X				3
Timing of design reviews [5, 8]								X									X								X				3
Create-read-update-delete (CRUD) [11]																									X	X			2
Responsibility assignment matrix [12, 48]											X																		1

Table 2. Purposes of modeling methods

Matrix ID—Purpose: Explanation	Matrix ID—Purpose: Explanation
P1: Evaluate design process complexity: level of complexity of development process (e.g., by number of activities, dependencies, or resources required).	P15: Indicate standard practices/tools: provide information about best practices and PD tools based on literature, benchmarking, and/or successful projects.
P2: Evaluate design process performance: in time, cost, productivity, number of error/reworks, etc. Also outputs performance (product quality, time to release, etc.).	P16: Interchange process data: provide interchange between different computer systems through an integrated database or common language.
P3: Evaluate design process risks/reliability: risks, stability, confidence level, failure modes, and their effects.	P17: Identify/manage process iteration: minimize, eliminate process loops/circuits. Rework management.
P4: Evaluate design process time-cost/ quality tradeoffs: support decision making in tradeoffs to minimize time and cost expenditures and maximize quality. Also project improvement to minimize time and cost expenditures.	P18: Monitor/control process/activities: show key performance indicators as activity status, completion percentage, and time to completion to allow process or project monitoring/control.
P5: Automate process: workflow modeling/management. Describe a process that can be performed by computer agents.	P19: Multiple process integration/coordination management: allow integration/coordination of multiple interacting processes and/or multi-party collaborations.
P6: Calculate slack/float time: deriving the degree of float (slack) or scheduling flexibility for each process activity.	P20: Organize process knowledge: documentation/ register of design process data/information about the work and how to do it. Manage process data.
P7: Define/show activities/sequences: process or project activities linear ordering, sequencing.	P21: Reduce complexity of design process: decompose process models to reduce complexity.
P8: Determine the timing of design reviews/gates: design reviews tradeoff (unnecessary reviews x great amount of rework) to determine optimal time for realization.	P22: Scheduling design activities/tasks: determine starting and finishing times for process activities and tasks.
P9: Estimate completion time of a process or project by showing the critical path or indicating the completion time for each activity. Estimate product time-to-market.	P23: Show activities hierarchy (parent/children): show parent/children relationship, structure decomposition. Indicate hierarchical levels of PD process.
P10: Handle the changes: analysis of process/project modifications. Provide alternative routing for process changes or allow model updating.	P24: Show flow of data or information: show how information enters and leaves the process (process or activities inputs/outputs).
P11: Identify and organize/allocate required resources: assign roles/responsibilities; optimize resource allocation; analyze resource sharing between processes; show organizational units involved; show stakeholders.	P25: Show process milestones/deliverables: highlight important process or project events. Show process or project times for a determined work package delivery/analysis.
P12: Identify constraints that can interfere in the PD process (e.g., paucity of financial resources or staff, regulation requirements, infrastructure limitations).	P26: Shows activities' effects on deliverables/flow of information: connect activities with deliverables and indicate cause and effect relations.
P13: Identify dependencies/precedence of activities/ functions: enable concurrent engineering (show parallelism, coupling, minimize overlapping); allow network analysis; show technical product dependencies.	P27: Simulate design process: predict process behavior in different scenarios.
P14: Improve/continuously improve design process: increase process efficiency; process reengineering.	P28: Visualize/understand design process: provide concise representation; communicate, explain process.

4 Discussion and Conclusion

Although the performed systematic literature review allows a comprehensive analysis of modeling methods and their purposes, it has limitations. The analyzed papers address the modeling methods from several perspectives and on varying levels of detail. Thus, the resulting set of purposes includes highly abstract purposes as "show flow of data and information" and less abstract ones as "define/show activities sequence." The same is true of the modeling methods, where a high-level model contrasts with a Gantt chart. Future research should classify the methods and purposes, identifying the groups that would help users with matrix comprehension and method selection. Moreover, the literature describes some modeling methods better than others, implying that more details about purposes are available for some methods than for others. This can produce a misconception about modeling methods' appropriateness to their purposes. For example, a modeling method poorly detailed in the literature can appear unsuitable for a purpose it can satisfy. This also turns infeasible to indicate the degree of purpose fulfillment for each method. The authors' critical analysis during the synthesis table refinement helped alleviate these problems, but further analyses and validation by experts and practitioners would be valuable.

Despite their importance to the PD process, some purposes—like "handle with changes" and "indicate standard practices/tools"—are attended by only a few modeling methods. This may result from the adaptation of methods originally created for process modeling, given that most PD process modeling methods are derived from methods created to model repetitive processes, or to the inherent limitations of the traditional interfaces and tools used for process representations (i.e., printed posters or software with limited functionalities). Furthermore, some papers describe modeling method purposes in combination with software tools or platforms, while others describe the purposes of modeling methods alone. Future studies should clarify which purposes flow from this combined use.

Despite these limitations, this study provides insights that can help researchers and practitioners interested in PD process modeling. The study's modeling methods list aggregates all the modeling methods found in the available literature reviews and provides additional ones. Although an exhaustive list is unfeasible, this research constitutes a comprehensive reference for future studies. The purposes list is also a valuable resource, as few studies have sought to identify PD modeling methods purposes. This study's matrix can help PD process modelers select the best modeling method for a given purpose. Future studies could give it more detail, showing the degree of purpose fulfillment provided by each modeling method (i.e., partial or full), which was not possible with the methodology applied in this research. It could also serve as a basis for a modeling method selection framework that combines process model purposes with other selection criteria, such as model change permissiveness. Moreover, it could serve as the starting point for future efforts to develop new process modeling methods more suitable for PD, by indicating unattended PD process model purposes and related shortcomings.

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Activity-Based Modeling and Analysis of Product Engineering Processes

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Abstract. Product engineering processes are subject to increasing complexity. In order to address this problem, various model-based simulation or optimization techniques have been published. However, these techniques are limited to the structure and quality of the data that they work with. In addition, modeling effort needs to be minimized, in order to efficiently support product engineering. In this contribution an approach for the activity-based analysis of product engineering processes is presented. It is intended to support modeling of complex processes with a focus on easy information acquisition. The overall suitability of the approach as well as ways to minimize modeling effort are discussed in two case studies.

Keywords: modeling, product engineering process, information acquisition, Integrated Product Engineering Model.

1 Introduction

Product engineering processes can be considered as complex systems [1]. They comprise myriad system elements such as goals or objectives, people, activities, resources, resulting objects etc. and myriad relations between them. High dynamics lead to a continuously changing system structure. Hence, uncertainty is an immanent aspect of product engineering (cp. [2]). Successful product engineering, however, demands high quality of both product and process. Effectivity and efficiency stand opposite to uncertainty and dynamics. Therefore, suitable approaches to manage the complexity of product engineering and to handle dynamic system changes flexibly are needed. Explicit modeling of information is a necessary condition to establish transparency among the relevant aspects.

The major challenge is keeping an overview of the manifold dependencies between the domains product and process, where relevant information flows occur (cp. [3] and [4]). The many dependencies are not only caused by the product itself but especially by the involved people (designers, managers etc.) and their activities. Hence, a suitable modeling of product engineering processes has to represent especially the people,

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their activities and the dependencies of these. With this, purposive process modeling aiming at transparency, improved coordination and planning can be realized (cp. [5]).

In this contribution, an activity-based approach for the analysis of product engineering processes is presented (Section 3). It is grounded on a systemic view on product engineering (cp. [6]) and uses elements of the Integrated Product Engineering Model iPeM (cp. [1]). With this, it is possible to address product- as well as process-related aspects from the perspectives of designers and managers. In two case studies, the overall modeling concept is applied in real engineering projects (Section 4). The exemplary applications are used to discuss the wholeness and the continuousness of the approach (cp. [7]), i.e. its suitability to compass any relevant element at necessary levels of detail (Section 5). Furthermore, different modeling strategies are reflected on with regard to efficiency in information acquisition. These issues are the background for the development of sophisticated support tools based on the iPeM in further work. In the next section the modeling approach is placed within the state of the art.

2 Modeling of Product Engineering Processes

2.1 Approaches for Modeling of Product Engineering Processes

A generic consideration of product engineering is the systemic ZHO-Model. It describes how socio-technic *Operation Systems* transform elements of S*ystems of Objectives* into elements of S*ystems of Objects* [8]. A derivative is the ZOPH-Model of Negele that adds a *process system* to the ZHO-Model [5]. Integrated Product Development of Ehrlenspiel considers also operation systems, systems of objectives and objects and integrates this consideration into a concept for interdisciplinary projects. A methodic conduction of individual process steps is approached with a problem solving cycle. It seperates problem containment, search for solutions and selection of solutions [9]. Also the Munich Procedure Model can be used as a problem solving cycle. It contains also aspects of planning and structuring, analysis and decision [10]. Also the iPeM as described in Section 3 is based on a systemic view on product engineering and a generic problem solving process. Based on this, models of concrete projects can be represented.

Literature on modeling of product engineering is multifarious. Wynn and Clarkson describe many approaches that aim at establishing transparency in the system of product engineering – each from a distinct perspective. The authors distinguish phase- and activity-based models, solution- and problem-oriented models, abstract, procedural and analytic models with a focus on either design or management [11]. There is a gap between these focuses: well-established models such as the approach of Pahl and Beitz are used in design activities, for instance to ensure a methodological procedure. For managerial purposes, especially quality gate processes which separate development stages with milestone gates where decision criteria are evaluated are widely spread. There is no integrated view that would allow a communication between these disciplines based on their models (cp. [1]). Consequently, product engineering processes today cannot be improved through one modeling approach alone.

In this paper, a modeling approach is presented that is assumed to be comprehensive enough to comprise engineering processes holistically. Given this, analysis techniques are expected to be a suitable concept for process improvement [11]. Such techniques have been discussed in literature as well. They are based on formal frameworks such as PERT (process evaluation and review technique), CPM (critical-path method), IDEF (Integration DEFinition), Signposting, Petri nets or DSM (design or dependency structure matrix). They allow amongst others calculating or simulating process duration or likely process outputs. Furthermore, an analysis of failure modes and their impact on cost and scheduling become possible. Strategies of process improvement generally aim at a limitation of risk promoters or a re-arrangement of resources, people and activities [12]. However, the authors point out again, that there is no modeling framework yet, that would be suitable to compass any relevant aspect.

Such a holistic consideration can be found in Systems Engineering. It focuses on the human being as an actor, but also as a stakeholder or as “the user”. In his 5-Layer-Model Hitchins considers product-, project- or system-, business-, industry- (e.g. Supply Chains) and socio-economic aspects to describe the overall dependencies of product engineering continuously [13]. The approach of Haberfellner et al. can be divided into an overall philosophy, a problem-solving process and explicit techniques of design and project management [14]. However, Systems Engineering today is only applied in large projects such as aerospace. A wide industrial application is missing (cp. [7]).

2.2 Applications of Product Engineering Processes Modeling

The modeling approaches presented in the section beforehand have been applied in several research studies more or less successfully. Smith and Eppinger describe an approach to determine the duration of iterative processes. It is based on the coupling of “tasks” in DSM networks [15]. The approach uses analysis methods such as directed graphs, PERT, SADT (Structured Analysis and Design Technique) and matrices. The latter allow algorithms like partitioning, triangularization or ordering within triangularized blocks (“tearing“) [16]. Browning describes DSM application using “clustering“ and “sequencing“ for component-based, team-based, activity-based and parameter-based models. A more sophisticated simulation environment based on DSM is presented by Cho and Eppinger for the management of complex projects. The simulation heuristic comprises stochastic, resource-oriented planning problems considering iteration. It aims at process optimization through determining relevant leverage points [17].

Approaches such as DSM offer many algorithms for analysis. However, their benefit is limited to the kind and quality of the information in the matrices. It was already 1999 when Wallace et al. stated that DSM representations are limited in their usability by modeling effort and the effort of information acquisition. Consequently, they are often reduced to static, very abstract models. In order to reduce the effort of information acquisition the authors follow a software-based approach in which the process model is built automatically with the help of a service-network during engineering activities [18]. Stacey and Eckert describe what designers “can do” and “should do” as „knowledge level models“ – based on cognitive science. Their approach to modeling engineering processes is close to social science [19]. Again, the design activities are central elements.

Summing up, there are many modeling and analysis techniques for product engineering processes and also simulation and optimization is being done. Today, common approaches address either design or management. Nevertheless, all these approaches are limited by the available information basis. For distinct purposes, a consideration of engineering processes that is based on activities has been found helpful to focus on relevant aspects in many cases. This can also be justified with the help of system theory and the central role of activities: they connect various information (e.g. goals, people, and results) as pointed out in the following section.

3 Activity-Based Modeling of Product Engineering Processes

3.1 Integrated Product Engineering Model iPeM

The Integrated Product Engineering Model iPeM is based on the system triple of product engineering. It describes product engineering as a continuous interaction of three systems: the System of Objectives, the System of Objects and the Operation System. The System of Objectives contains all explicit objectives (i.e. goals and their constraints) as well as their interrelations (e.g. conflicts) and justification (Design Rationale). It represents expectations towards the future product (cp. [20]). The system of Objects contains all synthesized artifacts (virtual and physical). This is the final product but also any intermediate object.

The Operation System is a socio-technic system that contains structured activities, methods and processes. Additionally, it contains the involved people and required resources. The Operation System analyzes and synthesizes the Systems of Objectives and of Objects in an explorative, iterative and co-evolutionary process (cp. [20]). It combines generic activities of product engineering with generic activities of problem solving (German acronym “SPALTEN” representing the individual steps of problem solving [1]). These form an Activities Matrix which allows a well-structured, granular consideration of the Operation System (see Figure 1).

The iPeM makes it possible to model activities, the acting people and used resources in explicit relation to the objectives that they are based on and to the resulting objects. Since the sub systems of the system triple can be modeled hierarchically at various levels of detail (cp. [21]), a purposive consideration can be achieved as discussed in the next section. The iPeM is an integrated approach that aims at supporting both design and management. While activities and knowledge work can be assisted by the Activities Matrix, time-dependencies can be visualized in sub models which represent general best practice patterns (*Reference Model*), individual plans (*Implementation Model*) and actual courses of individual projects (*Application Model* – cp. right side of Figure 1). These allow set-actual-comparisons that can be used to derive management ratios.

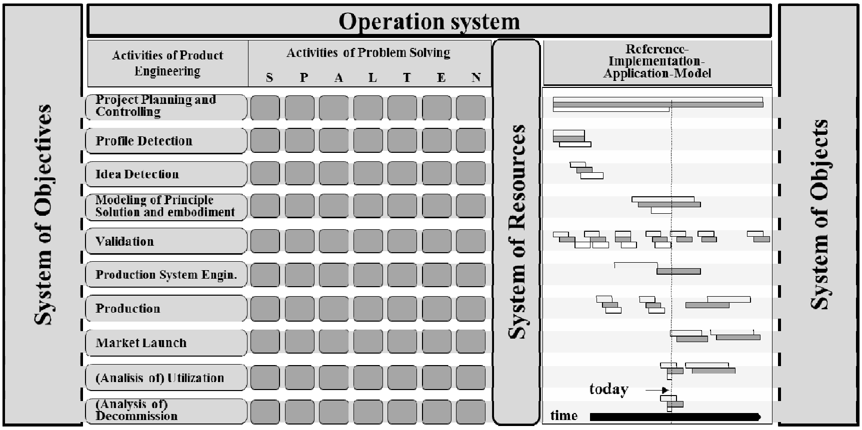

Fig. 1. Integrated Product Engineering Model iPeM

The iPeM approach appears to be suitable for holistic and continuous modeling and analysis of engineering processes with the aim of supporting both designers and managers.

3.2 Activity-Based Modeling of Product Engineering Processes with the iPeM

Useful modeling of product engineering processes requires a specification of the modeling purpose (cp. [5]). This can be analysis for mere or better understanding of a process (descriptively) or the intent to optimize a process (prescriptively). Such a consideration is inevitable since models are always a reduction of reality. For this, one must not spare relevant information (cp. [7]). At the same time, a reduction of the modeled information allows to reduce modeling effort to an acceptable amount. The system triple that the iPeM is based on can help focusing a model: one could be interested in a representation of an actual (real) course of a process in contrast to an initial plan. Here, one would focus on activities and their duration, decision criteria at milestones etc. Another purpose could be the representation of the continuous evolution of a System of Objectives in order to learn for a new product generation.

Information acquisition needs to be based on the specified modeling purpose. A resulting model has to be a representation of all relevant elements (objectives, objects, activities, resources) and their interrelations. It has to be structured in a way that allows further analysis and/or improvement. This includes hierarchic modeling that ensures that a reduced amount of information can be focused on at higher levels of abstraction. In this paper it is shown that the iPeM and the focus on activities in its Operation System is a suitable way to achieve this. A benefit of the integrated modeling with the iPeM is that it allows bridging the gap between basic design work and overall management. The criteria that are needed for decisions at milestones in a quality gate process are generated during design activities. Even though management needs an overall picture, the required data originates from activities at the operative level. In the next sections it is shown, that the iPeM approach is capacious enough to comprise all relevant aspects on the one hand, and allows analyzing process models continuously over distinct levels of detail on the other hand. The fractal iPeM structure ensures consistent model use. With this, it is possible to observe processes and criteria such as maturity levels during actual operation and to condense the information to overall models that can be used for managerial decisions.

4 Analysis of Product Engineering Processes

In this section, two different studies are presented. They show the suitability of the iPeM modeling approach and illustrate strengths and weaknesses of the respective applied modeling strategies.

4.1 Case Study 1: Manual Modeling of a Student Project with Interviews

The academic course integrated product development (IP) of the Karlsruhe Education Model for Product Development (KaLeP) [22] has been chosen as a use case for the test. Even though IP is a student project, it can be considered to be close to reality. The students are all in their final year and thus almost fully educated. Boundary conditions such as working environment, working hours etc. are deliberately close to reality as well. It is a four-month PE process with an industrial partner that includes all stages and challenges of a (totally) new design – all the way from the definition of the market niche to the production of functional prototypes – as well as project management (time, real budget etc.). The project's initial task description is very vague; hence uncertainty is particularly high in IP. However, the entire process is well observable as the supervisors have access to all intermediate files, sketches, documents, project plans etc.

Information Acquisition. Information about the engineering process of one team was gained through weekly open interviews. The interviewee was the team leader; the researcher took notes. The information was structured with the help of the iPeM afterwards by the researcher. It was modeled manually as a network where the sub systems of the iPeM (of Objectives, of Operation and of Objects) served as clusters in which the respective information was modeled hierarchically. Connections between these 'model elements' were indicated by arrows where e.g. objectives and resources were input to an activity, or where an object resulted.

Analysis of the Process. Even though modeling effort was considerable (200 hours of interviews and model creation for 800 interlinked 'model elements'), the explicit representation of information is remarkable. All aspects that were mentioned in the interviews could be modeled at comprehensive levels of detail. Hence, the iPeM can be considered to be suitable for representing the deep fractal character of product engineering processes (cp. [21]). The fact that any information that occurred could be modeled explicitly indicates the wholeness of the approach. However, with the aim of efficiency, a suitable level of reduction has to be defined to focus on relevant (i.e.

purposive) information. Limitations of manual modeling in terms of ergonomics, for instance when retrieving information again from the model, can be addressed with computer supported approaches as discussed in the following.

4.2 Case Study 2: Model Creation with a Collaborative Work Environment

Information Acquisition. One lesson learned from case study 1 is that reducing modeling effort is inevitable. Hence, the iPeM approach has been used to model another student project differently in the following year: by the students themselves. For this, a MS SharePoint environment was configured according to the iPeM's sub systems. The students were then advised to use this platform to do their project planning. They were asked to plan their team activities in detail and with the respective underlying objectives and resources.

Analysis of the Process. The modeling resulted in seven explicit models. The student teams modeled an average of 130 activities which belonged to average of 82 objectives. Figure 2 shows models of two teams. The layout of the models represents the iPeM (cp. Figure 1). Note that connections between the elements are in the SharePoint database but not depicted in the figure. Gray shades indicate the number of modeled elements of objectives, activities and resources (larger numbers are indicated by darker background color). The right in each model shows the activities on a time bar. One can see that the students planned their processes differently – even though they were given the same task (cp. uniqueness of engineering processes in [21]). Also obvious: a process does not proceed sequentially, but activities overlap and may reoccur iteratively.

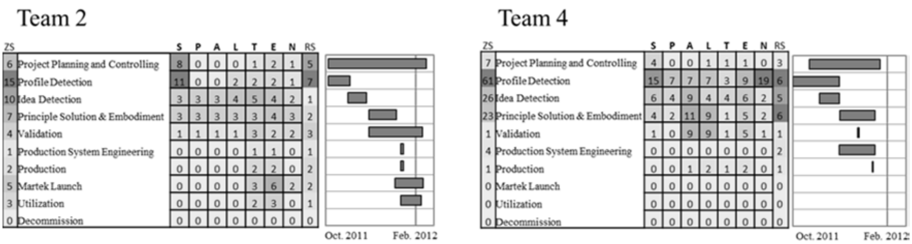

Fig. 2. Comparison of two resulting models

Another interesting observation can be made when the seven models are summed up. Figure 3 shows a 'common' model of the seven teams. The time bar here resembles the process course that the students were taught. This taught model is a reference process that obviously was used as a pattern for planning. One can conclude that the iPeM approach is suitable to compass different model levels continuously – from reference patterns to individual plans and back to a consolidated model.

ZS		S	P	A	L	T	E	N	RS
86	Project Planning and Controlling	61	18	12	10	7	17	7	35
209	Profile Detection	67	47	28	34	37	36	43	45
126	Idea Detection	30	23	37	24	36	34	16	37
105	Principle Solution & Embodiment	26	21	35	27	27	33	24	37
34	Validation	4	2	12	13	10	24	8	18
5	Production System Engineering	0	0	0	0	1	1	0	3
3	Production	0	0	1	2	3	4	0	3
8	Market Launch	0	0	0	0	3	9	4	3
3	Utilization	0	0	0	1	3	4	0	1
0	Decommission	0	0	0	0	0	0	0	0

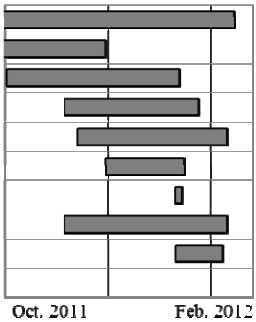

Fig. 3. Consolidated model of all teams

5 Discussion and Outlook

5.1 Wholeness and Continuousness of the Modeling Approach

The case studies imply that the iPeM approach is suitable to compass any aspect of product engineering that appeared to be relevant during the interviews and for the students when they planned their processes. Hence, wholeness as a necessary condition for purposeful modeling and analysis of product engineering can be assumed initially. In order to result in an efficient modeling approach, a purposive reduction of the information that has to be represented in models has to be defined (Section 5.3).

The continuousness of the approach is also substantiated by the case studies. The first study confirmed that comprehensive modeling at user-defined levels of detail is possible with the granular understanding of activities in the iPeM approach (cp. [23]). The second study revealed that also aggregating models to a common, consolidated representation is possible. Hence, continuousness both in detail as well as in generalization is given. This makes it possible to adjust a project plan to a given reference pattern as shown in the study. The consolidation of individual project plans can be compared with the reference in turn.

Another important insight is that the activity-based modeling approach allows comparisons between different projects. It is detailed enough to comprise individual issues such as the focus that the individual teams laid in their projects. On the other hand it is still generalized enough to allow quick comparisons and recognizing differences – for instance with the help of simple shading as illustrated in Figure 2.

5.2 Applicability – Purposive Use vs. Efficiency

In a general perspective, application of process models in industrial practice serves two major purposes: methodological support of design activities or management in terms of planning and controlling. The second case study implies that the iPeM approach is suitable to bridge this gap. It allows compassing activities at the level of actual operation. Here, in daily engineering work, designers can be supported e.g. with explicit objectives. Cumulating these to coherent phases on a time bar, on the other hand, allows managers to control projects in terms of stages and quality gates.

As introduced in Section 2 there are various analysis and optimization techniques to improve product engineering processes. They have in common that they depend on the available information basis. The case studies presented above point out in two directions. On the one hand, a modeling approach needs to be comprehensive enough to compass relevant aspects of engineering processes entirely. On the other hand it is no solution to model “anything” since modeling effort is proportional to the model element’s count. A purposive reduction of the overall information to the core of necessary elements is the key. The positive experiences of the two studies presented beforehand motivate the application of the activity-based iPeM approach for both information acquisition and model creation. Computer supported approaches furthermore ease model use e.g. with searching or filtering functionalities.

5.3 Outlook

Further work consequently addresses a classification of iPeM elements that are to be modeled for distinct purposes. This includes checklists of information elements as well as standardized interfaces to analysis tools.

An important finding of case study 2 is the applicability of collaborative work environments such as MS SharePoint for explicit model creation. The configuration of the user interface according to the iPeM approach made it possible to integrate the modeling tool in daily workflows (here: for planning purposes). The model was created, updated and checked for internal consistency “on the fly”. This is a promising perspective for efficient application in industry but also for research. As showed in the study, it is possible to gain a comprehensive database directly without biasing through interpretation of the interviewer etc. Future efforts will follow this direction.

However, also improvements of the usability of the work environment are to be addressed in order to result in a modeling platform for productive use in industry. In future work, not only planning in advance, but also tracking of actual courses of projects needs to be integrated. Automation (e.g. with the help of time trackers) can help to reduce effort through easy modeling of the IS-process in addition to the SET-process. This would allow a set-actual-comparison and be the basis for advanced process optimization at the level of individual activities – even during running projects.

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An Enhanced Interface Analysis Method for Engineering Change Management

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Abstract. The complexity of automotive systems has increased dramatically, driven by the requirement to address environmental and safety concerns and the pressure to offer higher level consumer technologies. This places a great challenge on product development organizations to manage the multidisciplinary systems integration in a reliable and robust manner. Engineering changes, which are integral part of the iterative automotive product development process, need to be managed in a way that efficiently addresses the integration requirements of complex multidisciplinary systems. The aim of this paper is to present a structured approach for engineering change management which is based on an enhanced interface analysis method which aims to identify comprehensively the system integration functional requirements as the basis for both engineering change prediction and support of robust engineering change design. The framework will be illustrated with an industrial case study on the development of an electric vehicle powertrain. The effectiveness of the proposed approach will be discussed in contrast with other methods for engineering change management.

Keywords: Interface Matrix, Interface Analysis Table, ECM.

1 The Business Case for Engineering Change Management

The engineering challenge within automotive systems engineering design has been increasing rapidly over the past couple of decades, largely due to the accelerated pace of introduction of new technologies to address environmental concerns and the drive to enhance customer satisfaction. In spite of the development and use of enhanced CAE and virtual engineering tools, the efficiency of automotive product development (PD) process has not increased as expected. This is clearly illustrated by the pattern and cost of engineering changes; for example the research reported by Cash [1] showed that on a typical new vehicle development program there were on average 5 engineering changes per part. These results are confirmed by a larger survey reported by Wasmer [2], who showed that across the supply chains for 3 major OEMs there were over 350,000 engineering changes per year, with an estimated cost of $50k per engineering change. While the iterative nature of the automotive systems design provides some justification for a certain level of engineering change within product

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design and development, research [1] showed that the requirement for engineering changes is largely due to issues discovered late in the design process, which require countermeasure development. This also explains the spiraling costs of engineering changes, as fixing failure modes late in the design process is difficult and has knock-on effects to other subsystems.

There is also recognition that the technical difficulty of automotive systems engineering design is related to the complexity and the multi-disciplinary nature (mechanical, electronic, software, control) of modern automotive systems. The role of systems integration in system engineering design is demonstrated by evidence [3] that the overwhelming majority of failures in the field are due to system interactions not being adequately managed during the design, leading to robustness failures. A structured approach using a coherent set of supporting tools is required to address effectively the complexity of the multi-disciplinary integration during system engineering design.

Research in engineering change management for complex systems [4-7] has focused extensively on predicting the effect and the impact of engineering changes. Most ECM approaches are underpinned by the Design Structure Matrix (DSM) [8-9] which is a concise, matrix based, representation of the system architecture, focused on identifying links between components or subsystems within the scope of the overall system. Change prediction approaches are substantially focused on identifying propagation paths for the effect of the engineering change based on the linkages identified in the DSM [6,7], and the associated risks assessment of the likelihood and impact of the effect of the change [4,5]. A criticism that can be brought to many of these approaches is that they are strongly focused on predicting the impact of an engineering change, and less focused on supporting the engineering design process that underpins the development of robust design countermeasures.

The Contact and Channel Model (CC) proposes a structured methodology for system decomposition, which could be utilized to support engineering change analysis and management. The method is based on analysis of a system through representing its functional and physical elements simultaneously. This is achieved via describing Working Surface Pairs (WSP) and Channel and Support Structures (CSS) to connect the WSPs of the system [12]. However, the method has not been implemented on a complex multidisciplinary system [13]. The approach to engineering change management presented in this paper is underpinned by a Failure Mode Avoidance (FMA) framework [10-11], which has been developed and adopted by the automotive industry as a way of enhancing the effectiveness of product development by "getting it right first time". The FMA framework aims to avoid late engineering changes by promoting early identification of potential failure modes and the development of robust countermeasures. The FMA framework is based on coherent information flow between a series of structured tools that support the systems engineering design integration. The FMA process places a strong emphasis on tools that support function analysis and decomposition, and promotes the use of an enhanced interface analysis to identify functional requirements for managing interfaces and ensuring systems integration.

This aim of this paper is to discuss the use of this enhanced interface analysis method to support engineering change analysis and management. The approach will be illustrated with an industry based case study of an electric vehicle powertrain for a small truck.

2 Interface Analysis Method

Within a complex and multi-disciplinary system engineering design framework, management of system integration on a functional basis has the utmost importance in ensuring that the system delivers the customer required functions robustly and reliably. The functional analysis of the system must provide a coherent structure for the vertical integration of the system with its subsystems and components, as well as being comprehensive in identifying *all* functions required at a certain level to manage interfaces between systems and subsystems. Thus, the functional architecture of the system must be fully be detailed to achieve the system integration through documenting:

(i) the main functions of the system, associated with the main flows through the system;
(ii) the integration of functional requirements for components to work within the system, i.e. to manage system interfaces.

Pimmler and Eppinger [15] discussed the principles of system integration analysis through interface analysis, providing the basis for a tool (Interface Matrix, IM) commonly used in the automotive industry to support the engineering systems design analysis, in particular focused on the development of robust design verification plans [3]. While the IM is structurally similar to DSM (i.e. relies on a contingency matrix between system design elements or subsystems), its aim is to systematically identify all the exchanges at interfaces which could affect the robust operation of the system. The IM proposes that the interface exchanges between components are characterized based on the general framework of Energy (E), Material (M) and Signal or Information (I) [14]. In addition, Pimmler and Eppinger [15] have introduced the Spatial (S) type interaction to describe requirements for adjacency or orientation between two interfacing components; in the industrial application of the interface matrix [3], the spatial interface exchanges are commonly referred to as “Physical” (P) interface.

The interface analysis framework has been considerably enhanced and extended [16] through the introduction of an Interface Analysis Table (IAT) to document functional requirements associated with interface exchanges. This supports the integration of the interface analysis with the systems engineering design analysis, by ensuring that all functional requirements (i.e. both main functions and interface management functions) are cascaded through the systems engineering process [17].

To illustrate this enhanced interface analysis approach we consider a case study on the system level design analysis of an electric vehicle powertrain for a small truck, discussed in [16]. The main functions of the electric vehicle powertrain EVP were defined as (i) to provide controlled torque at the rear axle, (ii) to provide power for low voltage (LV) vehicle consumers and (iii) to charge and store electrical energy.

Figure 1 summarizes the structure of the system in terms of a Boundary Diagram [16] constructed based on a structured functional decomposition of the EVP main functions using its System State Flow Diagram and Function Tree [16]. A Boundary Diagram identifies the inputs and outputs of the system, the boundaries of the system (thus defining the scope of responsibility for the system design team), the subsystems and components that achieve the system function (shown inside the system boundary), and the external systems that interface with the system. The arrows depict the flow (of Energy, Materials and Information) through the system, from the inputs (Driver Demand and Mains Energy) through to the outputs (Controlled torque at rear axle and LV/DC for vehicle consumer). The relationships between the system and neighboring systems are shown on the boundary diagram as a double-headed arrow (denoting that exchanges can take place in both directions).

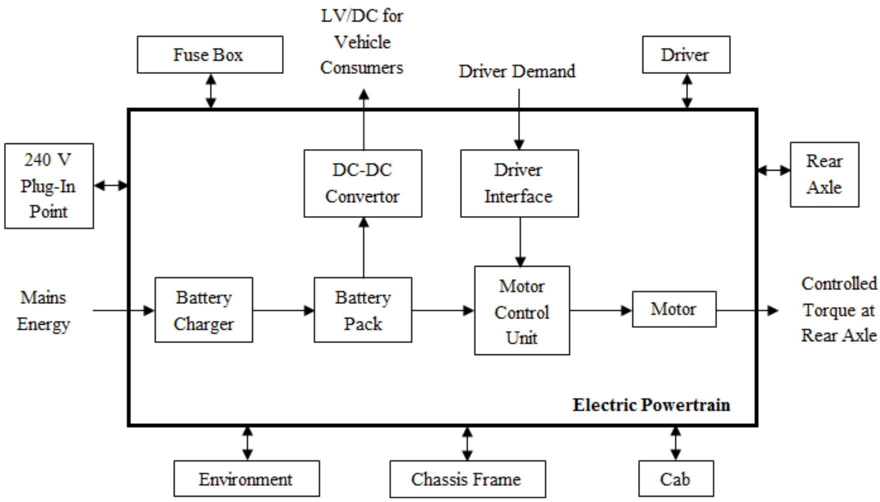

Fig. 1. System Boundary Diagram for Electric Powertrain

The purpose of interface analysis is to systematically identify and characterize all possible interfaces between subsystems, both within the system boundaries and with systems outside the boundaries. We define an interface between two subsystems in terms of the relationship between them, which, consistent with [15] and current automotive practice [3], can be defined as an exchange of material (M), energy (E) or information (I), or a physical (P) relationship relating to the spatial adjacency and orientation (e.g. packaging requirements). There could be multiple exchanges at an interface, and it is important that these are identified and characterized, because they can affect the overall performance of the system, either as "noise factors" or as "diverted output" [10-11]. Figure 2 illustrates an Interface Matrix (IM) which is a tool commonly used to document interface analysis.

In the IM, each cell documents the existence of an interface between the two subsystems on the corresponding row / column, with a summary description of the type of exchange (P, E, I or M). For example, at the interface between the "Battery Charger" and the "Battery Pack" there is an energy exchange (electric power from charger to the battery) and also an information exchange relating to the battery condition (state of charge and temperature) needed to the charger in order to control the charging rate.

INTERFACE MATRIX		INTERNAL INTERFACES												EXTERNAL INTERFACES													
		A		B		C		D		E		F		E1		E2		E3		E4		E5		E6		E7	
		Battery Charger		Battery Pack		Driver Interface		Motor Control Unit		Motor		DC-DC Converter		Driver		240 V PIP		Cab		Environment		Chassis Frame		Rear Axle		Fuse Box	
1	Battery Charger				E									P	E	P	E				E	P	E				
				I		I								I							M						
2	Battery Pack		E						E				E	P						P	E	P	E				
		I												I							M		M				
3	Driver Interface													P	E			P	E	P	E						
		I						I				I		I				I			M						
4	Motor Control Unit				E						E									P	E	P	E				
						I				I											M						
5	Motor								E											P	E	P	E	P	E		
								I													M				M		
6	DC-DC Converter				E															P	E					P	E
						I																					

Fig. 2. Interface Matrix for Electric Vehicle Powertrain

While the IM provides a compact analysis of exchanges at interfaces, both internal and external, it does not capture their details, normally discussed by the engineering team while analyzing a particular interface. This is particularly important as there could be multiple exchanges of the same type at an interface. More significantly, if an exchange (i.e. a flow of E, M or I) is identified at an interface, then a functional requirement must be specified to manage this exchange. An Interface Analysis Table (IAT) has been suggested [17] as an enhancement to the IM. The IAT, illustrated in Figure 3, shows two interfaces – one internal (Charger – Battery Pack) and one external (Battery Pack – Chassis Frame). The IAT includes a description of the exchange, the target/unit of the exchange, a statement of the engineering function required to manage the exchange and an evaluation of the effect of the interface exchange on the main ("high level") function and related high level function is also documented on the table. Coherent with [15] the rating of the effect on the main function uses a numeric scale from -2 to +2, the "-"sign indicating that the effect is detrimental to the main function and the exchange must be prevented to achieve the function, whereas the "+" sign indicates that the exchange must be provided to support a main function of the system.

3 ECM Based on Interface Analysis Method

Interface analysis, supported and documented by the Interface Matrix and the Interface Analysis Table, provides a structured framework for both systems engineering design integration (of a new system) and engineering change management. Focusing on engineering change management (ECM), the interface analysis supports and guides the ECM at three levels:

1. ***Identify the system impact of an engineering change***: The Interface Matrix provides an effective way of identifying the impact of an engineering change by

showing the interfaces between the component or subsystem that will incur the change and other subsystems *both within and outside* the system boundary. The interface exchanges are characterized in terms of P, E, I and M, with a description of the exchange being given in the Interface Analysis Table.

Cell Ref	Interface	Type	Target/Unit	Effect	Description	Function Required	High Level Function
1B-2A	Battery Pack/Charger	E	72 V	2	HV/HC from Charger to Battery Pack	Transmit Electrical Power from Charger to Battery	Charge Battery
		I	2mV	2	Battery Temperature Info from B. Pack to Charger	Transmit Battery Temperature Signal from Battery to Charger	Charge Battery
			2 mV	2	State of Charge Info from Battery to Charger	Transmit State of Charge Signal from Battery to Charger	Charge Battery
2-E5	Battery Pack/Chassis Frame	P	1mm +/-0.05	2	Installation of Battery Pack on Chassis	Locate Battery Pack onto Chassis	Provide Safe Operation
		M	<0.01g/s	-1	Chemical Matter Leakage from Battery to Chassis	Insulate Battery Pack from Chassis	Provide Safe Operation
		E	<30J	0	Vibration from Chassis to Battery Pack	Secure battery pack to chassis	Provide Safe Operation
			<50J	0	Heat Transfer from Battery Pack to Chassis	Isolate battery from chassis	Provide Safe Operation
			0 V	-2	Electric Leak from Battery to Chassis	Isolate battery electrically from chassis	Provide Safe Operation

Fig. 3. Interface Analysis Table for EVP

2. ***Evaluate the impact and difficulty of an engineering change*: In order to support engineering change decisions it is useful to be able to evaluate or quantify the impact and difficulty of an engineering change to a subsystem. The information available in the IM and IAT provides a powerful way of evaluating the impact of the engineering change by looking, for example, at the number of interfaces (extracted from the IM), the complexity of the interface exchanges (extracted from the IM in terms of the P, E, I, M types of exchanges), the number of functions that need to be provided for the system integration (extracted from the IAT), and the importance of the interface functions evaluated from the effect of the interface exchange, also documented in the IAT. In this way, the interface analysis method also provides an objective justification of the propagation path of an engineering change.
3. ***Support the implementation of an engineering change*: The Interface Analysis Table specifies the functions that need to be engineered in through systems engineering design in order to manage interface exchanges. We can therefore extract all the functions that need to be engineered in the subsystems that are subject to change, and ensure that these functions are delivered by the new design. In other words, the system design requirements for the system that is the subject of the engineering change should be cascaded from the IAT in order to ensure a flawless integration of the modified design with the system.

We will illustrate these concepts on the basis of the electric vehicle powertrain example. Assume that the potential launch of the vehicle for a new market use requires a slightly enhanced powertrain performance in terms of an increased range. An engineering solution proposed is based on enhancing the storage capacity of the battery pack. The engineering question associated with this proposed design change relates to its likely impact to the system, in terms of both design requirements and failure modes. We will answer this question on the basis of the EVP interface analysis summarized in the IM (shown in Figure 2) and the IAT (shown in Figure 3).

Figure 4 below illustrates (as an extract from the IM shown in Figure 2) the interfaces of the Battery Pack as a subsystem, with other subsystems within the EVP and external systems. This shows that the battery pack has interfaces within the EVP system with the Battery Charger, the Motor Control Unit and the DC-DC Converter. The Battery pack also has interfaces with the driver, the environment and the chassis frame. The IM gives an indication of the nature of these exchanges (P, E, I, M), with the full description given in the IAT (battery pack-charger and battery pack-chassis frame interfaces are illustrated in Figure 3 as an example). All interface exchanges need to be taken into account in the engineering design of the system with the new battery pack.

EXTRACTED INTERFACE MATRIX OF BATTERY PACK		INTERNAL INTERFACES												EXTERNAL INTERFACES													
		A		B		C		D		E		F		E1		E2		E3		E4		E5		E6		E7	
		Battery Charger		Battery Pack		Driver Interface		Motor Control Unit		Motor		DC-DC Convertor		Driver		240 V PIP		Cab		Environment		Chassis Frame		Rear Axle		Fuse Box	
2	Battery Pack		E						E				E	P						P	E	P	E				
		I												I							M		M				

Fig. 4. Battery Pack Interfaces within the EVP Analysis

It is convenient to carry out the systems engineering design analysis on the basis of functional requirements; the IAT contains a comprehensive list of interface functional requirements which need to be engineered in the system, which provide a focus for the engineering change analysis. Each interface function needs to be considered in turn to evaluate the impact of the proposed engineering change.

For example, the IM extract in Figure 4 shows that at the Battery Pack - Charger interface there are both energy and information exchanges. The IAT (Figure 3) documents further detail of these exchanges as “transmit electrical power from charger to battery”, and “transmit battery state of charge and temperature information to charger”. These interface function requirements are cascaded to both the Battery Pack and to the Charger, and the impact of the engineering change must be evaluated in terms of the internal complexity (i.e. within the Battery Pack) and transmitted complexity to the interfacing subsystems / components. For example, an internal requirement cascaded to the Battery Pack is to “transmit battery temperature information to the Charger”, which is achieved by a temperature sensing system (which includes a temperature sensor and the associated electronic circuit and harness connectors). Thus, the engineering team need to evaluate (i) internal complexity – i.e. whether the temperature sensing system can be carried over or a new system is required following the change of the battery capacity; and (ii) transmitted complexity – whether there is a requirement to have an engineering design change for the charger in order to fulfill this interface function with the new battery pack.

The external interface requirements are addressed in a similar way. The IM extract in Figure 4 shows that there are physical contact and material and energy exchanges at the Battery – Chassis frame interface. The IAT in Figure 3 shows the interface functions which the new battery pack must satisfy. These interface requirement functions are cascaded to both the Battery Pack and to the Chassis frame and the impact of the change must be evaluated in terms of internal complexity and transmitted complexity. For example, the "locate Battery Pack onto Chassis" interface function requires considering whether a new component should be used or an engineering design change is needed for the chassis to meet this interface function requirement.

In terms of evaluating the impact of the engineering change, the interface table (Figure 3) shows that the Battery pack has numerous exchanges with 6 subsystems out of 12 subsystems of the EVP. Also, the examination of the full IAT shows that the battery pack has 17 interface function requirements that must be managed to ensure the system integration. The IAT also details descriptions of these exchanges and all this information along with the IM gives an objective view regarding the impact and propagation of the battery change on the main system and into other subsystems.

4 Discussion and Conclusions

The aim of this paper was to present a structured approach for engineering change management based on an enhanced interface analysis method. The key features of this interface analysis method are that:

(i) It provides a comprehensive analysis of exchanges (expressed in terms of P, E, I, M) between subsystems both within the system boundary and external;
(ii) It provides a description of the interface exchange and a function requirement specification in order to manage the exchange at the interface to ensure the system integration.

This information is documented in the IAT, which provides a comprehensive basis for evaluating the impact of an engineering change in terms of the number of interfaces that need to be managed and the number of functions required, and also supports the implementation of the engineering change by providing a list of function requirements for system integration that must be satisfied.

This has been illustrated through the EVP case study discussion, based on an engineering change at the powertrain system level (upgrade to the battery pack). The interface analysis is normally cascaded through the systems engineering decomposition, so the approach will be applicable at all levels in the system hierarchy. For example, if an engineering change is required for the battery temperature sensor (e.g. due to the lack of robustness in the field of the current design), then the component level interface analysis, developed on the basis of a cascade of interface exchanges and functional requirements from the higher level systems, will guide the engineering change analysis by specifying the functional requirements for the new sensor.

The interface analysis method described in this paper is strongly integrated with other tools supporting the FMA framework. In particular, as discussed in [10] the interface analysis underpins the development of the DFMEA, which provides a structured approach to the evaluation of the criticality of function failure modes with their potential countermeasures. This enhances significantly the engineering change analysis by showing not only the functions that need to be provided to ensure the system integration, but also the potential critical function failure modes and their countermeasures. This provides a better platform of support for the engineering change decision – by quantifying the impact of the engineering change in terms of both interface function requirements and function failure modes.

This is a significantly different approach compared to the linkage modeling (LMM) and change prediction (CPM) methods which suggest managing changes by evaluating subjectively the likelihood (the average probability that a change in a subsystem may propagate into other systems) and impact (the average proportion of the design rework required to be done if the change propagates) of component changes [4]. Another disadvantage is that these methods seem to be focused exclusively on internal interfaces, and do not appear to formally capture and evaluate interfaces with external factors. It can be argued that the interface analysis requires extensive resource investment for a complete analysis, which appears to provide some justification for a subjective evaluation of the impact of an engineering change as a more pragmatic approach. However, the authors' extensive experience with automotive systems engineering design shows that interface analysis is treated as the backbone of the systems engineering cascade, and part of the normal engineering design process.

Further work will concentrate on the development of a more substantive approach to engineering change management based on the enhanced interface analysis method, to include a comprehensive risk management framework for engineering changes based on critical parameter management through failure mode and effect analysis (FMEA) and robust design verification. This framework will be illustrated through industrial case studies developed in partnership with industrial sponsors and collaborators to the University of Bradford Engineering Quality Improvement Centre (BEQIC).

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Optimizing Overlap between Testing and Design in Engineering Product Development Processes

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Abstract. To reduce product development time, upstream testing and downstream design processes are often overlapped. Existing studies do not recommend overlapping in situations where test results may have a significant effect on downstream redesign. However, this study identifies that, due to long procurement time and lengthy physical tests, companies may have no choice but to overlap these tasks to meet product delivery deadlines. This research investigates how a case study company manages these overlaps, and proposes a model to support the overlapping of testing and subsequent redesign phases during the development phases.

Keywords: Product development process, physical testing, virtual testing, overlapping.

1 Introduction

For engineered products to succeed in competitive markets, performance, reliability, safety and durability are critical issues. A potential design may fail to meet customer requirements, have technical design faults, or raise issues about manufacturability and maintainability [1, 2]. Testing can identify these problems and is central to product development (PD) [3]. Product development is not a linear process of "design-build-test"; rather, the design process and the testing process are intertwined. However, physical testing can take a long time, and delayed or negative results in one phase potentially jeopardise project schedules. Therefore, design for the next phase often starts before testing is complete, causing testing and design activities to overlap.

Overlapping testing and design activities can incur risk, since redesigning without test results might perpetuate faults or miss opportunities to respond to emerging problems. The literature suggests that overlap models of product development do not apply well where most changes occur towards the end of the process perhaps due to long duration testing (ie slow evolution) and where substantial redesign results from these changes (ie high sensitivity). This paper proposes modifications to the product development process structure which identify a more prominent role for virtual testing and, allow overlap models to be applied more effectively.

2 Background

Overlapping occurs when a downstream activity is started before completing an upstream activity. This can reduce development time. The advantage of overlapping has

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been recognized in several studies [4-7]. Clark and Fujimoto [4] suggest that optimal overlapping may depend on organizational characteristics and effective communication. Overlapping might identify design flaws [5], but may allow accidental omission of key steps [6] and may introduce uncertainties which can increase iterations [7]. In the worst case, development costs may increase and product quality may worsen [7] .

Two studies are particularly relevant in setting the context and background for this research in modifying process structure for effective overlap. First, Krishnan et al. [7] develop a model which formalizes the tradeoffs based on two key concepts: upstream evolution and downstream sensitivity. If the primary information about a product's parameter values are given as intervals, as the product development progresses the intervals are narrowed and finalized, some faster than others. When the final values are achieved early in the process this is called fast evolution, whilst slow evolution occurs if most design changes happen towards the end. In low downstream sensitivity, substantial changes in the upstream tasks can be accommodated readily in the downstream activities. High downstream sensitivity happens when small upstream changes require large amounts of iteration in downstream activity. This analysis concludes that in general a fast evolution and low sensitivity situation is favorable to overlapping, and conversely, high sensitivity and slow evolution is less favourable.

Second, Terwiesch and Loch [8] present a statistical measurement of the effectiveness of overlapping development activities in reducing project completion time. Fast uncertainty resolution projects benefit from overlapping. This is similar to Krishnan's conclusion above. This paper also identifies that testing in projects with fast uncertainty resolution seems to have a delaying rather than an accelerating effect. These conclusions might implies that testing with long lead time and slow uncertainty resolution is not favorable for overlapping test with redesign unless accompanied by structural changes in the product development process.

It is observed that engineering companies overlap testing and design as essential practice; regardless of the situation with respect to evolution, sensitivities and resolution, and this happens in the case study company. This paper proposes modifications to the structure of design and testing processes which allow effective overlap for fast evolution and low sensitivity as well as in situations without fast uncertainty resolution. The benefits of overlapping can then be realized more widely in practice.

3 Methodology and Case Study

A case study was undertaken at a UK-based company that designs and manufactures diesel engines; complex, highly regulated products with high levels of testing to meet customer requirements, performance standards and statutory regulations. Interviews were carried out, recorded and transcribed, between March 2011 to May 2012 with six engineers: a senior engineer, a development engineer, a CAE engineer, a verification & validation manager and a validation team leader.

Complex overlapping activities were observed in the company, but this study focused on single layer overlapping where much of the existing research has been conducted. There were two main objectives:

1. To identify a means of effective overlap, even where the upstream evolution of information is slow and downstream sensitivity is high.
2. To identify ways to speed up testing to give quicker uncertainty resolution.

The next section starts by reviewing the process structure and overlapping in the case study company, then section 4 analyses the ways that the company overlaps testing and design, and section 5 proposes changes to the process structure for more effective overlapping of testing and design.

3.1 Process Structure in the Case Study Company

The case study company has a structured gateway process for New Product Introduction (NPI) (Fig. 1). It has eight stages starting from “Launch” to “Gateway 7”. Most of the testing occurs between Gateway 2 (GW2) to Gateway 4 (GW4), thus this research focuses on these three main phases of the PD process (as in Fig. 2).

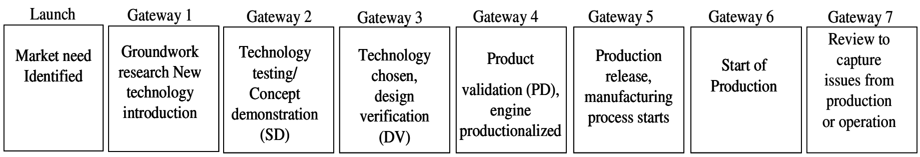

Fig. 1. An outline of the company's gateway process

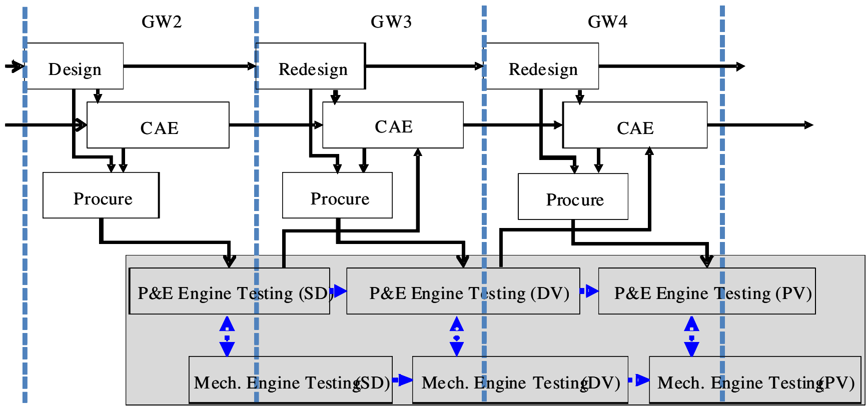

Fig. 2. A schematic of the PD process from Gateway 2 to Gateway 4

Among the large number of activities in these stages, Re/Design, Computer Aided Engineering (CAE) (eg Simulation), and Procurement (of test prototypes) are considered as drivers for testing. For simplicity Fig. 2 presents these activities as time limited boxes, but in reality, a core team keeps working on Design and CAE, and Testing goes on almost continuously, in parallel to these activities. Design, CAE, Procurement and Testing undergo at least three iterations from GW2 to GW 4, and serve different purposes in each stage.

Three phases of testing are distinguished: (i) Concept/System Demonstration (SD) shows that the technology can deliver the required performance; (ii) Design Verification (DV) aims to ensure that design outputs meet the given requirements under different use conditions, and (iii) Product Validation (PV) which tests the product against customer requirements and specifications. Both the product's characteristics: Performance and Emission (P&E) and the mechanical durability and reliability are tested in each of the three phases. The mandatory tests required for acceptance usually occur during PV phases. The engine level testing blocks (Fig. 2) contain a large number of tests. Some tests are grouped and some are individual. Some test results can be obtained quickly whereas some require running the tests till very end of the testing phase.

3.2 Overlaps with Testing in a Single Product Development Stage

In each gateway stage there are overlaps between activities. Design, CAE and Procurement overlap but the focus is on their overlaps with testing:

- CAE - P&E testing: CAE analysis, e.g. Computational Fluid Dynamics (CFD) is used to support the design, optimization and verification of an engine's fluid system. As the company freezes the design, some CAE work is still ongoing, and/or additional CAE work might be required parallel to the physical testing.
- CAE-mechanical testing: Finite Element Analysis (FEA) provides accurate, timely and cost-effective guidance when testing the durability of engine components.
- Procurement-testing: Testing starts as soon as a component arrives at site to minimize the testing lead time. Even system-level testing continues with prototype parts.
- P&E testing-mechanical testing: Early results from P&E enable the mechanical testing phase to start earlier.

Note that the significant overlaps which occur between testing and (re)design in the next phase, is an area of interest of this paper. Fig. 2 illustrates how engines are tested in sequence for SD, then DV and PV. However, in reality, several versions of the same engine are tested simultaneously in parallel test-beds. Some components are tested for concept demonstration whereas others are tested for design verification. Therefore, each testing phase overlaps in a complex manner.

4 Analysis of Overlapping Design and Testing in the Case Study Company

In analysing the company's design and testing processes, two key issues emerge in overlapping tasks. Firstly, long lead time procurement and secondly, the long duration physical tests.

4.1 Long Lead-Time for Procurement

There are some cases, for example during design verification (DV), when the company needs to start a certain test to meet the schedule of the next GW stage, but a core hardware component is not available from the supplier. The company cannot afford delay, and instead tests using alternative components. The validation managers need to identify suitable alternatives and calculate trade-offs. For example, an engine requires a piston to run a test, but the piston will not be delivered until a later date, so they will either continue physical tests with a prototype piston, or else simulate the ideal engine computationally and identify the associated risk. These alternative tests may give a risk reduction of, for example, 30% instead of the planned 50%. In this scenario the product cannot be signed off yet, and physical testing of the new piston in an engine is still necessary for verification or validation. This situation causes the DV or PV phases to extend over two GW stages instead of one.

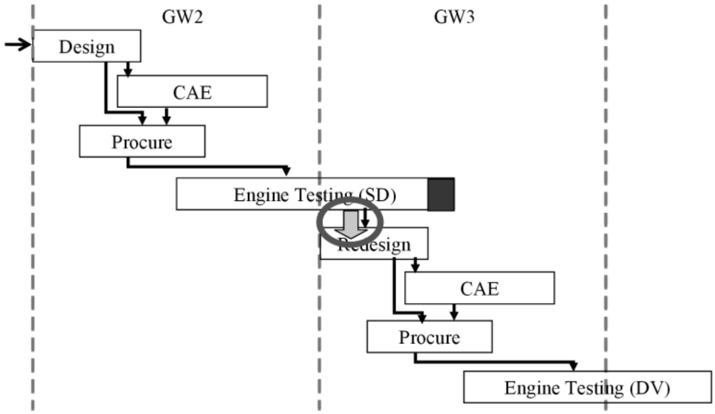

Fig. 3. Overlapping between testing and redesign in two phases

4.2 Lengthy Physical Tests

Testing physical prototypes is essentially a slow and expensive process. However, it is a high fidelity method for ensuring the product's characteristics and in some cases is mandatory for acceptance and essential for assuring the product's function and behaviour. Ideally, physical testing results from one phase should drive the design and CAE of the next phase. However since testing takes a long time, it is not often viable to wait. For instance, the SD phase testing may still be on-going while the (re)design for the DV phase is started (and sometimes finished), and while procurement for the subsequent DV testing begins, as seen in Fig. 3.

Without the testing results being available, there will be uncertainties in redesigning and procuring for the next phase. This is a case where upstream evolution of testing information is slow and has high sensitivity on downstream design phase, resulting in significant number of iterations in subsequent phases.

4.3 The Current Approach to the Issues

To overcome the issues mentioned above, the company has developed two main methods: firstly frontloading the tasks, and secondly reducing physical testing through supporting CAE.

Front loading (a) increases the rate of problem solving cycles at early stages (activity frontloading) or (b) uses prior knowledge about past problem solving (knowledge frontloading) to reduce the necessary number of problem solving cycles at later stages [4]. To minimize long lead time procurement, a clear and accurate specification of the product is required. CAE analysis drives design requirements and engine settings for test. Optimization takes place earlier in the product development cycle (front loaded), to improve product specification to the supplier. The company makes virtual prototypes with many iterations to enable the first physical prototype to be built closer to target. One engineer commented, "*computer simulation is becoming increasingly important to the companies to minimize the effort and expense involved in product development*".

Reducing physical testing through CAE analysis and simulation, can identify improved boundary conditions for physical test, which then becomes more focused. For example in a performance test, simulation can predict when to measure a value or conditions, so less time is spent on the physical test. Physical test results validate the product as well as the simulation model, which is then reusable for future products, reducing time and cost for subsequent iterations of the model. Iteration in physical product testing requires building a new physical prototype and might involve redesigning, reordering, building and testing, In contrast, virtual testing supports fine tuning of selected parameters and rapidly produces new models of components or products.

5 Proposed Process Structure

In the review of literature in Section 2 two key papers [7, 8] were identified. Krishnan, V. et al. [7] recommend circumstances where activities should be overlapped. From their model, the worst case is where the upstream evolution is slow and the downstream sensitivity is high; in this case overlapping is not recommended. In this situation, it is suggested that exchanges of information should be disaggregated, to see if any information can evolve faster, or can be practically transferred in a primary form.

On the other hand, in the other key paper, Terwiesch and Loch [8] indicated that lengthy testing might have a delaying effect on a fast uncertainty resolution project. For this case study company, it is difficult to gauge the speed of uncertainty resolution. The company has to finish a project on a given timeline and bring the product to the market. Even for a complex new product, the timeline may vary little. Terwiesch and Loch [8] also suggest that "*if the uncertainty resolution over the course of the project is unfavourable for overlapping activities and cannot be sufficiently accelerated by defining standards and architectures, the project organization has to search for other means of uncertainty resolution*" [8]. For the case study company, testing is the primary method for uncertainty confirmation and identification. Subsequent tasks such as redesign are uncertainty elimination tasks. Testing is a slow process; so the company undertakes downstream design activities before testing is finished. Knowing the associated risk of an extensive rework, the company has no choice but to overlap these design tasks with testing, a design proposal is needed to commence another lengthy procurement process. Thus for this case, a way of accelerating the testing process was essential.

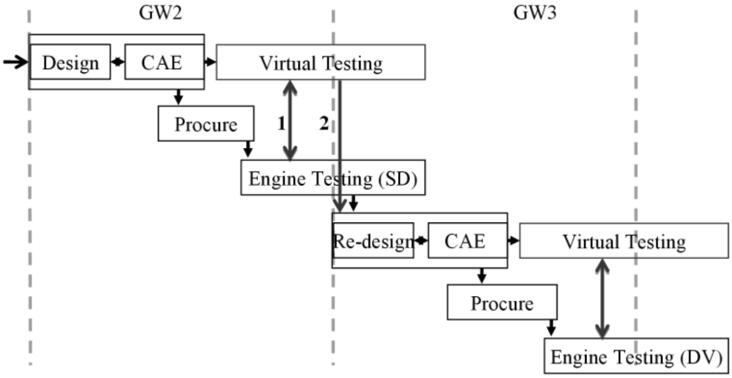

Fig. 4. The proposed process structure

It is suggested for this case that these issues can be solved by introducing virtual testing parallel to the physical testing in each PD phase, as shown in the model presented in Fig. 4. Simulation or virtual testing can be regarded as distinct from CAE analysis proper. Initial CAE analyses may check interference and stress on components and assemblies using general purpose tools, such as FEA. A virtual test is designed specifically for a given situation and conditions and is representative of a physical test. Virtual testing of a piston should create a use scenario over the full range of parameters on a piston which might be encountered in a test bed. This virtual test for a piston would not be appropriate for another component like a connecting rod. Such virtual test models are founded on the expertise of engineers and the software development team in formulating mathematical models for the interacting engine components, writing appropriate numerical solution algorithms, and integrating the resultant programs into workable analysis. However, it is also noted that physical test results help to improve and validate virtual test models. Early CAE analysis helps to reduce uncertainty, thus frontloading activities. In contrast virtual testing is aimed more at reducing the time and effort of physical testing.

The proposed model separates virtual testing from the initial CAE analysis. Initial CAE analysis should define the specification for procurement and virtual testing should assist the physical testing. Not all physical tests require virtual testing, or might be assisted by it. Initially, it is necessary to build a virtual test model, which is representative of the physical test, and can be validated in physically. Engineering experience, prior understanding of the product, previous product testing and historical data should all contribute to the boundary conditions for the virtual test model. The model is further validated against the values gained from the physical tests. The limits of variation in the variables are adjusted in the virtual testing model through several iterations until the simulation model is representative of the physical tests.

5.1 Benefit from Virtual Testing

Integrating virtual testing into the process structure can help to address the two key objectives in Section 3. The first objective is to create effective overlap when upstream evolution is slow and downstream sensitivity is high. For instance, in cases where results from a physical test cannot be delivered before the end of the test, the durability testing of a new engine component may not produce any failure until very late in the testing process. This type of failure can prompt modifications with serious consequences (such as material changes) and may lead to an additional iteration in design and procurement. As information does not evolve quickly in upstream testing, which has a high level of sensitivity to downstream design, overlapping is not favorable. This paper suggests using parallel virtual testing. When the sensitivity in the downstream design is high, the faster evolution of useful test results is required to make the overlapping possible. In this case, this paper suggests starting the downstream design work once the virtual testing has produced results which are representative of the physical testing results. Virtual test model simulation will predict parameter values faster than a physical test, and the faster evolution or disaggregation of useful results will be possible. Early prediction or indication of failure can support an early design decision.

The second objective is to make testing faster. Different tests benefit from integrating virtual testing with physical testing in different ways. Some benefit by focusing the tests, and identifying future values to minimize the number of iterations to yield a satisfactory design, while others require running for shorter periods of time. For example, for constant speed and load, an engine has its intakes of fuel and air regulated, with the goal of achieving desired power ratings. An engine might require several iterations in design and test to achieve these desired power ratings. A virtual testing using a mature model can predict the likely consequences of certain values of fuel and air intake of the engine, thus suggesting appropriate values for next iteration.

Reliability and durability tests ensure performance without failure over an extended period of time. When a virtual test is able to accurately predict the behaviour of the engine, then the number of physical testing hours for durability can be minimized, saving time and reducing cost. The virtual testing might also indicate the points where the product might fail, making it possible to avoid unnecessary testing, or to replace a component before it fails and damages the whole engine.

5.2 Costs for Introducing Parallel Virtual Testing

Companies might be reluctant to accept the introduction of a virtual testing model if the costs are higher than the benefit. The cost will depend on two main factors: communication cost and virtual testing model establishment cost. Effective communication between physical testing and the CAE team is a key success factor for this structure of parallel physical and virtual testing.

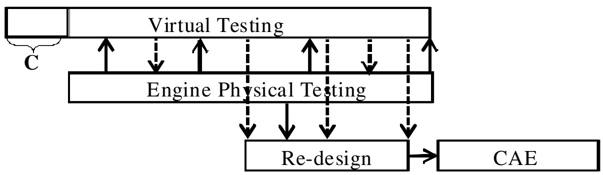

Fig. 5. Information exchange between virtual testing, physical testing and design

Initially, virtual (simulated) and physical testing results may differ in several ways. Discrepancies may determine the number of meetings required, and increase with the level of uncertainty and potential dependencies [9]. The cost for introducing the virtual testing block can be calculated as follows. Initially a fixed cost C is required to build the virtual model (as shown in Fig. 5). This cost will depend on the company's capability in CAE modelling and simulation. With a well established CAE department then this cost might be lower than outsourcing. We are assuming that the cost for each meeting is X_i, for meetings i = 1, 2,.. n. After the model is mature, the frequency of meetings is reduced. Each meeting results in modifications and further simulation in the virtual model, at cost Y_i. A regular maintenance and opportunity cost M is incurred per unit time, for the virtual test duration T_V. If a company has committed human resources for CAE analysis throughout the process, this maintenance might not add extra marginal costs. Thus the cost of additional virtual testing model is:

$$C_{VT} = C + \sum (X_i + Y_i) + M\,T_V \qquad (1)$$

Savings denoted C_T will be accumulated in several ways. Learning from the parallel virtual testing will reduce the uncertainties in design and procurement. The gain is highly dependent on the sensitivity of the downstream work. It is assumed that this virtual testing will make the physical tests shorter without any quality loss, and that the virtual test is representative of the physical testing. A benefit in using parallel virtual testing will accrue when $C_T > C_{VT}$. However, the real benefit of using parallel virtual testing continues during iterations as this might avoid extending a testing into a subsequent gateway. Even with another iteration (of DV for example), the cost of running the virtual testing phase will be approximately $\sum (X_i + Y_i) + MT_V$, as the model building cost C will be small as the virtual testing model is already mature, the number of meetings will also be relatively low. The duration of physical testing in this phase will be shorter, and uncertainty decreased. Thus larger savings in physical testing are possible.

6 Discussion and Conclusion

The question remains as to whether such virtual testing models can be constructed. The case study company has partially done this, both to assist the physical testing and to apply when physical components are not ready. The performance, reliability and durability predictions of engine components using CAE is developing rapidly. For example, the material and structural analysis group's understanding of the principles of fatigue behaviour in complex materials, combined with historical data from high temperature applications, modelled in commercial (and internal) software, with a comprehensive materials database means that the durability of engine components can be reliably predicted and probability distributions applied to perform failure rate calculations. Whilst the company recognises there are still many technical challenges to overcome, ongoing investigative work in virtual testing currently includes gas flows and combustion chemistry, cavitations in bearing oil films and metal fatigue under extreme temperatures.

This research suggests a model to reduce the uncertainties associated with overlapping between testing and redesign. This paper has considered the scenario where the information evolution of upstream testing is slow and the sensitivity on downstream design is high a case which the literature suggests do not provide favourable conditions for overlapping. However, companies often have no other choice but to practice overlapping. The proposed model suggests a possible strategy for overlapping providing several benefits: (1) reduced uncertainty in design and procurement, (2) focused physical testing, (3) reduced duration of physical tests (4) reduced iteration and overall cost saving.

Further work will extend validation of this model in an industrial context, including the original case study company. In particular, overlapping considerations for the design and testing of products at different scale, complexity and maturity will be compared. The model will be extended to consider multiple layered overlapping.

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Do(PLM)Con: An Instrument for Systematic Design of Integrated PLM-Architectures

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Abstract. Today, the purpose of many PLM implementation projects is the realization of PLM-Architectures which aim on product data integration over the dimensions domain, business unit and product line along the Product Development Process. Currently, these projects are mostly addressed like IT-Projects for implementation of domain specific products (e.g. CAx, PDM- or ERP-Systems). Hence the implementation focuses on functional aspects. This focus usually lacks consideration of semantic and progression conception which are key aspects for PLM implementation. To improve this situation the Do(PLM)Con methodology was developed. It provides methods for abstract design of integrated PLM-Architectures including semantics and progression. The following paper will explain the terms semantics and progression in PLM and describe the Do(PLM)Con method as an instrument for systematic design of integrated PLM-Architectures.

Keywords: PLM, Product Lifecycle Management, PLM-Architectures, Do(PLM)Con.

1 Current Discussion of Integrated PLM-Architectures

Today industry is working on digitizing the entire process chain from product to production. One of the essential goals of this is to bridge the gap between virtual and real world. To do so, it is necessary to design integrated virtual Product and Production Models across the product lifecycle which presupposes the implementation of integrated PLM-Architectures. A major task to realize this is to define a suitable IT-System landscape.

An ideal picture discussed in this context (see Figure 1) is the concept of service oriented PLM-Architecture which aims on separation of business logic from applications and database layer [1]. The idea behind this approach is that IT-Systems offer standardized "services" which can be used by other IT-Systems. This approach of loose coupling has substantial potential, but does not solve persistent semantic integration which is a key aspect while implementing integrated PLM-Architectures.

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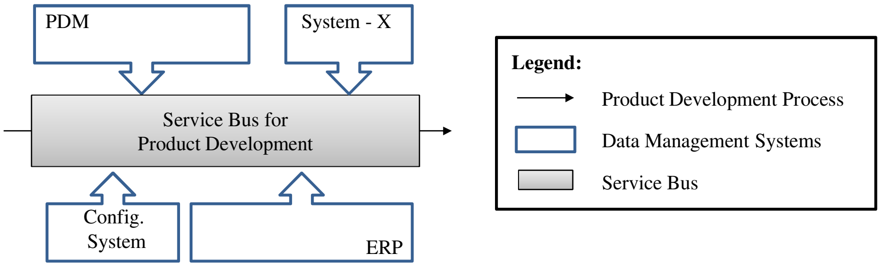

Fig. 1. Ideal picture of an integrated PLM-Architecture

2 Semantic and Progression as Key Aspects for PLM-Realization

Product models are realized as product structures within IT-Systems. IT-functions used in product development traverse these product structures and extract portions of data to be authored by the user. To do so, they demand specific semantics from the respective product structure. If the structure does not meet the demanded semantics, the function is not or only limited available. This issue becomes particularly relevant when building integrated PLM-Architectures since integration requires the consolidation of different product structures with distinct semantic aspects. Hence the resulting consolidated structure usually contains significant semantic changes.

Figure 2 shows an example for such a case. The business intent of the scenario is providing a digital product prototype in a correct positional arrangement that can be configured based on customer-selectable variant options. The business intent should be realized within a PDM-System. The relevant functions to fulfill the use cases, as the most important the visualization of virtual prototypes is mentioned, will take place in the PDM-Client.

On the left hand side of Figure 2 the implemented "Current State" Scenario is shown. A product structure is maintained in a PDM-System. The Client in pairing with the business logic of the PDM-System traverses these product structure and extracts the data which has to be visualized for and authored by the user (Figure 2, Detail A).

For realization of the integrated "Future State" (Figure 2, right hand side), structure extracts with specific semantics from the BOM-System are inserted in the product structure of the PDM-System (Figure 2, Detail B). In this specific case it is the position, the part and the usage including the variant condition. To complete the modeling, the incorporated structure extracts have to be semantically integrated. In this specific case semantic integration is done by Product Engineers through assignment of CAD documents to the respective design usages. This nourishes the product structure with prior to this not explicitly documented information of geometric variance. As a result of the described semantic integration, the basis of information for realizing the new visualization use cases is set.

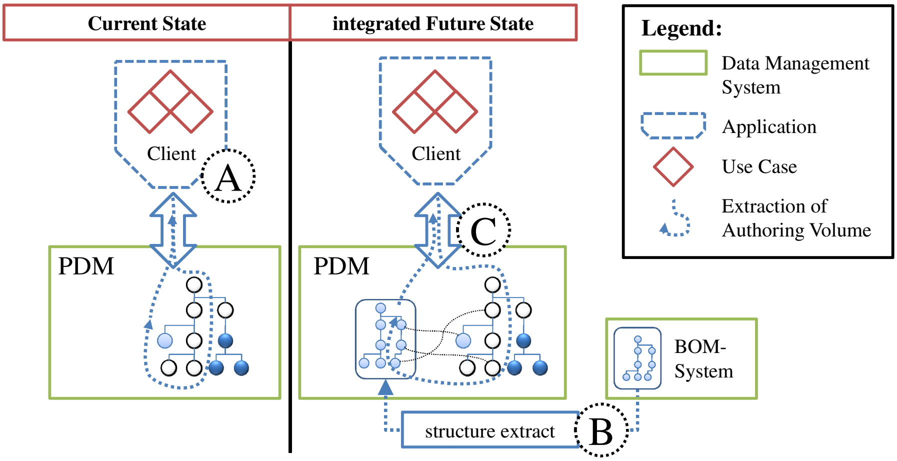

Fig. 2. Example for an industrial integration scenario

The use cases are performed by the user with the help of IT-Functions. These Functions (see Figure 2, Detail C) access the specific product structure represented in the PDM-System, extract an amount of data and provide these data to the user. Pre-condition for the function to perform successful is that the semantic consistency the functions expect from the product structure in the PDM-system is met. Therefore, a function could be considered only in pairing with the semantics of the given product structure.

Taking into account that semantic necessities are driven by methodical, organizational and technical aspects [2] whereas the first two are typically customer specific and that integration presuppose conjoining diametrical semantics it becomes obvious that semantics is a key aspect of the design of integrated PLM-Architectures.

Another important aspect to be considered is the progression of product information during product lifecycle. Figure 3 outlines the principle dimensions of progression within PLM. Entity progression refers to the gradual development of product information across product lifecycle. Typically known concepts to depict this aspect in product structures are revisions and releases. The dimension granularity modification denotes on changes of data granularity happening regularly during daily work. It occurs if information has to be transferred in another level of detail. A typical example for a situation could be that the designer recognizes that the axle he wanted to design as a single part has to be subdivided in different parts connected via a gearbox or a BOM-Engineer notes that filter and sealing ring have to be ordered separately, thus he has to transfer the previous component into two separated parts within the BOM-System. Content separation contemplates that a partial portion of a structured information including semantics is taken to use it somewhere else. Export to Excel or XML would be the standard example for this kind of progression. The important consequence of this case is the fact that in the moment this data is separated a parallel redundant lifecycle of the separated data accrues, which might has to be adjusted by manual or automatic activity during the development process.

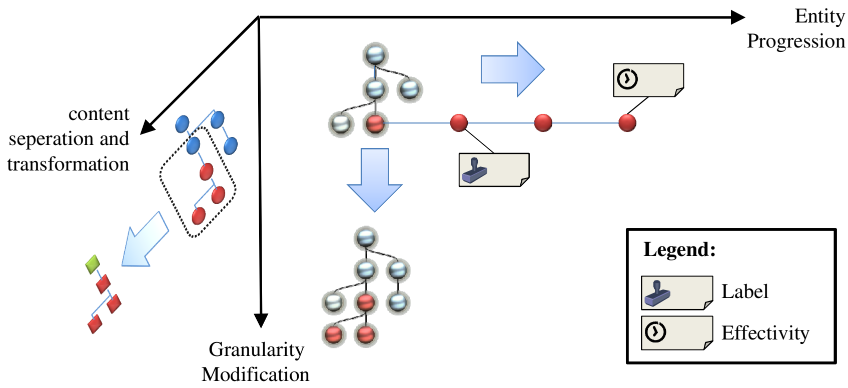

Fig. 3. Progression dimensions

The aspects of progression are substantially known and handled in common PDM-Systems today, but considering integration, the progressions of different product structures have to be synchronized. Since this is, due to organizational premises, in numerous cases not possible asynchronous progression has to be realized instead. This is usually challenging and has significant impact on structure semantics and semantic consistency of integrated structures.

In consequence of these considerations PLM-Functions can not be seen on their own anymore. They have to be considered in combination with semantics and progression. Thus, semantics and progression becomes a central design aspect while realizing integrated PLM-Architectures. Today’s typically taken functional view often leads to the obstacle that the necessity of carefully semantic and progression conception is not considered as part of the project. Thus in the course of the project integrated structures evolve, but their semantics and semantic integrity is adapted through an exhausting "trial and error" process until they fulfill their purpose.

To solve this, an instrument is needed which allows to design integrated PLM-Architectures including the key aspects semantics and progression. The Do(PLM)Con method is such an instrument.

3 An Abstract Layer

During conception of the Do(PLM)Con method it became obvious, that a construct was needed, which allows to depict functional requirements including belonging semantic and progression necessities. Beyond this, the construct should be able to simplify the complex coherencies of PLM and detach PLM-Architecture discussion from limitations of already given IT-Systems or IT-technology.

When considering the Product Development Process it can be seen that such a construct exists, but its significance has not been recognized sufficiently. During the Product Development Process teams of Product Engineers of different field of applications create and use models of the future product. Each of these models reflects partial aspects of it. Typically known product models are solid CAx-Models combined as product structures in PDM-Systems, BOM-Models realized in BOM-Systems or Requirement Models created in Requirement Management Systems (for additional examples see [3]). Further, usually unsought models can be found all across product development departments in standard tools like Excel and Access or as piece of paper in the drawer of an engineer. Key to successful product development is to create, align and combine these partial product models until the real product can be build out of them.

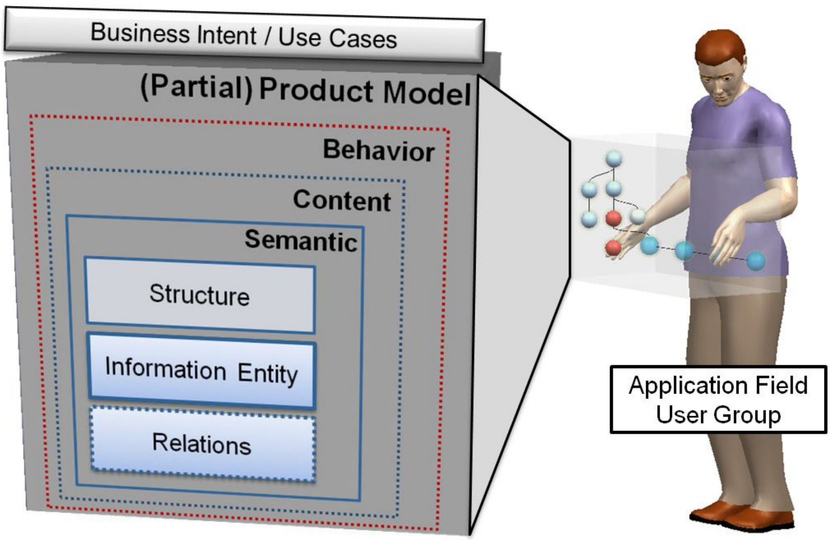

Fig. 4. Partial (Product)Model

Hence, Do(PLM)Con takes "Partial (Product)Model" as its abstract core element (see Figure 4). A "Partial (Product)Model" in Do(PLM)Con is seen as a depiction of a sum of relevant aspects of the product out of the perspective of a specific field of application or users (a more detailed definition is given in [4]). In Figure 4 the aspects of the Do(PLM)Con definition of Partial Models are delineated. A Partial Model exists because of its purpose (Figure 4, Business Intent). To realize this purpose, it has to cover defined use cases of product development. The use cases themselves require specific semantics from the Partial Model. The semantics subsumes the areas structures, information entities and relations between information entities. A Partial Model is designed for an explicit content, for example to subsume a single product or a complete product program etc. Due to the aspect of content a Partial Model possesses behavior. Behavior can be subdivided into the categories progression, access and extraction whereas progression is the most important aspect of the behavior (see progression dimensions in Figure 3).

With the help of the Partial (Product)Model concept the various models generated by product engineers within the Product Development Process can be easily expressed. If in addition also analyzing the lifecycle interaction between the Partial Model, the Partial Model concept becomes an essential basis for understanding the customers individual Product Development Process.

To support this the Do(PLM)Con-Method provides different diagrams which are able to depict Partial Models including their interaction in Current (meaning already implemented) and Future State. To give an impression a planned "Future State" outlined in the "Lifetime & Information Flow Diagram" is shown in Figure 5. The example focuses on the scenario of Figure 2 but beyond this includes additional Partial Models which have to be considered.

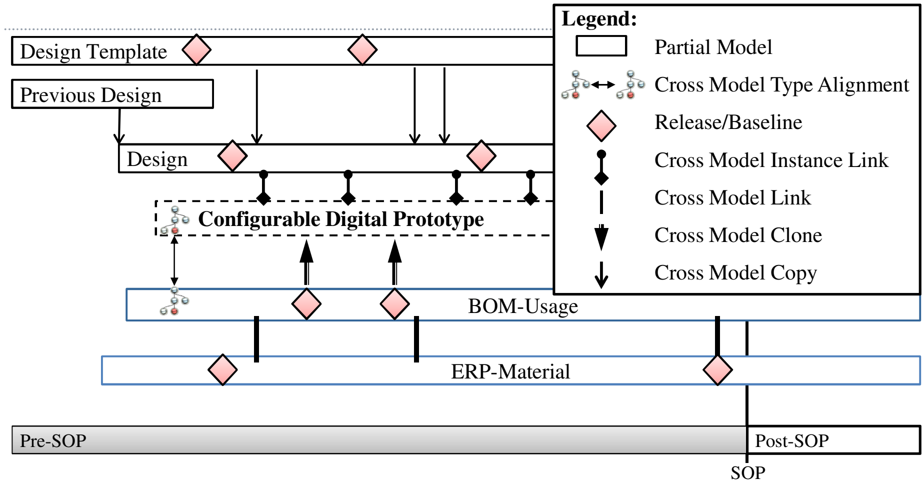

Fig. 5. Example for working with abstract Partial Models

The Lifetime & Information Flow Diagram enables a simplified overview of relevant Partial Models, their rough lifecycle and their lifecycle interaction. The models are shown along a time axis which subdivides into Pre- and Post-SOP (Start of Production) of a given product. Rectangles depict Partial Models in their rough lifetime. The type of arrows between the Models represent the principle model integration and the rhombus indicates releases within the Partial Model. All different symbols have specific methodical significance.

The Business Intent behind the scenario shown in Figure 5 is a typical integration scenario in industries today. It aims on visualizing a digital product prototype that can be configured based on customer-selectable variant options. In the depicted Future State scenario a new Partial Model for "Configurable Digital Prototype" is realized. It integrates information from the "BOM-Usage" Model via "Cross Model Clone" which indicates that the information (e.g. the part and usage) transferred is cloned to the "Configurable Digital Prototype" Model. This solution concept allows for a progression splits between the two Partial Models, which enables working on both models simultaneously. The "Design" Model is connected very closely through "Cross Model Instance Links". Linking Models via a "Cross Model Instance Link" denotes that Model A and B are sharing some identical Information Entities but the instant link adds model specific context information (e.g. Design Variants or Variant Specific position information). This kind of a design near realization of the "Configurable Digital Prototype" Model is chosen because one business intent of the scenario is to support the Pre-SOP design with the configurable visualization.

As seen above the Do(PLM)Con Partial Model concept and diagrams allow for simplified analyses of integrated PLM-Architectures consisting of interacting Partial Models on pure methodical level. This creates a neutral base to discuss and define future concepts not being influenced by already realized IT-Systems. This kind of reduction to the substantial demand generates high transparency of requirements and enables savings in implementation costs since only requirements which are really necessary will be implemented.

4 There is No Green Field

Management of the product lifecycle is nothing new. Every manufacturing company has to manage the lifecycle of their products and they did it long before PLM became a significant topic in manufacturing industries.

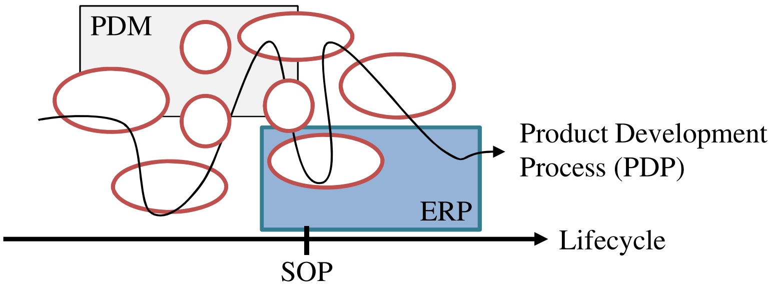

Fig. 6. Typical "Current State" IT-System landscape

The purpose of realizing PLM-Strategies is essentially based on the fact that an effective management of the product lifecycle contains enormous improvement potential which could realize high competitive advantages. Also it is necessary to manage the increasing product complexity. Thus there is no green field while realizing PLM. In every manufacturing company a "Current Situation" is found and the aim of PLM is to improve this current situation. In Figure 6 a typical "Current State" IT-System landscape is shown. A grown Product Development Process is mainly supported by standard IT-Solutions (e.g. PDM- and ERP-Systems). Additionally, a number of mostly individual systems is used.

In a first implementation stage of PLM industries aimed on reducing the number of individual systems by integrating them in standard solutions such as PDM and ERP. Currently there is a tendency to think in a large-scale on digitizing the entire process chain from product to production in a multi disciplinary Engineering Network Repository [5].

5 "Value Design PLM" with Do(PLM)Con

For this each company has to find and define an individual "Future State" PLM-Architecture. Do(PLM)Con is an instrument, containing systematic approaches, tools and best practice methods which help to design such a "Future State". Do(PLM)Con is based on some principle paradigms which are listed below.

- Integrity of functions, semantics and progression
- Model before process
- Stay Focused
- Value first

The paradigm **"Integrity of function, semantic and progression"** refers to the necessity to consider the aspect function only in context of semantics and progression and to ensure decoupling of the architectural discussion from functional blocks in IT-System landscape maps by using the Do(PLM)Con concept of "Partial Models". **"Model before Process"** denotes that while analyzing a "Current State" situation it is easiest to first focus on Partial Models, secondly on the engineering tasks which are performed with the help of these models and thirdly on the engineering processes following out of this. The reason for this is the experience that Partial Models are the seed crystals of the interrelated engineering processes in product development. **"Stay Focused"** indicates that there should be a clearly defined PLM-Area which is in focus to avoid the risk of overcharging the project. **"Value first"** emphasizes that it is only reasonable to implement a Partial Model if it is possible to describe the kind of business intent it fulfills and which value this will bring for the Product Development Process.

The Do(PLM)Con approach follows a procedure model (see Figure 7) which defines different realization phases. The two most important phases are

- Pre-Framing and
- Realization Packaging

In "Pre-Framing" the "Current State" of implementation and the Product Development Process is investigated. The fundamental tasks in this phase are analyzing existing Partial Models, identifying their business intent and investigating the user groups maintaining and using these models (cf. Figure 7, "Current State" from Implementation to Partial Model Layer). In a directly following step interactions between Partial Models are also examined.

The outcome of the Pre-Framing analyses is documented in the diverse Do(PLM)Con simplified graphical representation diagrams (see as example Figure 5).

Following these investigations “Value Design PLM” is done as part of Pre-Framing. “Value Design PLM” is based on similar ideas as "Value Stream Design" in "Lean Management". As "Value Stream Design", "Value Design PLM" is oriented at customer view [6]. The customers in case of Do(PLM)Con are the users of the different Partial Model, their needs and the core tasks which they have to perform with the Partial Models. Consequently, that connotes that if a Partial Model does not support a defined business intent it is not needed and thus the necessity to create and maintain it, is to be questioned. Also it is to be called into question whether or not two models are necessary if supporting similar Business Intents. Following out of this “Value Design PLM’s” first goal is to reduce the number of Partial Models.

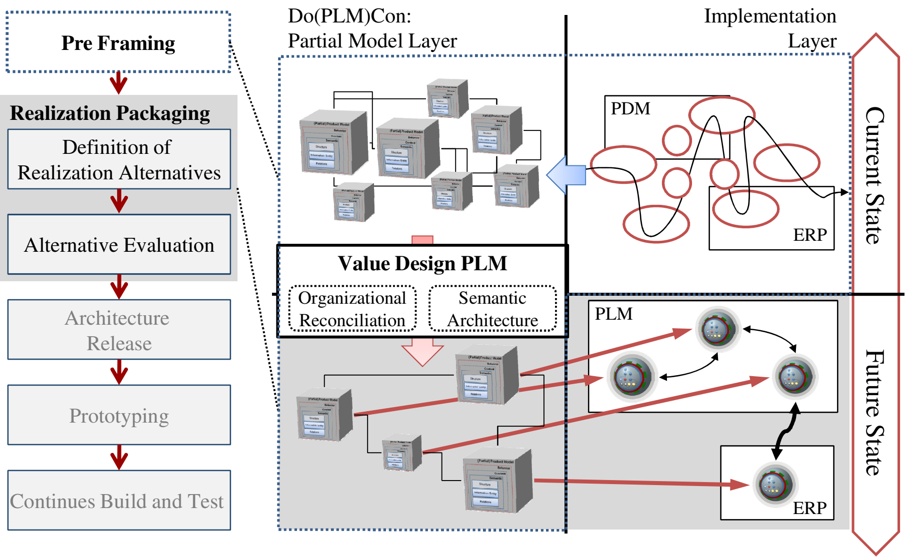

Fig. 7. Do(PLM)Con Procedure Diagram

As a further step a new lean integration of the different models is designed. This has on one hand the target to realize self-acting, automatic interaction wherever it is possible and on the other hand the goal to discover the integration potential of different Partial Models by analyzing their communality. The aspect of communality and possibilities to use them for “Value Design PLM” has a specific significance for integration approaches but is too complex to be discussed in terms of this paper having an overall focus. Outcome of “Value Design PLM” is a Future State of Partial Models including their semantics and progression and the definition of necessary integration and interaction processes.

In the "Realization Packaging" phase the desired "Future State" is realized in different concepts of possible implementation alternatives (cf. Figure 7, "Future State" from Partial Model to Implementation Layer). For this Do(PLM)Con defines the construct of Realization Package (RP). A RP encapsulates a complete scenario for an implementation landscape to be carrying the different Partial Models. A RP also includes the definition of necessary function packages and PLM-Applications realizing this functionality. A RP is thus a concrete definition of a specific framework for a possible solution that can be evaluated, simplified depicted and thus discussed transparently on management level.

Since chosen IT-Systems and applications are providing a semantic and behavior frame as a next step "Future State" Partial Models have to be fitted into the semantic and behavior frame of the Carrier IT-Systems given by the specific RP. Do(PLM)Con supports the fitting with the help of "System Mules". "System Mules" in Do(PLM)Con are constructs similar to development mule in the automotive industry. System-Mules are IT-System installations equipped with experimental components for testing to try out aspects before starting the full customization, implementation and roll out. Significant goal is to discover typical issues, especially semantic inconsistencies which might occur due to intensive integration of Partial Models.

The "Realization Packaging" ends with the release of one specific realization package which should be implemented as the future integrated PLM-Architecture. After this the chosen Realization Package serves as a guiding model for the implementation in following project phases.

6 Conclusions

Do(PLM)Con provides instruments that help to derive lean and flexible concepts of integrated PLM-Architectures. By Pre-Framing and Realization Packaging as the underlying main design steps it is possible to provide a specific design proposal already in an early project phase which could be used as a basis for discussion, scientific object and experimental environment. The systematic analysis helps to avoid complex amendment and to speed up usually long drawn-out integration projects. Do(PLM)Con therefore enables an effort-reducing implementation of integrated PLM-Architectures. Also the expenses for the maintenance and care of the structure during the application are substantially reduced.

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Meta-data-Model for the Development of Adaptronic Systems

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Abstract. Active systems are characterized by an integration of electronic components into mechanical systems and can be distinguished into mechatronics and adaptronics. In adaptronic systems the electronic components are full structural integrated. The Department of Computer Integrated Design (DiK) has developed the W-model as a new proceeding model for the integrated development of adaptronic systems which is based upon a virtual cross-disciplinary integration and verification in all phases of product development. Therefore the W-Model insists on the use of special development environment which is based on the product data management functionalities. In this paper a proposal for a meta-data-model for such an environment is presented. Following the W-model the meta-data-model allows the definition, import and analysis of complex system models, the derivation of hierarchic requirements-, function- and product structures and the definition of integrated system simulations for the virtual verification of results.

Keywords: Adaptronic, Development, Systems Engineering, W-Model.

1 Introduction

The development of active systems is characterized by an increasing integration of electronic components. In addition, these devices are no longer additions to mechanical systems but more and more structural integrated. This leads to a further development of mechatronics towards adaptronics. The increasing level of integration is an additional challenge for product development, as the variety of dependencies between systems elements must also be considered in the development process.

The application of existing process models for the development of mechatronic systems has proven to be an issue due to increasing complexity. Therefore, a new process model for the development of active systems, as an extension of existing models, has been developed. This new model, called the W-model, insists on the use of a specific development environment.

The aim of the work presented was to develop a meta-data-model for such an environment. The W-model as well as the meta-data-model is presented below and a possible implementation using a representative example is shown.

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2 Adaptronic Systems

Active systems are distinguished into mechatronics and adaptronics and are characterized by an adaptation of the mechanical behavior to changing external and internal conditions.

Mechatronics refer to systems in which, in addition to different active principles for functional performance, other disciplines such as control, regulation, and information technology are used [1].

In adaptronic products the sensors and actuators are structurally integrated. This means they are embedded in the load path of the basic mechanical structure. In adaptronic systems sensors and actuators are often made from multifunctional materials (e.g. piezo electric materials). Due to the adaptive materials, the material properties can be adjusted by the control system to achieve the desired characteristics [2], [3].

The difference between mechatronics and adaptronics is described by using an Euler column with actively controlled buckling behavior. In Figure 1, the column is shown both in a mechatronic (left) and in an adaptronic (right) configuration.

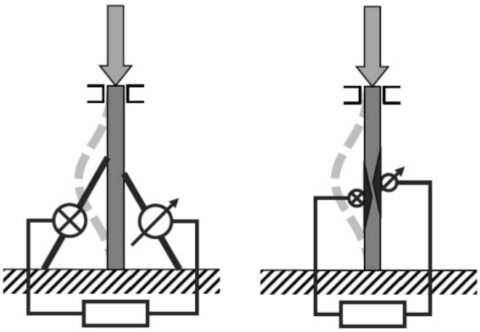

Fig. 1. Euler column in mechatronic (left) and adaptronic (right) configuration (cf. [4]

The large numbers of dependencies between the involved domains in adaptronics, compared to mechatronics, have to be considered in the product development. This requires not only improvements in the domains involved but also an adaption and improvement of methods and tools used in product development. For the further development of adaptronics the German federal state of Hessen has founded the AdRIA-Center (AdRIA – Adaptronic, Research, Innovation, Application) in 2008, as part of the LOEWE-project (LOEWE – federal initiative for the regarding of scientific excellence). The aim of the LOEWE-Center AdRIA is the further development of adaptronics in scientific depth and width to the industrial usability. The ADRIA-center has been established as a cooperation between the Technical University of Darmstadt, the University of Applied Sciences Darmstadt and the Fraunhofer Institution LBF [3], [5].

3 State of the Art

Current industrial development projects are often based on the V-model for the development of mechatronic systems. The V-Model proposes a development process which consists of three steps [6]. In the first step an analysis of the requirements takes place, a system model is defined and the development tasks are distributed into the involved technical disciplines. In the second step the detailed development is done parallel by the corresponding disciplines. When the disciplines have reached a specific level of maturity, the discipline specific solutions are integrated in a third step. The integrated solution is analyzed with respect to the systems behavior and the fulfillment of the requirements. Then the necessary changes and adaptions are determined and the discipline specific development process starts again [6].

Analyses of industrial development projects which use the process defined in the V-Model have shown that problems occur during the integration of the discipline-specific solutions, caused by a lack of communication [7]. The cross-disciplinary communication deficits lead to divergent development processes during parallel development, resulting in a large number of failures in the phase of system integration. The corrections must be done by the individual disciplines, leading to an iterative process with little progress between the iteration steps. To deal with increasing complexity of development processes of active systems typically two different approaches are used.

The first approach is to analyze the systems to be developed with respect to their elements, the allocation of the elements to the various disciplines and their mutual functional dependencies. A method that is often used in this context is systems engineering. Systems engineering is based on the concept of systems theory. According to the approach of systems theory, a complex system is structured by the decomposition into various elements as well as the documentation of the relations between the system elements [8].

In this context also a number of methods for managing the complexity of system models exist. As an example, the Dependency Structure Matrix (DSM) is mentioned. The DSM provides a systematic mapping of system elements and their relationship [9]. Through the use and analysis of the DSM, in particular indirect relations between system elements are identified.

The second approach is to increase the communication and the alignment of results between the disciplines through the use of additional tools. As an example the cross disciplinary integration platform developed by Bellalouna is mentioned [10]. Here, a product data management system is used as a platform to centralize the data-sets of the various disciplines. The connection to the discipline specific data management solutions is accomplished by the use of a service oriented architecture (SOA).

Gräb describes a mechatronic product development process on the basis of parametric product models. Thereby the discipline-specific results can be matched by the use a common parameter structure [11].

In this paper a meta-data-model for an integrated development environment as described in the W-model is presented and the single packages referring to the different parts of the environment are described.

Furthermore a possible implementation of the development environment based on commercial PDM systems is explained.

Concluding it can be stated, that the V-model results in a large number of iterations if applied on the development of highly structural integrated systems. In the past a number of research projects aimed to resolve this problem. Nevertheless there is currently no continuous methodology for integrated development of active systems, taking into account and addressing the increased capabilities of computer-based design methods.

4 The W-Model for the Development of Adaptronic Systems

To counter the increasing degree of structural integration Nattermann and Anderl propose the W-model as a new process model for the development of active systems [12], shown in Figure 2. The W-model is based on the previous V-model and extends current developments in the field of mechatronic product development.

Contrary to the three steps of the V-model the W-model consists of five steps which are explained briefly below.

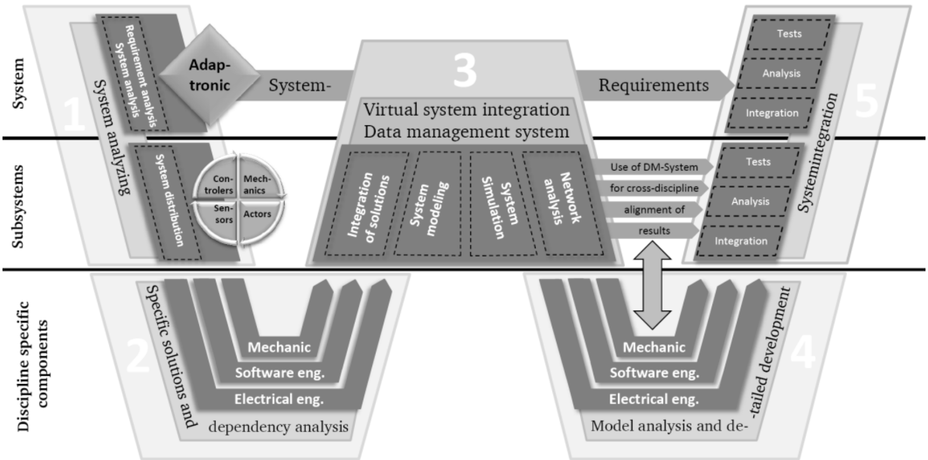

Fig. 2. W-Model for the development of adaptronic systems [12]

System Analyzing. In the first step of the W Model, the system to be developed and the requirements, documented in the requirement specification, are analyzed. In addition, a first definition of the system states and the functions, based on the requirements, as well as a breakdown of the system development tasks in the various disciplines is performed [6], [12].

Specific Solutions and Dependency Analysis. In the second step the W-model proposes basic discipline-specific problem solving. This is performed in parallel and independently of each other in the individual technical disciplines involved. Here the required product development methods are applied to define the discipline-specific solution space.

Additionally, a network of dependencies between system-critical parameters and properties of the elements of the solution space is created [12].

Virtual System Integration. Following the definition of the discipline-specific solution space the integration and limitation of a cross-disciplinary solution space and the derivation of potential alternative solutions is developed. For the later version evaluation criteria based on the requirements are determined.

For each solution variant then interdisciplinary, holistic system models are established. These system models contain the atomic requirements, functions and system components, as well as their known interdependencies. After the creation of the system model various techniques of complexity management can be applied, in particular to analyze the indirect dependencies between model elements. To support the later detailed hierarchical product structures are derived from the system model.

System simulations are generated from the system model. These simulations are used for analyzing the global system's behavior on the basis of critical system characteristics and parameters. The defined system simulations are bidirectionally linked with corresponding system model elements.

Following Nattermann and Anderl, a specific development environment is used for the definition and documentation of the system models and system simulations, which is based on the functionality of the product data management [12].

Model Analysis and Detailed Development. The definition of the system model is followed by a detailed discipline-specific development. Therefore the hierarchical product structures, derived from the system model in the third step, are used. During detailed design the system model created in the third step model is used throughout the development process in order to perform a cross-disciplinary integration of the discipline-specific development results. This is performed e.g. by the application of appropriate parametric geometric modeling systems.

Changes to data sets of individual disciplines can thereby be automatically transferred into the system model. In addition, the defined system simulations are used to analyze changes during discipline-specific development in relation to the overall system behavior and cross-discipline dependencies. Through the permanent virtual validation in the context of the entire system diverging development paths can be avoided [12].

System Integration. In the fifth step the W model describes system integration. Here, the integration with both physical (e.g. prototypes) and virtual results are provided, possibly to meet one validation milestone. Also a verification of integrated results in terms of requirements fulfillment takes place.

5 Meta-data-Model

In the following, the developed meta-data model for an integrated development environment is presented. The meta-data model consists of several packages that represent the creation of system models, the derivation of hierarchical product structures, the definition of system simulation approaches and the creation of parameters-property-networks.

Package *ActiveSystem*. Central class of the package is the class *ActiveSystem* which describes the System combining data-sets involved in development. This class therefore provides compositional relationships with system models, system simulation approaches, and documents used for the development of components, functions and requirements. These are hierarchical structures in which the elements may include any sub-elements. The structural elements themselves are realizations of the information contained in the system model elements. It is important to preserve the relationship information contained in the system models during the conversion into hierarchical structures allowing traceability.

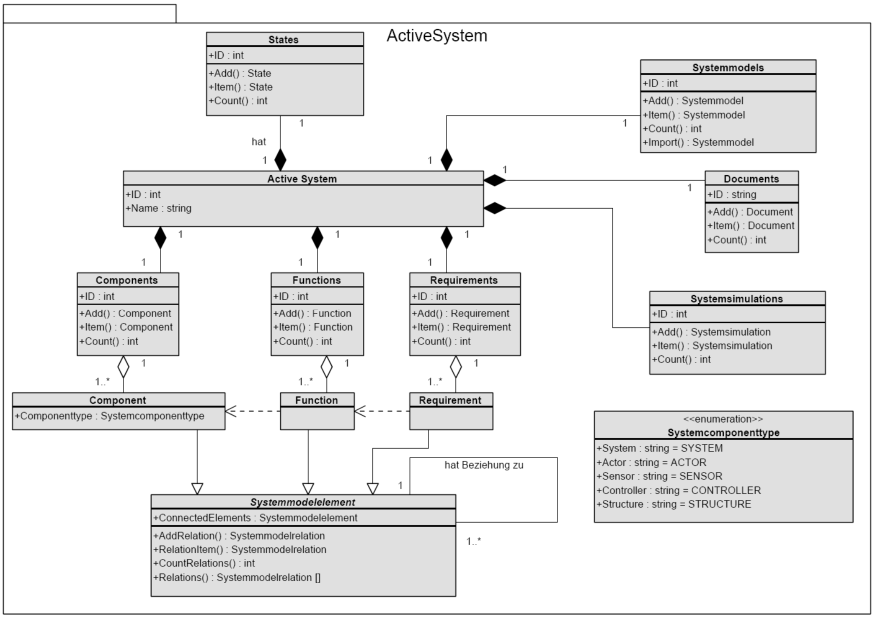

Fig. 3. Package *ActiveSystem*

Package *SystemModel*. The package *SystemModel* contains the definition of system models through their elements and their mutual relations. The package allows the definition of new system models as well as the import of existing system models. The package not only supports methods for analyzing system models with respect to indirect dependencies but also includes methods for the control of model complexity described in [9]. Since the W-model proposes the linking of system models, system simulation approaches and discipline-specific documents by the use of parametric structures, the individual system model elements also combines links both to properties as well as parameters. In this context, parameters are values which are not dependent on other values and freely modifiable (e.g. geometric dimensioning). Properties depend upon parameters or other properties and can be adjusted only by adaptions of parameters (e.g. volume) [13].

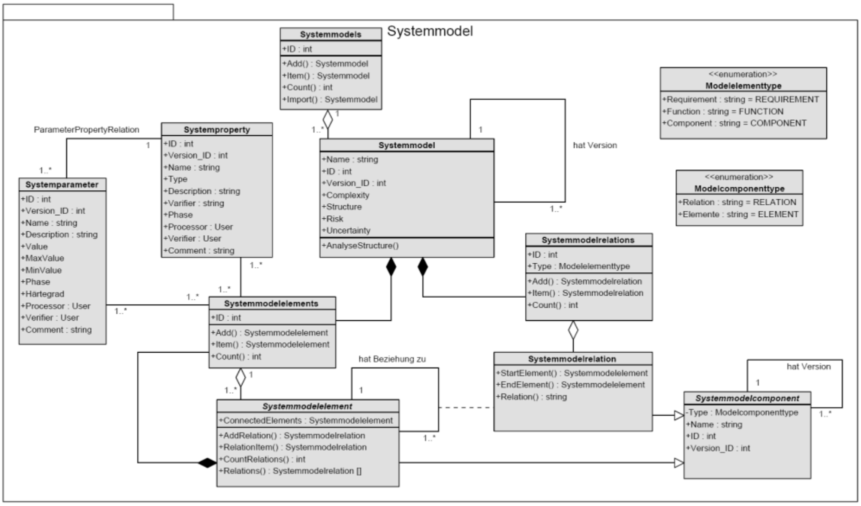

Fig. 4. Package *SystemModel*

Package *SystemSimulation*. In the package *SystemSimulation* the definition of integration simulation approaches is described. The meta-data model supports the methodology for the modularization of system simulations and the development of library modules for typical system elements developed by Herold et al. [14]. The input and output files of the simulation blocks are linked with the parameters and properties. It should be noted that the simulations don't access the parameters and properties directly but via links.

The relationship between these links and the actual parameters as well as the relationships between simulation approaches, parameters and properties are presented in the following package descriptions.

Packages *SystemParameters* and *SystemProperties*. In the packages *SystemParameters* and *SystemProperties* the meta-data-model represents the definition of a central parameter-property-network. Parameters and properties are explicitly distinguished in the meta-data model, as parameters with their values are not mutually dependent; properties on the other hand are depended solely on other properties and parameters [13]. In both cases, the meta-data-model provides the establishment of clusters to create groups of parameters properties belonging to the same system sections.

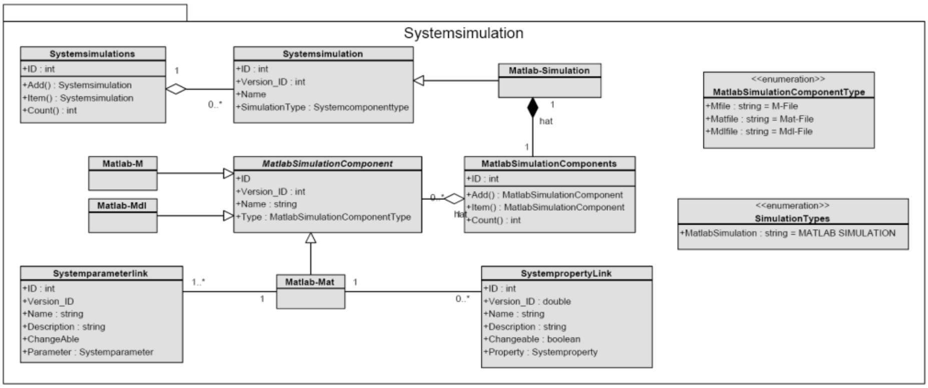

Fig. 5. Package *SytemSimulation*

The access and use of the system parameters and properties is not possible directly but through the use of appropriate links synchronizing and controlling the access. This avoids redundancies when using a single parameter in multiple documents.

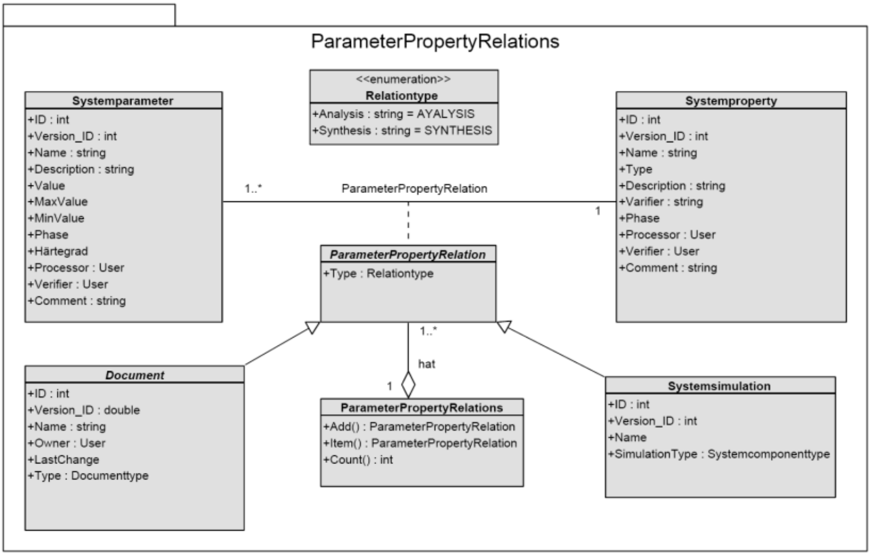

Fig. 6. Package *ParameterPropertyRelation*

Package *ParamterPropertyRelation*. The package represents the relationship between system properties and parameters. The meta-data model utilizes the approach of Property-Driven-Design, after which parameters are transferred into properties [13]. The meta-data-model allows the transfer of parameters into properties through documents as well as integrated simulations. Thereby simulations can be used to determine system critical properties without having to access discipline-specific documents. Thereby simultaneously with changes to properties and parameters, the impact on the global system behavior can be analyzed.

6 Implementation

For the implementation of the presented meta-data model the commercial product data management system ENOVIA SmarTeam V5 was chosen to be used as the basis of the integrated development environment. The decision is in line with the proposed W-model allowing the application of an adapted product data management system. One advantage of this approach is that in the standard product data management functionalities such as workflow, privileges and file management are already available and can be used. Currently, the adjustment of the data-model of the selected product data management system to the presented meta- data-model is developed. For this purpose, the classes of the meta-data-model are transferred in to the data management system and already existing classes and functionalities are adapted.

For the implementation of the integrated simulation, the mathematical simulation solution MATLAB from Mathworks with the graphical modeling environment Simulink is used. The simulations are based on the concept of modular system simulations developed by Herold et al. [14].

After implementation of the meta-data-model, the development environment will be validated using a representative example. For this purpose an adaptronic engine bearing, developed in the LOEWE-Center AdRIA [15], is used.

7 Conclusion

Adaptronic systems are characterized by the structural integration of electronic components into mechanical structures. The mutual impact resulting from the high degree of structural integration must be considered in all phases of product development. It has been shown that existing process models for the development of mechatronic systems lead to issues with an increasing degree of structural integration. For this reason, the W-model for the development of active systems is developed by the Department of Computer Integrated Design. The W-model is based on a continuously integrated development and proposes the use of a central integrated development environment. In the present work, the W-model was explained in detail and a meta-data-model for a corresponding development environment is presented. The single packages of the meta-data-model were explained and an outlook on the currently ongoing implementation and validation is given.

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Web Services to Product, Processes and Resources Data Integration: Results and Perspectives of FEDMAN Project

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Abstract. A production system can be treated at various levels beginning on components and going on machinery, plant, factory and even company. As for each level there are specific IT tools, every level necessarily implies an increase of the amount of data to be managed. To accomplish this integration of multiple sources the FEDMAN project uses the concept of federative databases and organizes this data in a model with three orthogonal domains: Product, Processes and Resources. The integration is based on a service-oriented architecture, which provides the access to specific information via web services requesting to the owner of information. This federative approach treats the data encapsulated in order to keep the partial autonomy of specific tools, without significant loss of flexibility. This model of integration is promising in the sense of integrating large amounts of data involved in a production system, maintaining the flexibility of each information technology tool.

Keywords: Web Services, Data Integration, Federative Databases.

1 Introduction

Nowadays the management of a production system can be considered as a distributed and collaborative activity. For collaborative means that activities over time are performed by different actors, who must work in a common way. As these actors are scattered over both space and in relation to time this activity can be considered distributed. The complexity arising from the inherent characteristics of any distributed activity can be managed through information systems, but there are still some requirements that need to be improved, being the first data exchange between different systems since each of the actors' process uses proprietary solutions, developed according to specific needs, which adds data to the heterogeneous process.

Consider each activity as a service and to structure these services within a service-oriented architecture is a possible solution to handle the complexity and heterogeneity, so that each stage of the requisite services and receive the information needed to progress. The service-oriented architecture is also shown as a solution for dealing

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with legacy systems, enabling the system to aggregate existing solutions still in use, but with the development and maintenance discontinued. Being services dedicated to the development process of the product available on the web, any actor's process can have access at any time and place and, therefore, reach the requirement to attend a distributed system. Web services are defined as software agents designed to work with interaction between networked computers with an interface described in a format processed by computers. Other systems can interact with the Web service using a message sent and received via a simple object access protocol (SOAP). Web services usually use hypertext transfer protocol (HTTP), with data described in extensible Markup Language (XML).

This paper presents a proposal for integrating data from a production system through a service-based architecture (SOA), with the use of Web services to exchange messages written in XML and enveloped in SOAP. So that integration can take place in a distributed and collaborative environment dealing with the issues of flexibility and dynamism.

2 Production System Information Management

Managing a production system represents a set of activities with collaborative and distributed issues, demanding enterprises that must be flexible and adaptable, and also demanding processes carried out in increasingly interrelated and independent of time and place in which they are applying the concepts of concurrent engineering and agile production [1]. These characteristics enable complex and innovative products available to the market in increasingly short time. The systems that support these activities within the Product Development Process belong to PDM/CAD/CAM/CNC chain, and only for those systems there are different ways of data management.

If all these systems are within the same container, the data can be stored in a single database, making the necessary information available to all systems. But even with all the effort of the major system developers to consolidate this model, adding to a monolithic database with all necessary information, this is not the reality found in production systems today. The phases existing in a production system are executed, each by experts in a highly distributed network and are therefore distributing the information pertaining to each system. The knowledge that involves production activity is spread across various systems and persons in different organizations, in different places, and you cannot leave aside this knowledge especially with the possibility now existing to access all this information. By involving several individuals and organizations, in which all has the control of a specific part of the process and no one have an absolute control of it, the production system is seen as a collaborative and distributed process, where each partner implements its own business process [2].

The framework of information technology that supports these processes should reflect this distributed environment, so ensuring the right information at the right time for decision making, regardless of which actor holds this information.

3 Federative Databases for a Production System

The scenario of a distributed production system can be understood as a complex scenario, especially when taking into account that for each type of existing production systems or applications, they have their own characteristics. The product development also considers factors from external fields of knowledge which act by increasing the number of interactions and the variety of information. At the same time that is required of these systems to perform the management of information coordinately [3]. Another important consideration is about legacy systems, since historically production systems working with autonomous systems that are often chosen for strategic criteria rather than for operational criteria [4]. These legacy systems should be incorporated into the product data management system allowing the aggregation of its information to the core model. Besides these factors, the presence of more than one factory in the same scenario, with different operating systems, only increases this complexity [4].

To obtain a framework to support product development that is more flexible, able to adapt quickly to market needs, responding to pressures such as launching new products with quality assurance, it is essential to develop information technology tools capable of working with high volume of data in a decentralized environment.

The data generated by several and independent information technology tools are heterogeneous because each application has its isolated autonomy to generate and to manage data. The integration of these data requires the resolution of the conflict between transformation and heterogeneity of documents and data sources into an integrated concept [5]. Even though the data management systems like PDM and ERP are fairly matured, however the collaboration between these systems does not present the same level of development. All domains involved in product development have to collaborate with the central model; currently the data integration problems arise and must be solved.

The distributed data management in a collaborative manner can be done in three different ways according to [6, 7, 8] as shown in Figure 1.

The maintenance of data in isolated applications ensures a high degree of distribution, and preserves the autonomy of data that can be handled independently by each application. Each application, in a isolated way, is responsible for the coupling to the central product model. This model has little flexibility and low degree of integration due to the implicit coupling between the tools of information technology that make up the central model. One difficulty with this model is the way to deal with the data of coupled systems, which require a specific application for each insertion to the central model.

Another option is the option for a fully integrated model, where the data of the partial models are integrated into the core model, generating a monolithic database. In this model there is no data distribution, since all applications are integrated and the connection to the central model occurs through direct links. As with the previous model, this does not present much flexibility due to the fact that every change in an application, or a partial model, impacts on change in central model, which is a further difficulty, especially when dealing with existing systems. The high degree of interaction allows for total control of the system, but the loss of autonomy, because the applications are no longer responsible for generating or manipulating data on partial models.

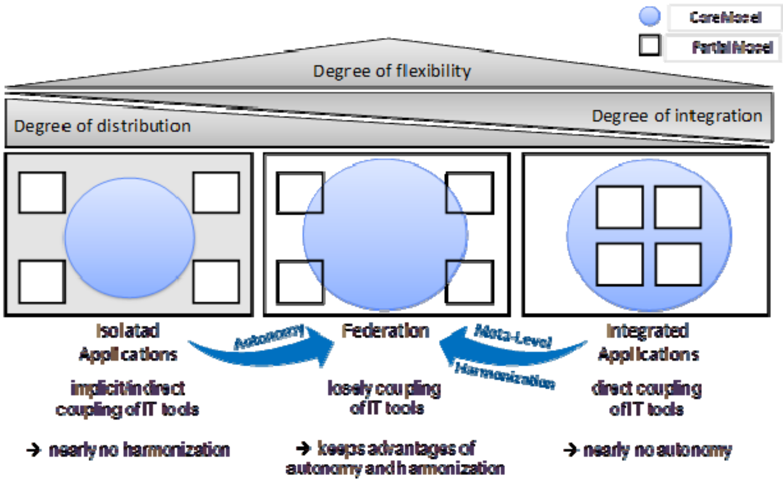

Fig. 1. Data management models [6, 7, 8]

The intermediate solution between the two models presented is to allow data to be distributed in isolated applications, but the construction of the central model is made by means of loosing couples. Thus, the characteristic of autonomy for managing the data for each application is maintained, while preserves the consistence of the central model. This intermediate solution keeps the independence of each application and makes every part collaborate with all without losing its own features [3].

4 Applications Developed for the FEDMAN Project

This paper considers the problems generated by information management of a production process, even if generated from different sources, in different formats, in large quantities and relationships in n-dimensional, can be reduced to simple problems. The information applications can be decomposed, analyzed and synthesized keeping an order, which is nothing more than the assumption of the scientific method.

Based on a theoretical model of federative database applications were developed a model linked to current commercial systems and also linked with web services for the domains of product, processes and services. An application was developed for the demonstration of the federative management and integration of information.

Applications for CAD and CAM systems are developed using the NX Open application programming interface library, provided by Siemens PLM to access the functions of computer-aided systems. Web services are developed using the language and tools of ASP.NET inside of .Net-Framework, within the paradigm of object orientation. The services are made available through an Internet Information Server.

A prototype implementation for the integration of product, processes and resources through Web services was developed using the layers concept. In the innermost layer were developed applications within CAD and CAM systems for product data and process data, respectively. For the availability of data in the Web services, a layer Web services was developed for reading and analyzing the data available on the Web to answer requests to the application that makes the role of integrating all data of a production system. Finally, the application developed is also able to request to web services data of product, process and resources [9, 10]. A scheme of internal applications, web services and application integration is presented in Figure 2.

All development was done using the .NET-Framework within the paradigm of object orientation. In this development the Web services environment, such as internal applications to CAD and CAM systems, as well as the application and services are implemented in ASP.NET and VB.NET applications.

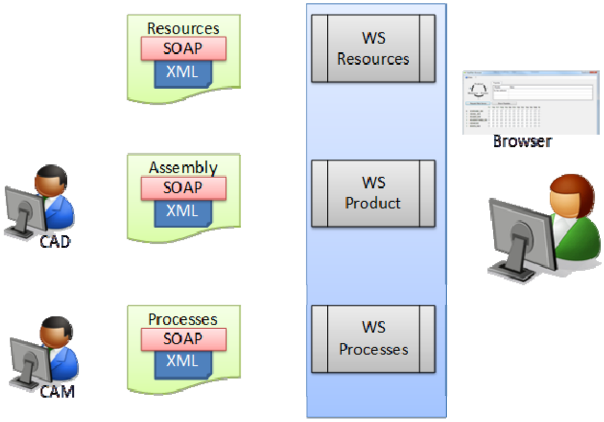

Fig. 2. Schema for Applications and Web Services

4.1 Add-On in CAx Systems

Computer Aided Systems are available for several areas of engineering. The development of these systems follows the general pace of development of information technology, especially for support systems to design and manufacture, new versions are released annually. Such speed renovation makes it a common practice of the end consumer not to update all versions, but waiting for the deployment of two or more updates.

These releases meet the demands of consumers, which, however, may have a lack for very specific needs, so that to make possible a more specialized support, computer systems are developed allowing applications that work internally. These system applications are known as "Add-on".

From the original system it is possible to start the application that can access the internal functions of the system using the same user interface to make the use of the application quite friendly. For the demonstration of the concepts proposed in this paper applications for managing product releases and manufacturing are developed.

As the system is used for demonstration modules integrating CAD and CAM are developed using a common interface for both systems, which also includes the features for estimating the time of a machining operation and the determination of measuring points and vectors for a Coordinate Measuring Machine. The FEDMAN functionality is included in the title bar of the program, which opens the possibility of release management and consequently opens a dialog box for the functions described, as can be seen in Figure 3.

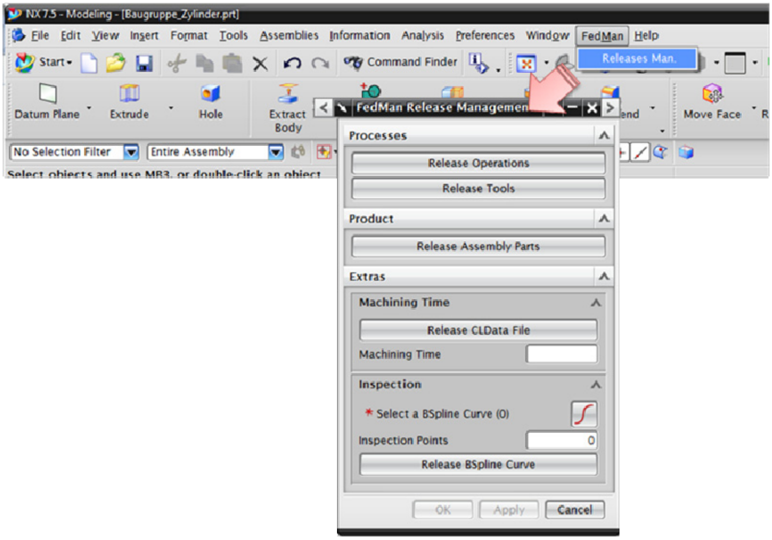

Fig. 3. Application Dialog Box

This dialog box is divided into three blocks: Processes; Product and Extras.

The product functionality interacts with the Web service that provides access to the federative databases' information, including the geometrical model and material of each component, its location in the coordinate system, the material, and the total amount of the same part in the assembly. The file maintains the hierarchical structure of the assembly.

The processes functionality, inside of CAM System, can interact with a Web service and provide the necessary information tools for the manufacturing process and also provide the specific machining processes for each component.

4.2 CAD Application

The application for the CAD system that provides product information is accessible in the CAD System via the button "Release Assembly Parts", inserted in the "Product", as showed in Figure 3. This button activates a method to collect in their CAD product components, including - at this stage of development - the position, material and the amount of times the component appears in the assembly. These are then compiled into an XML file and sent to a distributed database via a Web service.

The CAD system keeps the product structure that has a role in the integration of the systems, because it defines the physical relationship between modules and components comprising the product [11]. The links between the product components are stored in this structure, which may contain sets and subsets of chained mode, the structure can be presented in the form of tree or indented list [12].

To guarantee that all levels of the tree construction are read and the information in the product structure is kept, a recursive method is designed which gets the data from child components to its innermost level. the method continues to search for child components into the lowest level, when data is collected and made available in an XML object. All these objects are transferred to a XML file using its own methods of .Net platform and a file XML is created and transferred to a distributed database.

4.3 CAM Application

The information system of Computer Aided Manufacturing are within the scope of information regarding processes, considered here as manufacturing processes, such as drilling, tapping, milling, etc.. Also information concerning the resources can be obtained, since the CAM system contains information about the equipment used in the manufacturing process.

Likewise the internal application of the CAD system, this application is accessible via the button "Release Operations" within group "Resources" (Figure 3). When pressing this button a sweep is made of all machining processes envisaged for this part. The transactions are then compiled into an XML file which is sent in turn to a distributed database. The step of transmission to the database is made via a Web Service.

Each operation is linked to a specific tool. The CAM system provides information on the operation being one of the options that can open the dialog window that shows the information about the tool. The system stores the CAM operations within an object of type collection of objects, which are the information for each operation and its characteristics. The application gets access to that object and searches the information by doing a scan all operations therein.

The XML file generated and sent to the federative database has a list like structure containing the attributes of the operation and tool used, indicating for example: the diameter and length. Because of its extensibility, other transactions can be entered without prejudice to the operation of the system. Once transferred to the federative database is reported to the user a dialog box informing the operation's success.

4.4 Product Data Analysis and Recovering

The product data information are in the Web in a XML format file, the access to this information is made through a Web service that can return the requested data. The product data available through the CAD system are stored in the Web service which offers six functions for product data recovery.

It is possible with these functions to access the product information necessary for integrating the fields of product, processes and resources. For example, to obtain information of the material of a existing component in an assembled a set up the following sequence of operations is used: "AskAllPartsNameInAssembly" (to get the name of the components) and "AskPartMaterial" (to get the material with the component name).

The answer to these functions is an XML file with the names of the components, with component names. It must be pointed that all communication with the web service is made through objects encapsulated by the SOAP protocol, both the name of the component to which you want to know the material and the response of the material from which the component is made. However, all this communication is transparent to the user of the service.

4.5 Processes and Resources Data Analysis and Recovering

The process data are stored in an XML file in Web for retrieval and the information contained therein is accessed through a web service with other six specific functions.

With these functions it is possible to access the complete information of the processes. For example, to know what kind of an operation defined for a product you must first obtain a list of all existing operations. This is done via the "AskAllOperationsNames" which returns an XML file with the list of operations. This information can now be obtained with the use of the function "AskOperationType" to get the type of operation, using the operation's name as a parameter. All communication is done with the information described in XML and enveloped in a simple object protocol (SOAP).

The resources considered here are the tools used in machining processes. The information about the tools were obtained directly from the CAM system for a specific application and transferred to the Web in a file in XML format. For these functions is required to provide the name of the tool you want to get the information. These functions can be verified in any browser with internet access.

4.6 Data Integration Browser

The integration of product data, processes and resources is done through an application that accesses Web services and enables the creation of links between the three domains. This application was developed in VB.Net, within the .Net platform, in the same way that other software components.

The application displays in the upper left three buttons of type radio to indicate the relationship between the three domains included. Once chosen the two domains is possible to request data from the federative database through the button "Request Web Service". Figure 4 shows in the first column, the result of data relating to the components of the pneumatic cylinder designed in the CAD system. Informing the number of times the component appears and the name of the component, in the first line are presented the tools listed in the CAM file.

The option to view the resource domains and processes is possible in the same procedure. In this case the tools are displayed in the same way as the previous machining processes and are listed in the first column.

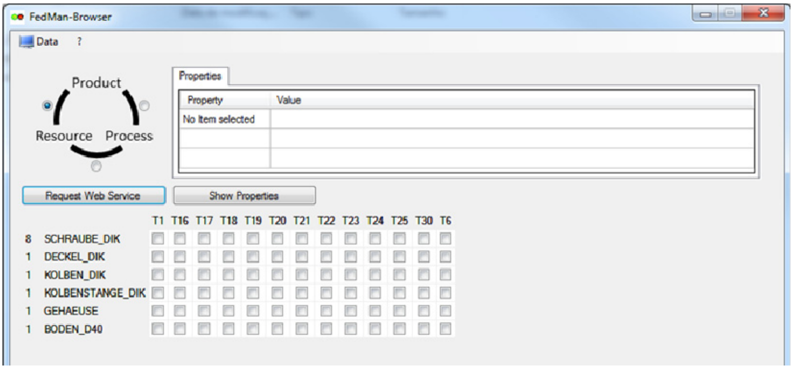

Fig. 4. Browser Screenshot with product data and resources

At any time the designer can create a link between product and process, or product and resources or resources to processes. These links are possible by the radio button shown in the windows above. The links can be archived and retrieved later.

5 Conclusions

The amount of information involved in a production system is growing and no indications that this process will stagnate or even fall back, on the contrary.

The concept proposed in this work is a promising alternative for the management of this large amount of data layers defining and structuring services. It also meets the requirements for incorporation of legacy systems, allowing applications already discontinued to be inserted into a central model.

The mentioned services maintain the possibility of constant updating, which ensures the end user to always obtain updated information. Due to this model be done in layers in case of services update there are no need to changes in other layers.

A scenario of multiple networks of customers and suppliers can be managed with this model through the implementation of various services. This scenario maintain compatibility with legacy systems and the possibility of updates.

6 Future Trends

Considerations about information security should be aggregated to this proposal. Just as a managing roles and visions for each of the user, who have access to information. Security issues should involve both the permission to access and ensuring correct usage. These two topics are present in the second phase of the project FEDMAN as well as an improved and increased application portability considering the use of mobile devices.

The use of mobile devices is growing and allows greater freedom of location, commercial applications for smartphones and tablets are available constantly and it is natural that this advance also covers applications related to production systems.

Another interesting possibility is the application of semantic concepts to enable the use of inference engines and artificial intelligence for information retrieval.

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Product Lifecycle Management Functional Reference Model for Software Support

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Abstract. The adoption of product lifecycle management (PLM) approach requires the selection and implementation of IT systems. Currently, there is a wide variety of IT systems focused on PLM available in the market. The problem that motivates this research is the difficulty faced by manufacturing companies to evaluate and to compare existing PLM systems available commercially, in order to select the most appropriate alternative to their business processes needs. At academia, the main problem is the lack of a widely accepted definition of the software functions that should be considered within the scope of PLM. This paper presents a PLM functional reference model for software support. The reference model is comprehensive and neutral, establishing a common base to facilitate software comparison and thus support software selection at manufacturing companies. Additionally, the presented reference model establishes a generic definition of PLM to be discussed at academy and industry.

Keywords: Product Lifecycle Management, PLM System, Reference Model.

1 Introduction

Manufacturing companies have been adopting Product Lifecycle Management (PLM) approach to increase productivity and effectiveness of product development process and to improve the management of product data along the entire product life cycle. PLM improves information distribution and flows, supporting better decision making on early stages of the product development. For instance, product designers can better access field and service data from existing products in order to improve new product generations. Moreover, PLM enables management of product data until end of life, supporting extended services like continuous monitoring and maintenance.

The adoption of product lifecycle management business approach requires the selection, implementation and application of IT systems. Currently, there is a wide variety of systems focused on PLM available commercially in the market. The existing systems stem mainly from three different software categories: evolution of CAD (Computer Aided Design) systems, pure player PDM (Product Data Management)

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provider and expansion of ERP (Enterprise Resource Planning) systems. The heterogeneous stems and market focus of each software house resulted in systems that have different functional capabilities.

In this scenario, scope differences among existing software hamper the selection of IT systems to support PLM at manufacturing companies. The problem that motivates this research is the difficulty faced by manufacturing companies to evaluate and to compare existing PLM systems available in the market, in order to select the most appropriate alternative to fit their business processes needs. At the same time, for academic research, the main problem is the lack of a widely accepted theoretical definition of the software functions that should be considered within the scope of PLM.

The aim of this paper is to present a PLM functional reference model for software support. The reference model is comprehensive and neutral from any software vendor, establishing a common base to facilitate software comparison and thus support software selection at manufacturing companies. Additionally, the presented reference model establishes a generic definition of PLM to be discussed at academy and industry. The model presented on this paper is an evolution of previous work conducted since 2006 [1-4].

The main expected applications for the model are: serve as the basis for the comparison of different commercial systems on selection processes at the industry; contribute to the definition of the theoretical scope of PLM systems; serve as reference for software companies to prioritize the inclusion of new features in their systems.

This article is organized in five sections. Section 2 provides information on literature review and field research about current software capabilities. Section 3 discusses the definition of reference model considered in this paper and presents the research method applied to construct the proposed PLM model. Section 4 presents the proposed reference model. Finally, section 5 discusses the conclusions and future research.

2 PLM Definition and Current Software Capabilities

2.1 PLM Definition

PLM is defined as an approach for the integrated management of all product related information and processes through the entire lifecycle, from the initial idea to end-of-life [5], [6]. Most authors currently agree that PLM does not only refer to individual computer software, but, moreover, it is related to a broad management concept which depends on the integration of multiple software components [5-8].

Based on this conceptual foundation, in this research PLM is defined as a business approach for the integrated management of business process and information related to products through the entire lifecycle. This approach requires integrated information systems to support collaboration over the extend enterprise throughout the product lifecycle [3].

PLM definition focusing on business process and information related with products allows the definition of a process scope, which includes but is not limited to the following business processes:

- Innovation planning;
- Proposal development;
- Technology development;
- Product and service development;
- Middle-of-life product updates;
- End-of-live product transformation.

In order to support theses business processes, software vendors offer PLM solutions described in the next section.

2.2 PLM Current Software Capabilities

PLM systems have been evolving within the limits set by other business applications. The boundaries of PLM systems are delimited with: CRM (Customer Relationship Management), used to manage customer data; SCM (Supply Chain Management), focused in production management and logistics; and ERP (Enterprise Resource Planning), with broad scope, including finance and HR management.

Within these boundaries well recognized in the software market, PLM innovates in defining the product as the central element that is used to aggregate information from various sources. Moreover, PLM considers the complete lifecycle as the time dimension used to integrate information. As a result, any product information can be accessed directly by every authorized person at any time [3], [4].

The analysis of current PLM software capabilities involved data gathering from ten relevant software suppliers available in the market (PTC Windchill, Siemens Teamcenter, Dassault Enovia, Oracle Agile, SAP PLM, IBM PLM, Audros, SofTech, ProFile Procad and Autodesk PLM 300).

The analysis shows that besides typical PDM functions, such as document management and product structuring, PLM has evolved to encompass other functions, including functions in the field of product management (e.g. requirements management), service and maintenance.

3 PLM Functional Reference Model Construction

3.1 Reference Model Definition and Types

The documentation of business processes may be performed by process models. A model is a representation of reality, usually with graphical notation, which describes the operation of processes in a logical, schematic manner. There are several methods for designing process models, and the degree of detail of a process model depends on the objective considered. Regardless of the possible semantic and notation variations, process models usually represent the following aspects: activities and their sequence, input and output information for each activity (information flow), organizational areas responsible for conducting each activity, and the resources used to perform the activities (e.g. a function of an information system).

A special class of business processes models is made up of more comprehensive models of wide application and benchmark character, called reference models.

Reference models of business processes are representations of business processes containing best practices. In addition, reference models are generic, so that they can reflect the reality found in various companies and various business situations. This allows reference models to be adapted for application in different contexts [9-10].

The specification of reference models can occur in two alternative forms. A reference model can be created inductively, based on the compilation of knowledge of several empirical cases and information systems. Alternatively, reference models can be deduced from the theory [9], [11].

In terms of application, reference models can be configured in specific models. The instantiation of a particular model from a reference model helps ensure that best practices are considered into the resulting model. With the use of reference models, it is expected that the deployment of specific models is faster and that the result is of better quality. Another possible application for reference models is in the evaluation of specific models. In this situation, the reference model provides a basis of comparison for identifying problems and opportunities for improvement in specific model [9], [12].

In addition to the reference models of business processes, there are other types of reference models. In the context of this paper, the reference models of information systems are relevant. These models represent the functions available in an information system [13-14].

3.2 Research Method

Research method involved four phases. First, PLM scope and its boundaries were defined considering PLM definitions on literature and requirements of business process related to PLM. Second, ten systems commercially available were researched and analyzed. Data gathering occurred in the second half of 2012. Considering the boundaries set on previous phase of the research, software functions identified in commercial solutions were grouped in modules according to their similarities in scope. Third, a three levels hierarchy was defined to organize the functions in modules (level 1), functional groups (level 2) and functions (level 3). On the last phase, a tabular description of the whole model was prepared.

4 PLM Functional Model for Software Support

The PLM system reference model focuses on the functions used to support companies' business processes. It is, therefore, a reference model of systems´ functionalities. Other aspects of PLM systems, such as supplier characteristics (e.g. size, geographical coverage, financial performance) are not considered.

Regarding its structure, the reference model of PLM systems is organized into three levels of detail: modules, groups of functions and functions. At the first level of detail, the model consists of 9 modules, illustrated by Fig 1.

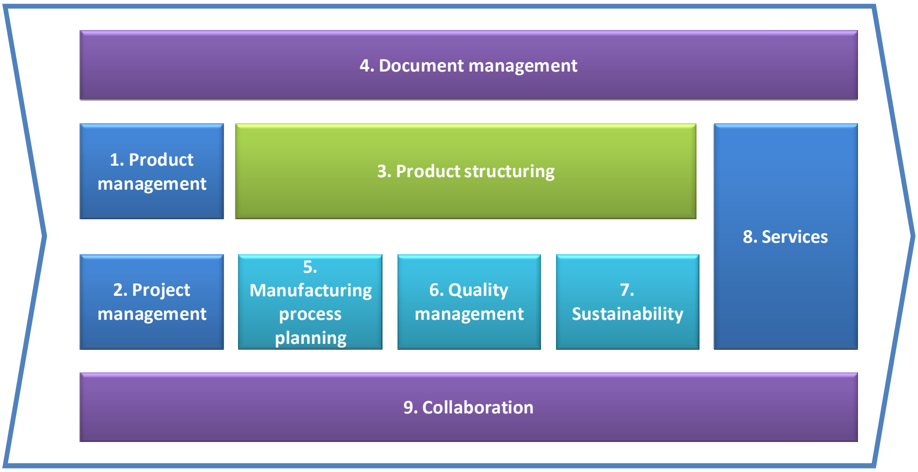

Fig. 1. PLM reference model modules (model level 1)

The layout of Fig. 1 indicates modules' role within the PLM system. On the left hand side of the figure, are displayed modules related to the planning and management of product life cycle. In top and bottom of Fig. 2, are displayed the modules related to functions that cover the whole lifecycle: document management and collaboration support. In the middle of Fig 1. is located the product structuring module, responsible to central data management, and modules focused on product data creation – manufacturing process, quality and sustainability. Finally, on the right hand side is located the service module, related to the downstream processes and activities of the product lifecycle.

The second view shows the modules and groups of functions (Table 1).

Table 1. Modules and corresponding group of functions of the PLM reference model

Level 1 - Modules	Level 2 – Group of functions
1. Product management	Ideas management
	Requirements management
	Portfolio management
2. Project management	Project planning
	Project control
3. Product structuring	Parts management
	Classification
	Bill of materials
	Variant management
	Product cost
	Engineering change management

Table 1. (*continued*)

4. Document management	Documents records
	Visualization
	Technical documentation
5. Manufacturing process planning	Tools and resources management
	Manufacturing process planning
6. Quality management	Quality methods (e.g. FMEA)
	Quality control planning
	Quality control and actions
	Customer complaints
7. Sustainability	Materials catalogue
	Lifecycle assessment
	Regulatory compliance
8. Service	Service parts management
	Service and maintenance plans
	Service and maintenance execution/records
9. Collaboration	Workflow
	Virtual workspaces
	Online meeting

The content of each module is summarized below.

Product Management. This module comprises functions that support planning and management of the product offering. It embraces functions concerning ideas, requirements and portfolio management.

Project Management. Includes functions needed to plan projects (e.g. activities, resource allocation, timeframe) and to control project execution (e.g. activities completion, budget).

Product Structuring. Product structuring module comprises functions which relate to the product engineering, allowing the user to create and manage items and products, including product variants that will exist through the lifecycle. The groups of functions within this module are parts management, classification, bill of materials, variant management, product cost and engineering change management.

Document Management. This module encompasses functions needed to manage every document created within the lifecycle. System manages document meta-data and controls access rights and versioning. Visualization functions allows document viewing and collaboration by multiple users. Technical documentation group of functions support preparation of service and support manuals.

Manufacturing Process Planning. This module refers to the production process, supporting users by management of resources needed to manufacture the products, including machine and tools that are applied in the process. Moreover, the module includes functions to support manufacturing process definition.

Quality Management. The object of quality management module includes quality methods, like FMEA (Failure Mode and Effects Analysis). Also the functions quality planning and quality control and actions are considered. Furthermore, customer complaints are registered in the system related to specific items or products to be accessed by other areas of the company, helping to close the information loop within the product lifecycle.

Sustainability. Comprises the management of hazardous materials through specific materials catalogues. Furthermore the environmental impact of the whole product lifecycle may be analyzed. Finally regulatory compliance management supports users to deal with regulatory documentation.

Service. In order to guarantee product consistency, it is necessary to provide services through the whole lifecycle. To enable this, the PLM software provides the tools to support this task, which are organized in three groups of functions: service parts management, service and maintenance plans and service and maintenance execution / records management.

Collaboration. Workflow management, virtual workspaces and online meetings enhance teamwork and collaboration in the extended enterprise.

Finally, the third view of the model in tabular format comprises all the three levels of detail. Table 2 illustrates this view including module, group of functions and functions for one specific group of functions, namely Documents records of Document management module.

Table 2. Example of the third view of the model encompassing module, groups of functions and functions – Documents records of Document management

Level 1 - Modules	Level 2 – Group of functions	Level 3 - Functions
4. Document management	Documents records	Define document types and their characteristics
		Create document and generate document ID
		Create document based on template
		Include document metadata
		Define document structure
		Classify documents based on classification scheme
		Search for documents
		Check-in and check-out documents
		Control documents version and status
		View document history

5 Conclusions

This paper presents an updated version of the PLM functional reference model for software support. The model characteristics – vendor neutral and it´s hierarchic structure in three levels (modules, group of functions and functions) – is intended to facilitate comparison with commercially available software in software selection procedures at the industry, defining a benchmark to compare the different systems in the market.

Moreover, PLM functional reference model contributes creating a common reference of PLM systems to be discussed at the academy level. Last but not least, software suppliers may also take advantage of the PLM reference model in order to identify gaps and define a development roadmap for the inclusion of new functionalities.

Future research on this field includes a survey with experts from academy and industry to enhance the third level of the PLM reference model (functions) and case examples of the application of the presented model at industry to support software selection.

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Design of Reconfigurable Automotive Framing System

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Abstract. This research introduces new systematic methods dealing with a *complete end-to-end design process* to production systems, where the uncertainty of product variety is mapped to product attributes and manufacturing processes, then mapped into a manufacturing and production line using product decomposition into systems, sub-systems, and modular assembly. Graph network (NW), change propagation index (CPI) and hybrid design structure matrix (HDSM) were introduced to: (1) establish connectivity between sub-systems (modules) before mapping design changes, (2) measure the degree of changes to the state of systems due to changes propagated through the entire systems, (3) estimate how much embedded flexibility is needed for these elements (design variables) to absorb future changes. A practical example of actual production systems was presented. Hybrid Design Structure Matrix (HDSM) is used to transmit knowledge gained, detailing design of production systems.

Keywords: Reconfigurable manufacturing systems, Automotive framing systems, Design methodology, Digital manufacturing.

1 Introduction

Manufacturing enterprises are forced to reassess their production paradigms, so that their products can be designed to maximize potential achievable variants, while the manufacturing and production systems can be designed to operate efficiently by robustly accommodating future product changes (product upgrading), minimizing time to market and providing a reliable production base. Typically, more than 80 % of the tooling and equipment in a body shop are not specific to an individual model but can be used for all models produced. The hypothesis is that if the right subsets of car body elements (product- product family) and production capabilities are designed with proper care for future flexibility based on the flexibility and reconfigurability principles, then the production system can better accommodate body styling changes, variants of family production without the need for tooling changeover with significant increase in throughputs.

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1.1 The State of Practice of Vehicle Framing Systems

The 'Framing system' is a process and the related infrastructure for a precise positioning and securing under-body platform with the upper body components [4]. Most passenger vehicles made today have a (structural) body that comprises 100–150 stamped metal panels, assembled into 18-22 modules (sub-assemblies) [1]. These modules are assembled into 3 systems to create the vehicle body formed (prior to painting, is referred to as body-in-white) in a multi-step manufacturing process, during which the modules are joined together by welding. Overall, a vehicle framing system can be divided into three subsystems, as shown in Fig. 1:

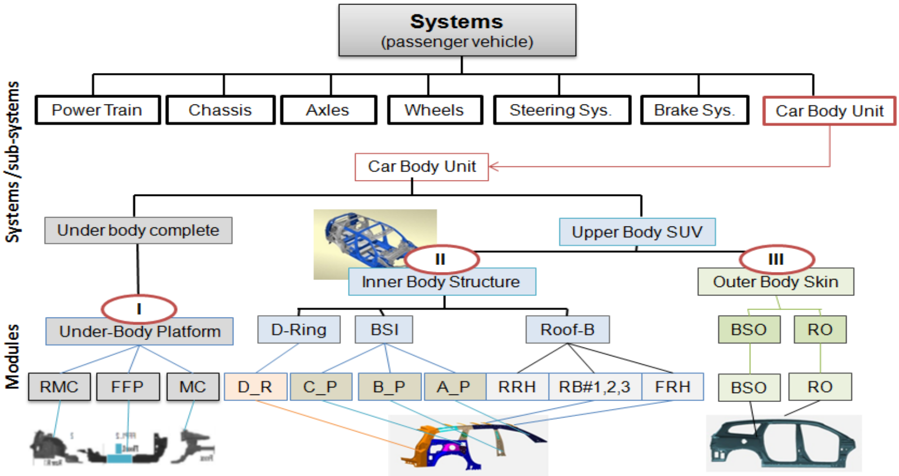

Fig. 1. Assembly Process of BIW Framing Systems- product decomposition

During the framing process, all modules have to be position-ally secured with respect to the under-body-platform and inner/outer skin, as only then the welds attaching the roof skin can be placed. In most production systems, the time required for all these activities is set between 45 to 56 s, depending on the vehicle size (smaller times for smaller bodies). The time required for framing also determines the cycle time (CT) of the whole line, and hence causes a bottleneck operation.

Historically, all current framing systems have evolved from the Open-Gate and Robo-Gate system, initially developed in the 1980's. When a body style change is required, the changeover can be performed in an average amount of time, 60 - 90 minutes. Otherwise, the operation of the gate is the same as described previously for Robo-Gate. The cost of lost production due to the changeover is estimated 70- 120 job with cost about 300.000 USD. Currently the automakers framing in North America, still using dedicated gates for each style at the final assembly see Fig. 2, to accommodate multiple styles gate storage mechanism were needed. As results of using dedicate gate systems for each style, there are key issues can be summarized as follows: (a) Changeover times have to be accommodated for in the production plan, as the line has to stop running, (b) Gates storage systems require significant amount of floor space, (c) Overall high cost, high lead-times for engineering and build time, (d) Very expensive to manufacture and maintain. (e) High cost of lost production due to downtime (breakdown or retooling). (f) High risk in capital investment.

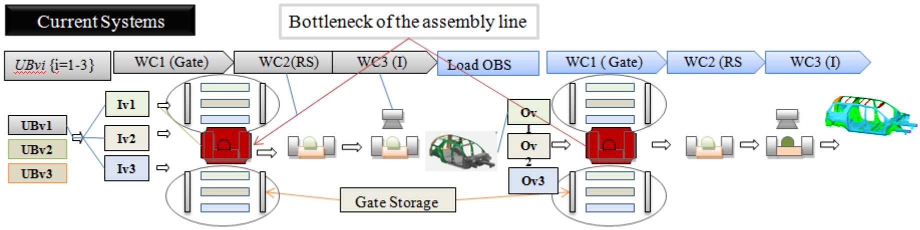

Fig. 2. Current practice of framing systems using dedicated gate with gate storage

1.2 The Goals of the Proposed Methods of the Framing Systems Are as Follows

The goal of the proposed methods is 1) to create a common understanding between product developer and systems design to execute the engineering changes due to product upgrading (markets segmentation), 2) To use a common tool to evaluate changes in product and equipment of the assembly line And 3) Joining process assumption needs to be made upfront to plan flexibility at the early stage prior to final design of production line see Fig. 3.

Fig.4 shows the proposed *Reconfigurable Open-Gate Framing Systems* (ROGFS); new modular structure with embedded flexibility and reconfigurability for the open gate to uncouple the top units devices and rear units that correspond to geometry styling due to engineering changes. With the proposed framing systems, top units devices are programmable, design constrain must be clear for the product designer to standardize product features across a product family, such as pin diameter and orientation of tooling access to secure the assembly (assembly details: non-functional features).

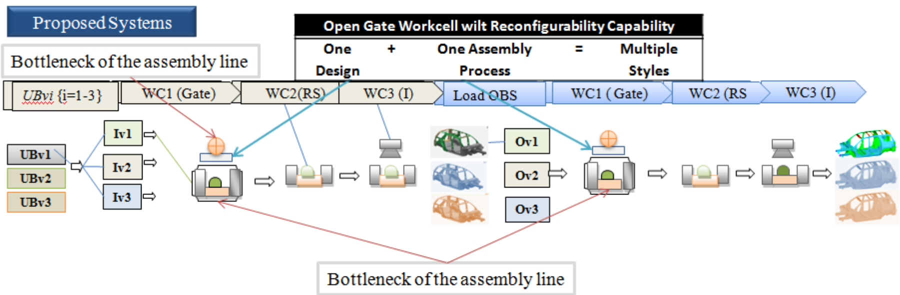

Fig. 3. The proposed systems: to run more styles using same Gate

The main aim of concurrent engineering is to integrate product and process development in order to reduce the design lead-time and improve the quality and cost. Design problems become complex due to multiple components such as tooling, positioning devices, transfer equipments, and joining process. In the last few years, markets increasingly require more customized products with shorter life cycles. In response, RMS systems have evolved from mass production techniques through flexible automation and mass customization, to produce at mass production costs [6][8].

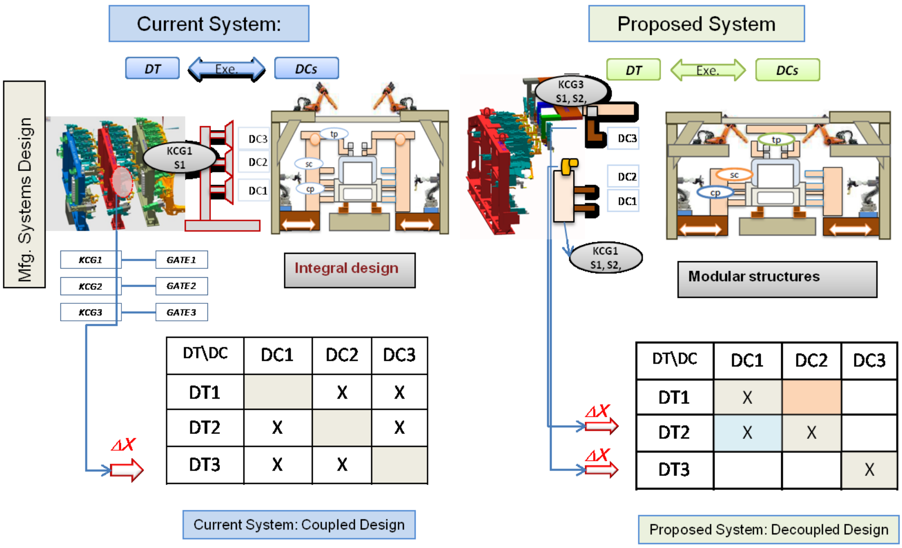

Fig. 4. Proposed Reconfigurable *Open Gate Framing Systems* (ROGFS)

2 RMS Framework and the Design Methodology

2.1 The RMS Framework of Automotive Framing Systems (Proposed)

The framework provides a guideline to support and to structure the different stages of the design methodology. This framework is mainly based on system life-cycle concept. Fig. 6 shows the main 4 stages of proposed framework; first, 3 transitional stages and lastly, the parallel stage:

(1) Manufacturing systems analysis, (2) Manufacturing systems design, (3) Manufacturing systems operation & maintenance, (3`) is the reconfigurability stage or the life cycle extension of production systems, and (4) is the refine offline gate combined with manufacturing support centre (*Teamcenter*). A brief explanation for each stage is:

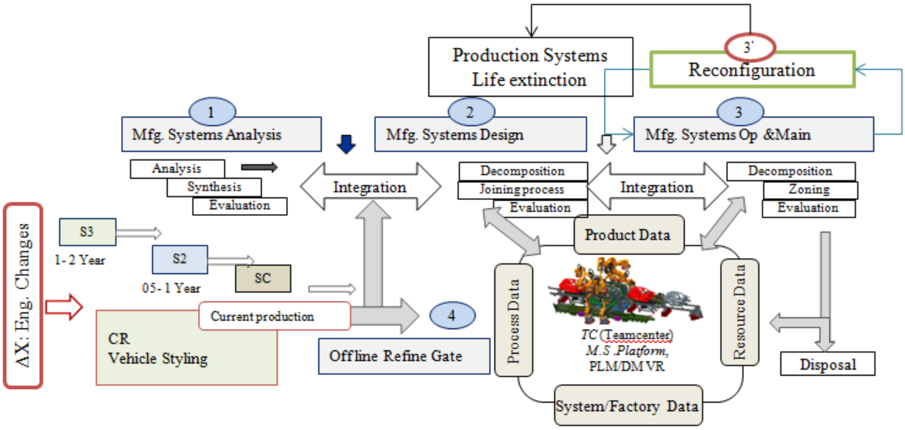

Fig. 5. Framework for RMS of Automotive framing systems

Stage 1: Manufacturing Systems Analysis – Analyzing Stage

The manufacturing systems analysis is the first stage of the life-cycle where the formulation and definition of the manufacturing system is performed to satisfy specific needs. The main constraints at this stage are the manufacturing strategy, the characteristics of the product, and the process. The automotive framing systems have complex product and processes; systems designers and product developers need to have a perfect knowledge of the decomposition and integration of all the modules and components of each module (interface components and their process) in order to upgrade to new vehicle styling.

Stage 2: Manufacturing Systems Design – Synthesizing Stage

The manufacturing system design is the second stage of the manufacturing system life-cycle. The main elements of this stage are: The main inputs for this stage are the requirements of the manufacturing system in terms of reconfigurability, which are the results of the assessment.

Stage 3: Manufacturing systems operation & maintenance

The third stage of the framework is the implementation or the launching of the manufacturing systems. Once the manufacturing systems are operating, it is important to establish operational matrices aligned with the design objective and the performance of the production line rate.

Stage 3': Reconfigurability stage -- Evolvabilty and survivability of the systems

Reconfigurability means enhancing the systems and extending the life-cycles of the systems [10].

Stage 4: Refine offline gate – Evaluation and testing stage

During the design activities, more detail is needed. The manufacturing characteristics such as product, operations, processes, and alternatives of layout are designed.

2.2 The Design Structure Matrix (DSM) Used to Identify and Measure Interaction

Design structure matrix (DSM-Component-Based Architecture) is used in the automotive industries as a tool and technique [9]. It provides a simple, compact, and visual representation of a complex system that supports innovative solutions to decomposition and integration problems. It is important to note that DSM models represent extensive system knowledge. Hence, DSMs can be difficult to build, especially initially, as they depict data that are not always at hand, easily gathered, or quickly assimilated. For a given change, it is important to establish how changes propagate throughout the systems. Fig. 6 (a), shows network (NW) representation of the systems that consist of eight modules M1 to M8, and shows how the final systems configuration is due to ΔX Changes in one element. Changes are applied M1, then changes are propagated throughout the systems. The direction of changes is propagated and classified based on the classification of element to changes by Eckert (2004). The classification were used to measure the degree of reaction in the system due to each of the changes of critical elements, there is a new metric called change propagation index (CPI) using equation (1).

The question is how can these classifications be identified and quantified to help systems engineers create better flexible and reconfigurable production systems?

$$CPI = \sum_{j=1}^{n} \Delta Ej,\, i - \sum_{k=1}^{n} \Delta Ei,\, k = \Delta Eout,\, i - \Delta Ein,\, i \quad (1)$$

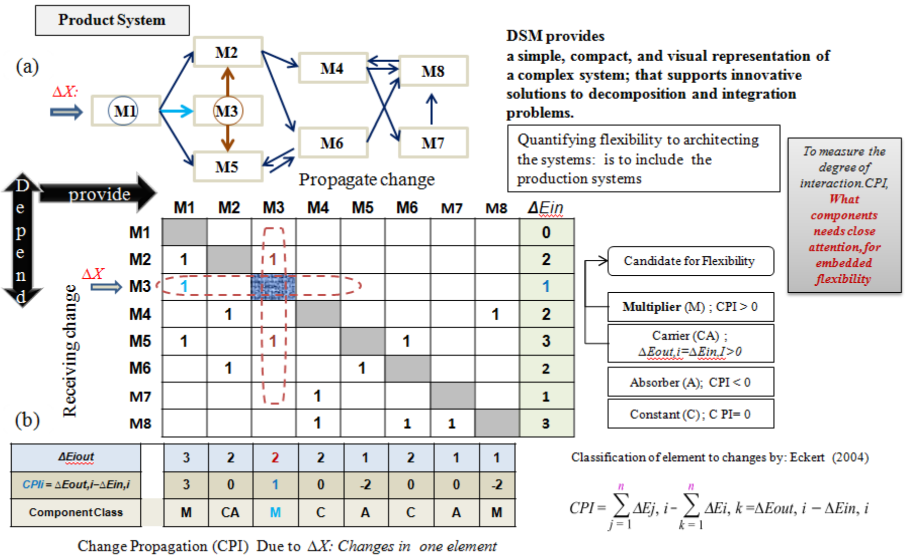

Fig. 6. Change Propagation (CPI) Due to Δ*X: Eng Changes* (adapted from [7])

The rows and columns in DSM is equal to the number of modulus/components of the systems 8x8 as shown in Fig. 6 (b). CPI can be measured as follows; for each modules i.e. M3 receives one input from M1 and send 2 outputs to M2 and M5,

CPI= ΔEout, M3 - ΔEin, M3= 2-1 =1 which is classified as a multiplier. The classifications for the rest of the system components are shown in Fig.6 (b).

The challenge is that the designer needs to determine how to eliminate or reduce the impact of physical interaction between modules. Multiplier elements can be turned to absorber or carrier by building flexibility abounded [7]. The answer to this question is presented in the next section, new tooling introduced and used in the proposed methodology.

2.3 The RMS Design Methodology of Automotive Framing Systems

Lastly, the methodology is the integration of these four stages by the RMS design framework which is proposed to decompose each stage into activities to analyze, evaluate, and synthesize the inputs and outputs of each stage in order to design/ reconfigure manufacturing system. Fig.7 shows the main stages of the methodology with PDM/DM; *Teamcenter* manufacturing support as a hub to the design methodology based on the proposed framework. Network graph representation and Design Structure Matrix (DSM - Component-Based Architecture) is used as an effective method for integrating low-level design processes based on physical design parameter relationships. Furthermore, it displays the relationship(s) between modules or components (which depends on the level of details) of a system in a compact, visual, and analytical format. It is important to note that DSM models represent extensive system knowledge. Concurrent processing to all steps using the new methods stated in three stages as follows:

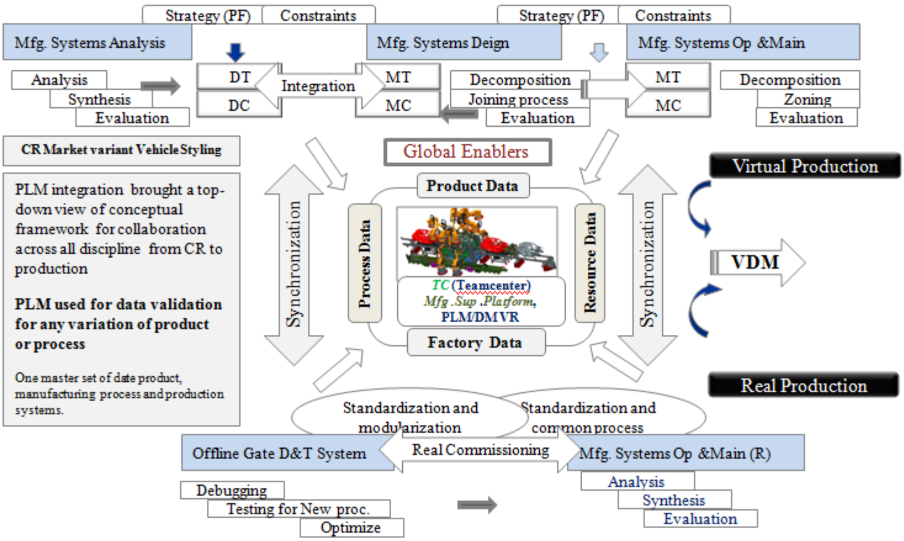

Fig. 7. PLM/DM is the hub of RMS design methodology

I): The first stage is evaluating the impact of engineering changes:
The evaluation of engineering changes (ΔX) on the manufacturing and production systems; usually received as a complete kit of data - geometry changes, weld data and processes (simulation input). Network representation for car body structures is built as shown in Fig. 8. These links between modules represent joining process such as weld spots, arc welding, laser welding or any other methods of joining upper modules to the lower-body. The network graphical represents two types of physical connections: As shown in Fig. 8, connection between modules of upper-body (M2, M3 and M4) to lower-body (M1 assembly) easily identifies changes in propagation throughout the system. Once the evaluation is completed, CPI can be calculated and then used to measure the physical interaction between modules assembly; the outputs of this stage are the identification of the key elements or components that need to have flexibility.

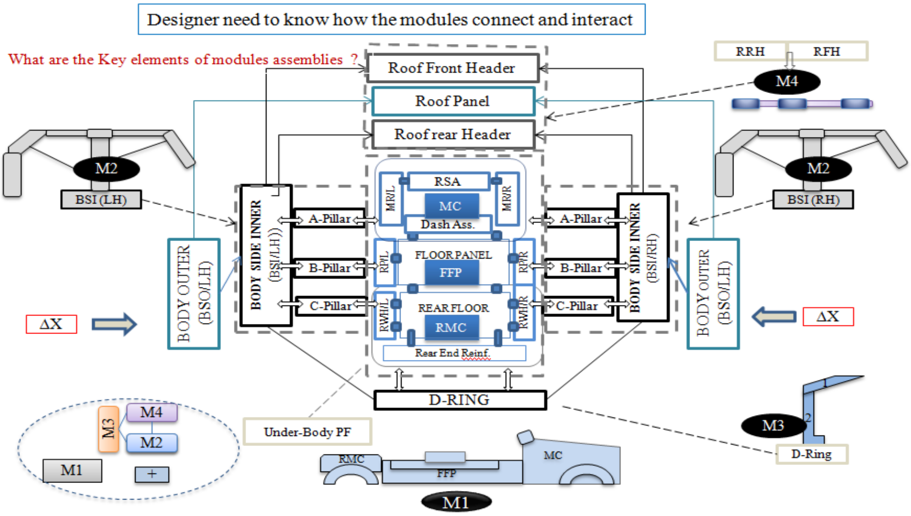

Fig. 8. Network representation *of car body structures BIW*

II): The second stage is the system design:
Start with conceptual design with virtual evaluation and make changes to the systems to achieve the design objective. New systems configuration HDSM used for mapping of product function to design configuration, as shown in Fig. 9; (two stages). The structure of HDSM is a high level representation of modules interaction of upper-body (M2, M3 and M4) with lower-body (M1); changes are initiated in M2 which is represented by square matrix 7x7 (the size depend on car body modules structures), M3 to the right, then M4 at the top (roof modules) and M1 (under-body complete). It is a straightforward mapping of low-level physical interaction as first stage indicates. The second stage is the evaluation for the positioning units (tooling) & joining processes (robot programs) of gate tooling using DM simulation as shown in Fig. 10.

III): The third stage is the manufacturing processes:
The output of this stage is the production data including tooling functionality, sequencing of operation, systems layout, cycle time for stations and robotics. Programming and automation to run virtual simulation of the production was done using Delmia IGRIP. Simulation outputs are used and can refine the design prior to building and installation of the production line.

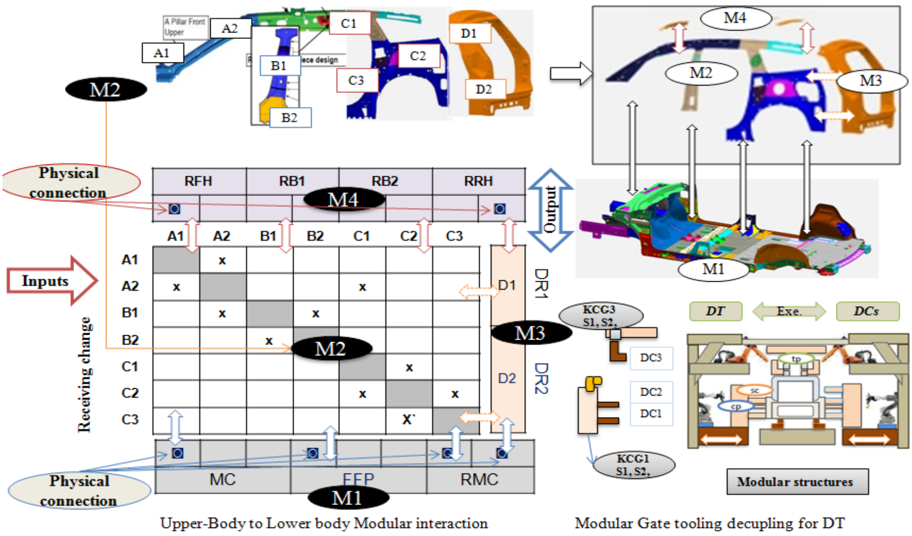

Fig. 9. HDSM key elements physical interaction for all modules

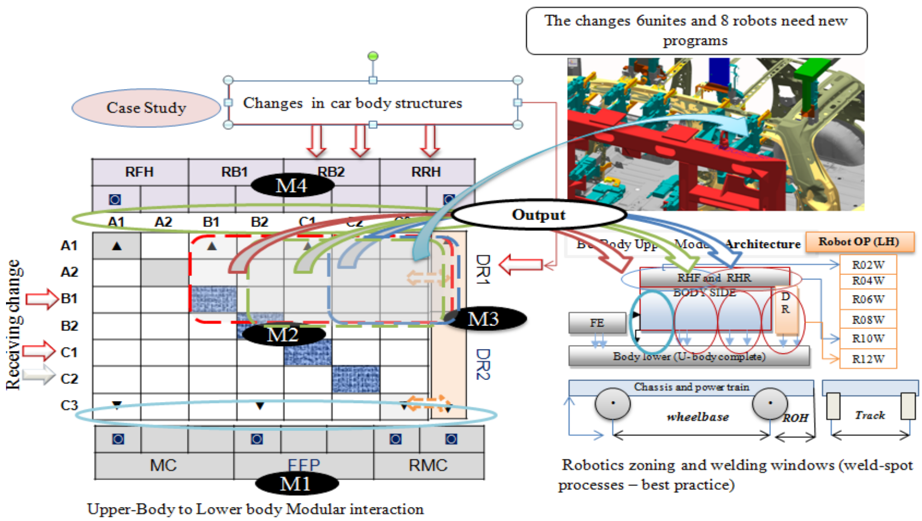

Fig. 10. HDSM evaluation of changes in positioning units and robot programs

3 Conclusions and Future Work

The proposed design method shows how to systematically pinpoint and value flexible elements in modules, despite a 30-50% higher initial investment in equipment and tooling. In return, it offers significant savings of up to 50% for each new style addition. When simulation is connected to process design and builds, lead-time is reduced by 80%. This work is the first systematic attempt at mapping product design-driven flexibility into manufacturing system capabilities.

HDSM, introduced in this paper as a new application of DSM to the automotive framing systems, can be classified as a special use in the automotive industry. The new configuration of DSM provides a new relationship perspective of dependency between modules. The use of this application helps in the following ways: a) To help systems designers understand changes in product design and mapping to physical domains (production systems) and to evaluate the effect of changes by connecting the process to DM simulation. b) Used to map engineering changes of car body structures to production systems; including positioning devices and joining process at the highest level

The future work will aim to: Continue to develop more low level details for multi domain interface product design to production systems with more interactive simulation.

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Mechatronic Machine Elements: On Their Relevance in Cyber-Physical Systems

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Abstract. This paper discusses the appearance of mechatronic machine elements (MME) in the greater context of cyber-physical systems (CPS). For this purpose it establishes classifications for CPS. Three groups of MME are identified, characterized and illustrated with examples. Regarding the advantages of MME, the text explains how they allow for new functions in mechanical systems and how they help to reduce the development effort for complex products. As desirable characteristics for MME in general are identified independent communication abilities, "plug-and-play" integration in networks and mechanics and the preprocessing of sensor data on the element itself. CPS with specifically designed MME can further become a valuable tool in product development for information collection.

Keywords: Cyber-Physical Systems, Mechatronics, Machine Elements, Product Development.

1 Introduction

In 2006 a group of computer scientists opened a new research field under the term *Cyber-Physical Systems* (CPS), which was coined by Helen Gill [1]. Expressing the new understanding of embedded systems in the context of the interaction of computers with physical processes, it is an indicator of an ongoing development in engineering and computer science. At first mechanical products were enhanced with electronics and programmable computing units, what climaxed in the 1990ies in the rise of the field of mechatronics. Now networking is being added to the physical systems. Embedded and remote computers are being connected within a single machine and over large distances as to collectively gather and exchange data about the physical world. This new stage in integrating engineering disciplines requires new questions to be asked and new vocabulary to be developed.

Lee and Seshia [1] define CPS as follows: "A cyber-physical system is an integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa."

Of course, many of the arising issues like network security, the computational handling of concurring events, and so on, are mainly to be discussed and solved by computer scientists. When it comes however to the contact point between the "cyber" and

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the “physical”, there are also issues in the mechanical engineering field that are well worth to be considered in the wider context of CPS. This also becomes clear from a position paper where Tabuada [2] presents a vision of a programmable sports car, able to emulate an arbitrary driving experience. The much one can argue about the technical feasibility of such a system, it is clear that developing such a system would necessitate new mechatronic solutions.

One of the issues to be considered in this new context are machine elements. Most machine elements used today are well understood and applied for decades. Recent developments mostly concern increase in robustness, miniaturization or better precision. However, over the past twenty years a development has gained momentum, which is about to revolutionize the way, complex mechatronic products are designed. Even more this development will make new mechatronic designs possible. It is about the increasingly tight integration of sensing, actuating and even computing and networking functions with conventional machine elements, resulting in what the authors call *Mechatronic Machine Elements* (MME). Why this expression has been chosen is explained in section 4.

An ideal MME the authors define as an element which has a mechanical function, is either able to generate and communicate information or to apply received information to a mechanical system, and is an independent instance in a data network. As an *element* is understood a small assembly of components which cannot be divided into subassemblies while any of its main functions is maintained.

The advent of MME is interpreted as the result of a technology push and a market pull. The advances in mechatronics push the development as they allow for an every tighter and more miniaturized integration of functions. At the same time the technical systems are increasingly dependent on comprehensive information about the state and condition of subsystems and its environment (i.e. they are developing towards every more complex CPS). This results in a pull for more mechatronic solutions and deeper mechatronic integration to extract information from and apply control to the inmost parts of the subsystems.

This paper aims at discussing the observed trend towards mechatronic machine elements in the context of cyber-physical systems, to set up a rough classification of different types of CPS and to illustrate three groups of MME. It further outlines how CPS in general and MME in particular can improve not only marketable products but also the process of developing them. Section 2 describes the initial observation of the trend towards MME which is then put into the context of CPS in section 3. In section 4 general considerations and examples of three distinct groups of MME are presented. Section 5 gives an outlook how CPS can be beneficially applied also in product development. The last section presents the conclusions.

2 Observation of Dissolving Borders

Starting from the 1960s with fast advances, first in electronics and subsequently in computing, machines and mechanical devices became more and more integrated with electronics and software. While devices and machines, mechatronic on a product level, for a long time could be clearly divided into mechanical and electronic components, a second step of integration is taking place at the moment on a machine element level. Traditional borders are dissolving and we can observe both: There are conventional machine elements enhanced in their capabilities by adding electronics to them and there are novel machine elements that were developed as mechatronic elements from scratch and did not exist before.

Good examples for the first are roller bearings. Probably already known in the ancient world was their sole purpose to support a rotating axis with little friction. In a recent patent [3] a roller bearing was presented that integrates an angular encoder in a cost and space saving way into the bearing ring. Machine element and sensor are inseparably merged to a MME.

A bit more difficult to classify as machine elements are active magnetic bearings [4]. They are rather complex systems by themselves. But looking at their function within a system they clearly serve as machine elements and they are elements from the perspective that their core function cannot be achieved when removing parts of it. Active magnetic bearings can be regarded as the first MME that were not conventional machine elements enhanced with mechatronic features, but mechatronic from the core.

3 The Web Reaching into Devices

The observed development of appearing mechatronic machine elements the authors would like to consider in the context of Cyber-Physical Systems. To date, many of the CPS discussed in the computer science community, which is primarily researching in this topic, are networks of independent devices or plants. An example are Advanced Electric Power Grids [5]. In such a network, instances like power plants, energy storages, control computers and consumers are connected on different levels in digital, physical or often both ways. These instances can in general be produced, installed and connected to the network independently. For the network existing outside the single products, this type of CPS shall be referred to as *External Network CPS*.

The great interest of automotive and aerospace companies in CPS topics leads us to a second type of CPS [6]. External network CPS like smart power grids are a web of things[1] with the things being plants and devices. Modern cars and airplanes are things containing an own web inside them. Their subsystems are mechanically connected and digitally linked to each other. The subsystems are controlled by electronic control units (ECU), e.g. to decide on the activation of the airbags, which are networked together. The single subsystems are still an assembly of mechanical parts, sensors, electronics and actuators, often provided by different suppliers and as individual elements. This type will be further referred to as *Internal System Network CPS*.

With the emergence of mechatronic machine elements the web is beginning to reach even further down, into the element level. The angular decoder-integrated roller bearing, described above, or seals equipped with sensors for condition monitoring [8] are machine elements, also able to generate information. It is a small step to MME

[1] The use of the term *web of things* is inspired by, but not necessarily identical to its use by Guinard and Trifa [7]. It is meant in this context as a network digitally connecting physical objects in its widest sense.

acting as independent instances in a computer network, able to communicate over standard bus protocols. Similarly, but the other way round, work machine elements receiving commands or information out of a bus environment, processing and applying it to actively adapt their properties according to the information. When in a CPS not only subsystems but even machine elements are digitally connected and act and communicate independently, the authors call that an *Internal Element Network CPS* (see Fig. 1).

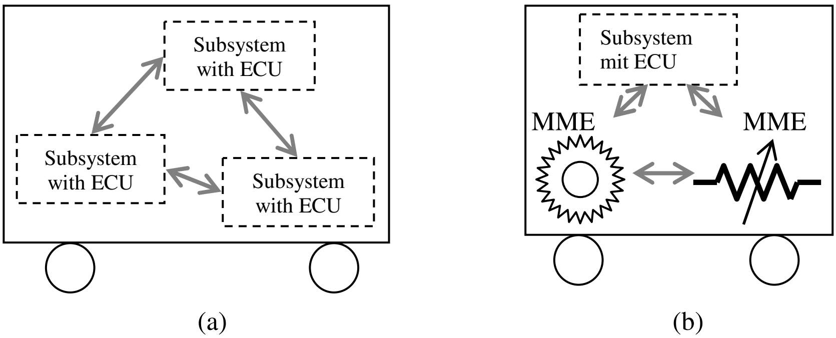

Fig. 1. Principle of an internal systems network CPS (a) and an internal element network CPS (b). The network nodes in (a) are subsystems, complex themselves, whereas in (b) the network reaches down to a machine element level.

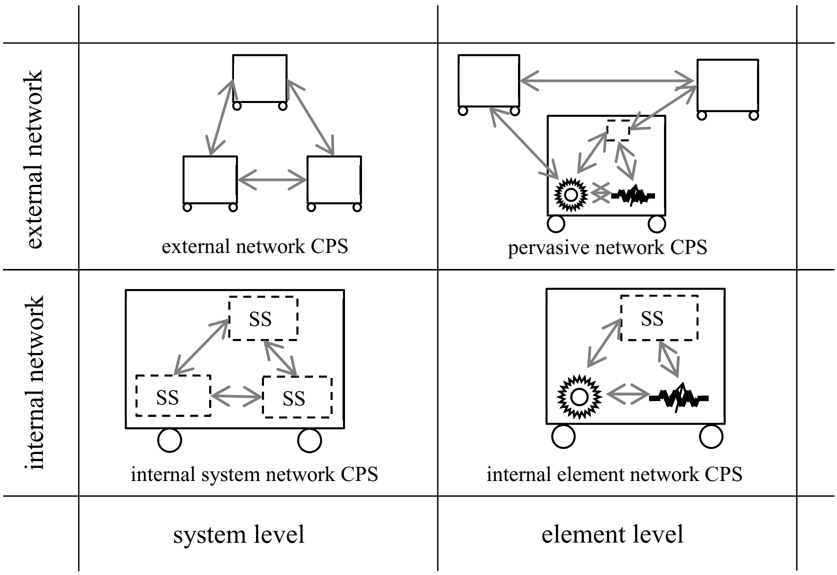

Fig. 2. Overview of the classification of cyber-physical systems used in this paper

This still being rather a vision than an observable development, it can even be imagined CPS, at the same time reaching down to an element level inside one machine and out to other devices. Imagine the timing belt of your car detecting a precarious wear on its own, before breaking. Through the internal element network of the car, the information will be transmitted to a mobile communication interface. From there a message is sent through external networks to your smartphone. The smartphone then helps you to schedule an appointment at a garage and sends a specific message to the spare part ordering system of your garage of choice. This type of CPS combining internal element networks and external networks shall be referred to as *Pervasive Network CPS.*

4 Mechatronic Machine Elements

4.1 Discussion of the Term

The term *mechatronic machine element* seems to have rarely been used to date. A Google search for the precise expression produces in September 2012 four hits. One of them leads to the encoder integrated bearing described in section 2. In the only publication found, using the term[9], it does not play a major role, nor is it defined.

The term was chosen for the following reasons: The part *machine element* refers first to the similar role these items have within a mechatronic product to conventional machine elements, especially in terms of mechanical function. Secondly it stresses out the element character as being a small integral assembly which only develops usefulness when all parts are contained. *Mechatronic* brings in the combination of mechanics, electronics and digital computing.

4.2 Standard Solutions Reduce Design Effort

As briefly mentioned above, typical CPS products which contain Internal System Networks are automotive vehicles and airplanes. These highly complex systems are developed by huge design teams. The high development efforts can be afforded due to the large number of vehicles produced or the high price paid for an airplane. Other products, as medical rehabilitation devices for example, are too specific to be produced in hundreds of thousands and cannot cost millions of euros, neither. In consequence the development effort has to be kept comparably low. Thus the cyber-physical integration is often minimal, although it might be highly desirable that they exchange more information with other devices and adjust better to the current task.

So we can see on one side the trend towards CPS and on the other side products for which the development effort to design complex internal system network CPS cannot be afforded. Here MME may close the gap. Having – in future – at hand a wide range of MME, which work plug-and-play in a bus system and can be selected and mechanically integrated by the development engineers as easily as today a gear box, this will enable also small teams to develop sophisticated CPS.

A similar development already took place in electronics a few years ago, looking at digital camera sensors for example, or GPS modules. In 1990 GPS receivers were bulky devices and due to their price only used professionally. Ten years later, GPS navigation devices were already handy and wide spread for navigation in cars or outdoor sports. Today the small size and cheap price of a GPS module makes them enhance devices like mobile phones and digital cameras with secondary functionality. But it also contributes to their broad application that developers do not need to understand the whole GPS technique anymore. It is enough for them to know the physical interface of the module and the *processed* digital values that it gives out.

(a) (b) (c)

Fig. 3. Historical development of GPS receivers, from bulky positioning devices (a) over smart navigation devices with map functions (b) to small modules integrated into smart phones (c)

From the example above can be deduced that mechatronic machine elements should have the following traits in order to have a great impact on future product development. Of course they should have reasonable costs and a compact design. Then they should process as much information as possible directly on the element. Thus the amount of data transmitted is reduced, and the transmitted data can more easily be interpreted by the integrating development engineers. For easy network integration it is important that the elements communicate according to an appropriate standard. Also regarding their mechanical design MME should follow general standards.

Three groups of MME, where important developments are going on, are examined more closely in the next three subsections. The examples given may not be MME exactly as defined above but they illustrate the key characteristics of each group.

4.3 Sensor-Integrated Machine Elements

An example of the group of MME which the authors call *Sensor-Integrated Machine Elements* is the roller bearing including an angular encoder, described in section 2 [3]. That this is truly one element can be seen from the fact that the angular structure detected by the transducer is manufactured into a bearing ring. Thus sensor and machine element are inseparable. While here the advantage of the fusion lies mainly in cost and space saving, sensor-integrated machine elements can offer more.

Dickerhof [10] showed in his research that it is possible to detect dry running and rib contact running of roller bearings through ultrasound analysis. Thus impending failure can be detected before it occurs. This detection is generally desired for roller bearings, as both, failure and unnecessarily early replacement is often very costly. So the demand for standard elements combining bearing and ultrasound analysis is given.

Now, from an ultrasound measurement the data flow is obviously large while one only needs one single value: okay or not okay. The analysis to get to this value requires considerable knowledge of the physical system, i.e. the spectrum of vibrations occurring in "healthy" and "unhealthy" bearings. Therefore it is useful that the manufacturer implements the raw data processing directly on the machine element, which then sends to other systems only the relevant okay/not okay status. Thereby it requires only minimum communication bandwidth.

Another advantage of sensor-integrated machine elements is also illustrated by Dickerhof's research. It is that damages on bearing races can be detected already from low impact energies, i.e. at low speed or with small damage, when the vibration is measured directly at the bearing. Often only a very tight sensor-mechanical integration regarding space and component parts leads to sufficient signal quality to extract relevant information from the system.

4.4 Semi-Actuators

A second group of MME is referred to as *Semi-Actuators*. While the main function of an actuator is to transform a certain form of energy into mechanical energy, the main function of a semi-actuator is mechanically passive. However, a semi-actuator can adjust the properties of its main function actively. Thus semi-actuators have generally the properties that they add degrees of freedom to the system, consume little energy and require often not so fast control cycles as principal actuators.

An example for this type of MME comes from robotics, where there is a lot of research going on in the field of variable impedance joints. The DLR VS-Joint [11] is a passive spring joint that produces in both directions forces towards a neutral position. Through an actuated spindle the pretension of the springs can be adjusted in order to change the joint stiffness. So this actuator does not actuate the joints but just influences the way the links are passively coupled through the joint.

Novel semi-actuators have the potential to make completely new mechanical solutions possible.

4.5 Sensor-Actuator Fusion

A third group of MME are *Sensor-Actuator Fusions*. Similar to sensor-integrated machine elements sensor function is deeply integrated into another element – here into an actuator. One motivation is again to save space. Another reason for such elements is to measure directly at the "hotspot of action". As an actuator by definition produces a change to a system, one often wants to measure the effects of it. On the one hand the measurement of the resulting effects of an actuator input is usually the most relevant the closest to their source, i.e. the actuator itself. On the other hand, as certain sensors are often deployed together with an actuator in a system, it can be very useful to develop and distribute them as a single element.

One example for a sensor-actuator fusion element is a self-sensing short stroke linear drive, developed for a force feedback keyboard [12]. It uses the identical hardware to produce force and to sense position. The position is derived from the damping of electric oscillations in the system, which is proportional to the position of the ferromagnetic core in the coil. A second example pointing in the direction of a sensor-actuator fusion is a highly integrated light-weight robot actuator [13]. Here the motor and sensors are still separable, but designed for a tight spatial integration. One cylindrical assembly contains a hollow shaft motor, motor and joint position sensors, torque sensors, a brake, a gear, plus ring shaped electronics boards.

5 Outlook: Insights for Product Development

So far cyber-physical systems are mainly discussed as marketable products or networks of such. The value of the intense exchange of data lies in operation states and services which are specifically optimized to the current situation, thanks to more situation awareness of the machines. Or, in another case, the value can be to free the human user from the task of acquiring, processing and deciding upon data. But CPS can also play an important role in the development process of products which are themselves low mechatronic.

To design good products, engineers need correct and precise specifications regarding the application of a product. CPS can provide information from prototypes in field testing in real time around the globe. This can be for example data on the frequency and duration of usage or the ambient temperature and humidity in the place of application. Much more powerful becomes the database if it provides information on the dynamics of the product in interaction with the user and the application.

As an example can serve the testing of hand-held power tools. Small units integrated in the prototypes record the operation of the switch and measured accelerations and temperatures. The data is sent via GSM network to the R&D headquarters of the company. It should be noted that relevant accelerations are to be measured at the force bearing structures inside the device and not at the housing. Additionally, not to alter the dynamics significantly, the data acquisition unit has to be light compared to the mass of the product.

With the need to measure relevant properties deep in the core structure of the prototype, this example again indicates the usefulness of mechatronic machine elements. New solutions should be actively sought for MME specifically designed to collect data for design purposes. The authors think for example of sensor-integrated machine elements, which are in the end product exchanged for conventional machine elements to save costs.

6 Conclusions

This paper in the first place documents the observation of first mechatronic machine elements being developed. This observation is brought into context of a general trend towards cyber-physical systems in engineering.

A major contribution is the introduction of a nomenclature for both, categorizing observed MME and existing or envisioned CPS. Four types of CPS are identified and named external network CPS, internal system network CPS, internal element network CPS and pervasive network CPS. Three groups of MME are identified so far. They are sensor-integrated machine elements, semi-actuators and sensor-actuator fusions (see Table 1). These groups are characterized and illustrated with examples.

Table 1. Comparison of the three proposed types of mechatronic machine elements

MME type	**Short description**	**Add mechan-ical energy**	**Change mechanical properties**	**Sensor output**
Sensor-integrated machine element	Passive machine element with deeply integrated sensing capability			X
Semi-actuator	Basically passive mechanical beha-viour, which is actively adjustable		X	
Sensor-actuator fusion	Deep integration of actuator and sensor functions into single element	X	X	X

While the emergence of MME is a consequence of the increasing integration of mechanics, sensing, computation and networking, they are at the same time a prerequisite for types of CPS that reach deeply into the machines, namely internal element network CPS and pervasive network CPS. Advantages of MME are most obviously saving space and better data quality, as they can sense very close to the source of measured effects. But they can also reduce the development effort to design complex products as they provide already more functionality, coordinately engineered and readily integrated in one element. Some MME also create mechanical functionality which can only be achieved through a mechatronic solution.

It is argued that for a broad success of MME it is crucial that they simplify further the work of the engineers deploying them in products they build. Therefore MME should follow mechanical and communication standards. For sensing MME it is important to implement as much preprocessing as possible on the element itself in order to boil down the data to the relevant information. This helps the deploying engineers in understanding and using the transmitted data, and it also helps to reduce the required bandwidth of the network.

In an outlook there is a great potential identified for building CPS not only as marketable products but also as a tool for gathering information in the product development process. It is suggested to develop MME specifically for this purpose to make best use of this potential.

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Approach for an Early Validation of Mechatronic Systems Using Idealized Simulation Models within the Conceptual Design

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Abstract. The success of mechatronic systems is determined by the close interaction of mechanical engineering, electrical engineering, control engineering and software engineering. During the design processes developers often rely on established and proven solutions. In order to ensure the desired system behavior simulations are carried out. This leads to considerable modeling effort to create the necessary simulation model. In this paper an approach for early validation of mechatronic systems is presented. The aim is to reduce the modeling effort for simulation models and to allow early simulations of different concepts. Therefore idealized simulation models are combined to a simulation-ready Modelica model of the system. The model is generated (semi-)automatically based on information provided by the active structure, a shape model and a behavior model. All models are part of a coherent system that describes the principle solution. Adjustments and changes in the simulation model are transferred back into the partial model.

Keywords: Mechatronics, Conceptual Design, Model-Based System Design, Principle Solution, Dynamic Analysis.

1 Introduction

Today the success of complex products is determined by the close interaction of mechanical engineering, electrical engineering, control engineering and software engineering. The design of such mechatronic systems requires a domain-spanning development process as well as a continuous validation of the system design. In order to improve the development of mechatronic systems, especially the early design phase, which the VDI-guideline 2206 calls system design, is of high importance. This part of the development is the conceptual design, where a domain-spanning system model is developed resulting in the principle solution as a first solution concept. Early analyses allow the discovery of existing weaknesses, the elimination of errors and the identification of possible improvements. The necessary analysis depends on the type of system in development and the application scenarios according to further

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operation. Examples are the thermal behavior of individual actuators, the electromagnetic interference of components or the dynamic behavior of multi body systems. The benefits of early, simulative verification are for example time- and money-saving during the development and an improvement of the product quality. Especially small and medium-sized enterprises (SMEs) decline the use of simulation and visualization tools as the effort seems too high and the benefits are not clear. Many of these companies do not have their own simulation department which is specialized on simulation models and environments. As a result the modeling and analysis must be done by the system engineers themselves. The required modeling effort depends of the development task at hand and restricts the developer with respect to the planned work. Another barrier is the high investment costs for the required simulation programs. These are profitable only in continuous use [1].

In this paper an approach for early verification of the dynamic behavior of mechatronic systems is presented. To reduce the modeling effort, the simulation model for analysis in multi-domain simulation is generated semi-automatically. A prerequisite for this task is a system model as well as the use of specially prepared and idealized simulation models for selected subparts. Comparable approaches are presented in [2]. In that contribution, two case studies are described for system modeling with SysML and the simulation analysis with Modelica. The first possibility is the continuous enrichment of the system model (SysML) with simulation relevant information. This allows a direct generation of the Modelica model using SysML4Modelica. Hence no simulation expert is required to create the simulation model. The developer of the system model however needs extensive knowledge of the simulation options and the required information. In the second case, only the basic structure of the simulation model is created based on the system model. Therefore the system model is not as extensive as in the first case. The elaboration of the simulation is performed by a simulation expert.

The approach presented here is a compromise between the two outlined ways. The basic idea is to build a fundamental simulation model based on a domain spanning system model. For the elaboration of the simulation model the predefined idealized simulation models will be combined. It is assumed that these are purchased from an external partner (e.g. supplier) or are available in-house. The effort of the simulation expert is reduced significantly, without overloading the system model with too much simulation specific information. The complexity of the system model thus remains manageable and the common understanding between the developers is still guaranteed. This contribution focuses the early stage of development and the verification of the system design. Chapter 2 deals with the development process within the conceptual design phase, in which a first version of the system model (active structure) is created. Chapter 3 shows the construction of idealized dynamic models and the semi-automated model building. The analysis of the system and the feedback of the simulation results will be discussed in Chapter 4. As an example we use the development and verification of a sorting station. The main task of this station is to sort small cylindrical samples in different stores. The samples differ in material and color. They are fed by a central storage to the station, inspected and finally transported to the desired store.

2 Conceptual Design of Mechatronic Systems

According to the VDI-guideline 2206 the design of mechatronic systems is divided into the *domain-spanning conceptual design* and *domain-specific design* [3]. These two phases can be further divided into the three processing steps *determination of objectives, synthesis* and *analysis*. Figure 1 shows the structure of the conceptual design phase and the results of each step in detail. The approach that is presented in this paper is based on a function-oriented design. This was defined by PAHL/BEITZ in [4]. To comply with the requirements of Model Based Systems Engineering a semi-formal specification technique is used to describe the principle solution of mechatronic systems during the conceptual design. The specification technique is CONSENS - "Conceptual Design Specification technique for the ENgineering of Complex Systems" [5]. The result of the conceptual design phase is a coherent system of partial models, which describes the principle solution of the new system holistically. The developers often rely on proven solutions and subsystems to create a new system. As a consequence the proposed system model combines all the information of the selected solutions like system elements and geometry parts. Although the different aspects of the system are represented by so-called partial models, the system model cannot be simulated directly within a simulation program.

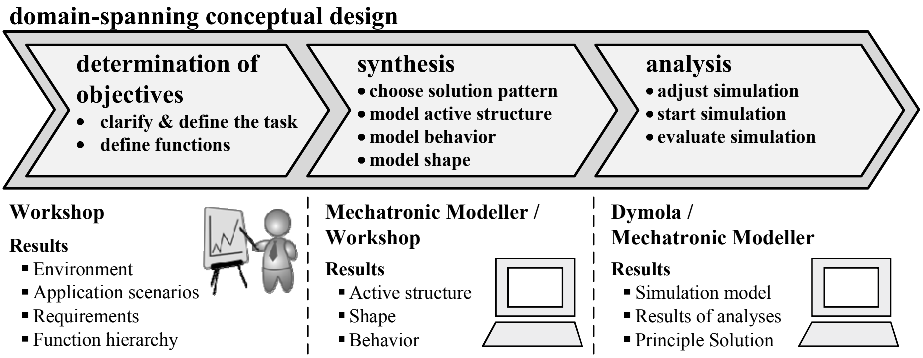

Fig. 1. Design process of mechatronic systems including an early validation

During the determination of objectives, the development tasks will be clarified and the environment model, the application scenarios and the requirements list will be created. For example it is defined, that the sorting station should receive commands from an operator (environment), store metal samples and plastic samples (use cases) or may operate with max. 230 Volt (requirement). It is advisable to create these models during workshops. This ensures a common understanding of the development task among all participating developers. In addition, members from other divisions as for example marketing or service can participate to contribute their views on the system. Afterwards the functional description of the system will be made. The result is the function hierarchy in which the sorting process is split up into required sub functions. Examples are "to eject sample", "to move sample to store" or "to identify sample material".

The selection of suitable solution patterns at the beginning of the synthesis is an important step in the development process. A solution pattern describes a specific product or solution element in an abstract form. Additional information about solution patterns and the synthesis are described in [6]. Using different solution pattern within the development process, various concepts for a new system are developed. While all concepts share the same functional description, they implement them differently. They vary in structure, shape and behavior. For example, one concept could use a pick and place robot to move the samples to the stores while a second concept uses pneumatic cylinders and a conveyor belt. Therefore an active structure and a shape model for possible concepts are defined. In Figure 2 these two models are shown for the second concept of the sorting station.

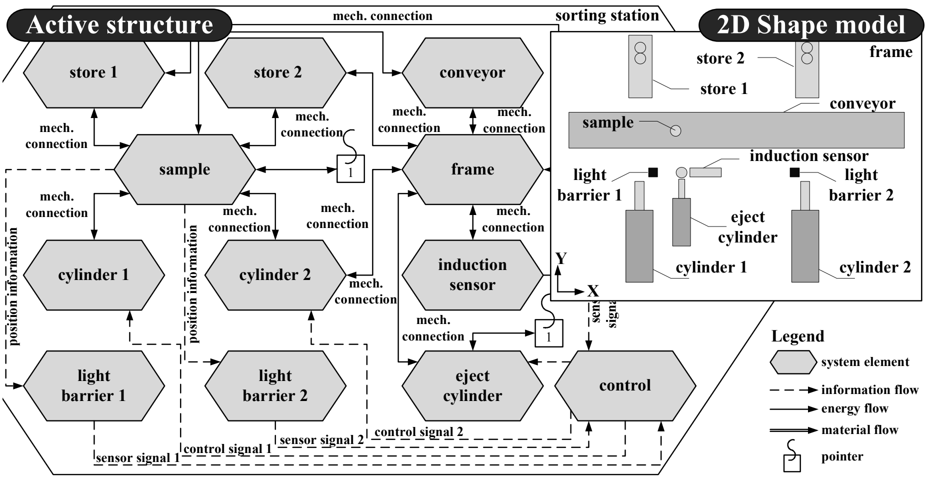

Fig. 2. Active structure and initial 2D shape model of the sorting station

The sample will be moved by pneumatic cylinders from the central storage to the conveyor belt and from the conveyor belt to the stores. Light barriers detect the position on the conveyor belt while it is moving. The active structure shows the different system elements and some of the flow relations between them. To keep it simple only two stores are shown. The 2D shape model outlines the position of each part on the frame. In addition to these models, the control of the sorting station is defined in a first behavior model. The simulation relevant information about the system is mapped to these three models. The internal computer-representation is performed by using the Mechatronic Modeller. The Mechatronic Modeller is especially designed for the specification technique CONSENS. All partial models can be modeled graphically and they can be parameterized [5]. In the following the modeling of the active structure and the annotation of simulation-relevant information from the shape model will be explained in more detail.

Each system element in the active structure is associated with one solution pattern. A system element represents a part of a system that is not yet defined finally in the conceptual design phase. The system element is described by parameters and has input and output ports. The elements are connected thought the system flows energy, material and information. To ensure the automatic generation of the simulation model, the modeling of the active structure has to follow some restrictions. These will ensure a clear link between system elements and the idealized simulation models:

- At each system element the class of the idealized simulation model has to be annotated. The name of the system element is still arbitrary as it was defined in the workshop for example.
- The input and output ports of the system elements are defined using the interface type and a port name. When no kinematic coupling exists between mechanical elements the type of the contact surface has to be indicated.

At the stage of concept development, no detailed CAD model is available in most cases. Nevertheless the simulation model requires some geometrical information. Therefore, the necessary shape information from sketches or rough 3D drafts is annotated to each system element. This includes the location and the coupling points of elements. The restrictions to annotate the shape information are as follows:

- The coordinates of the position are annotated in the system element through the label *position* = *{x, y, z}*. The rotation is specified by *angle* = $\{\varphi_y\ \varphi_x,\ \varphi_z\}$.
- The names of the contact surfaces are integrated in the ports of the system elements. The combination of two contact surfaces determines the choice of the contact block. This block will be integrated in the simulation model.
- Fixed points will be defined through the specification of a port. They have the purpose to displace and rotate the components in the model.

The basic control of the system is modeled in a state diagram. The modeling is done by using the Mechatronic Modeller. In accordance with the DIN EN 61131-3 simplified sequential controls for the system are created [7]. The connections between system elements are needed to generate a state diagram in Modelica. Restrictions are:

- Each state diagram is defined by an initial step and a final step.
- To define and use a flag (Boolean interim result) the annotation "*flag*" has to be set as an output value of a state in the state diagram.
- A concretization of a state it realized by sub states.

3 Model-Based Analysis of the Dynamic Behavior

During the conceptual design of a new mechatronic system the principle solution will be build, checked and revised. This is done gradually and with several iterations. Controlling the motion of the sorting station is a task where model-based synthesizing and analyzing methods offer great potential. Furthermore, to evaluate the functional capability, idealized control structures have to be designed. Therefore idealized simulation models are used which are assigned to the corresponding solution patterns.

3.1 Idealized Simulation Models for the Early Validation

Considering the conceptual stage, concrete solution elements cannot be chosen at this time of the design process. The designer only decides on the technology in general. So simulation models that are especially designed for this purpose represent the physical principles in an idealized way. However they have to take into account technical constraints and physical limits. The parameterization must be possible without having a full product datasheet at hand. Only a few parameters are required which are quite easy to determine. Rough calculations to determine respective default values for the remaining parameters are provided by the models [8]. Figure 3 shows the internal structure of the idealized cylinder model, which corresponds to the chosen solution pattern. Its main components are the two pneumatic chambers, the piston mass and the two stops. The latter represent limits of the actors, which are very important in this use-case. Furthermore the contact surface of the pusher is defined separately by means of a custom-made block.

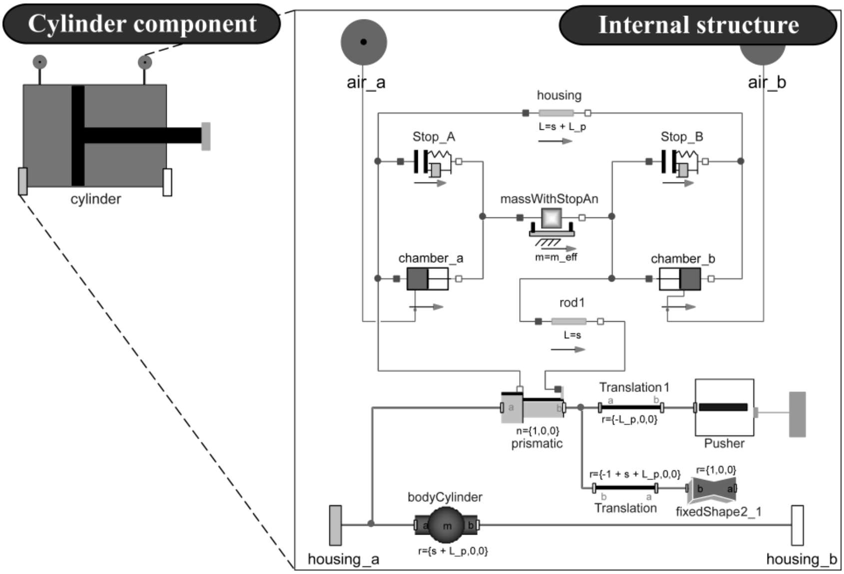

Fig. 3. Idealized Modelica model of a pneumatic cylinder (Screenshot)

In idealized models knowledge about the structure as well as about the physical relations of a solution pattern is stored and offered. Using these models the designer is able to reduce the modeling effort while comparing different principle concepts and validating the chosen configuration. This means for example the test of sensors and actors for the sorting station. As the interfaces of the models are defined and inherited via an interface model, the designer is able to exchange them and compare e.g. electric, pneumatic or hydraulic actuators [8]. In the described example a pneumatic cylinder pushes the samples onto the conveyor belt. In the corresponding idealized simulation model the designer has to define the diameters of the pneumatic chambers, the diameter of the rod and the stroke. These are parameters that can be obtained from the given requirements. A simple example for a calculated parameter is the required value for the mass in movement. This is estimated by knowing the piston geometry and by assuming that it is made of steel. By setting these values and checking them with the help of the simulation model of the sorting station, the designer defines target values to search for solution elements which are available in the market.

3.2 Automated Generation of Simulation Models

To evaluate the functional capability of the system by simulation, the modeling language Modelica is chosen [9]. Modelica allows an object-oriented, equation-based description of complex technical systems. The combination of closed sub-models for the components is possible [10], [11]. Numerous libraries that are free of charge already offer blocks which allow a relatively easy modeling of solution pattern models. We furthermore use the possibility of creating custom libraries to build up the "solution pattern library (SoPatLib)". The text-based description of models is another advantage of Modelica. It facilitates the automated compilation of the simulation model for the designed system. To simulate and edit the model we use Dymola. Dymola is a simulation tool for Modelica which offers graphical modeling as well as different analyzing possibilities. The latter comprise the graphical visualization of variables as well as 3D animations of the mechanical components of the system [12].

The automated generation of simulation models is divided into two phases. First, the sub-models are instantiated and their parameters are defined. Then the connections of the sub-models are described in the equation section of the model. The necessary information is described in the partial models according to the presented restrictions. A converter extracts the information and builds up the text based Modelica file automatically. It extracts the relevant data from the Mechatronic Modeller file and hence creates the Modelica model by combining, parameterizing and connecting the sub models. The idealized models are identified via an annotation in the system element. Figure 4 illustrates the transition of a selected part of the active structure. In the system element *sample* the corresponding complete path *SoPatLib.Components.SampleRound* of the simulation model is given. So the respective sub-models can be loaded and instantiated in the Modelica code of the sorting station model. Figure 4 displays also examples for the necessary port information. This implies a description, the port-type and a possible description of the contact surface. This information is used to generate the connections in the equation section of the Modelica code. Here the ports of the system elements *frame*, *cylinder* and *sample* are defined as *mechanical_3D*. The consistency of the connection can be checked in advance. The system elements are arranged according to the position statement with respect to inertial coordinates. Therefore a *FixedRotation* block is inserted and parameterized. Furthermore the surface port of the sample and the pusher port of the cylinder defines the contact surface. The combination of the two contact surfaces, namely a *round* and a *plain surface*, led to the appropriate idealized contact model. This is inserted from the contact library. At last the connections are transferred by means of the *connect* statements.

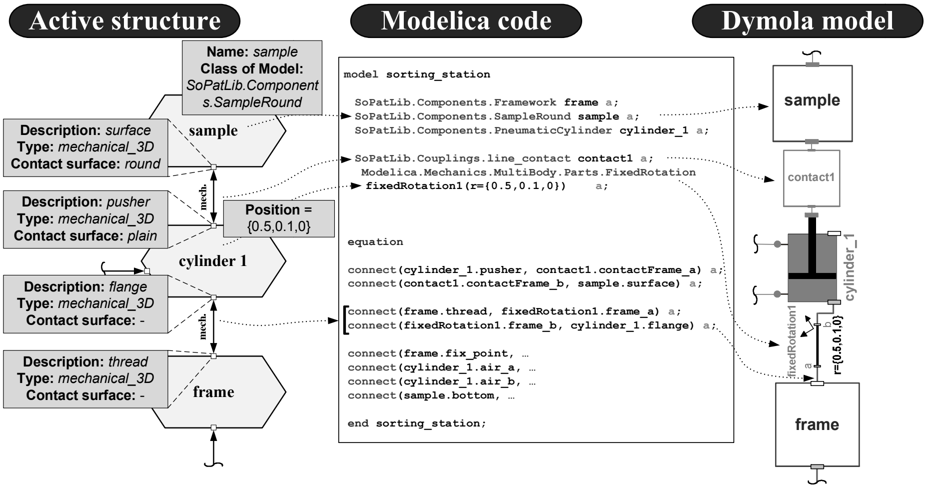

Fig. 4. Transition from the active structure to a simulation-ready Dymola model

To test the automated sorting process a first control sequence is generated using the Modelica StateGraph2 library. The starting point is the partial model *behavior*. Herein the developer defines the basic sequence of the sorting process. For this purpose he creates a state machine within the Mechatronic Modeller using states and transitions. The automated generation of StateGraph2 model is analogous to the presented approach for the generation of the structure model of the sorting station. Figure 5 shows a screenshot of the created simulation model. According to the selected parameter and positions the model can be simulated immediately. In the Figure 5 sorting process just started and the eject cylinder pushes a sample on the conveyor. The simulation model is a starting point for further optimization of the system design.

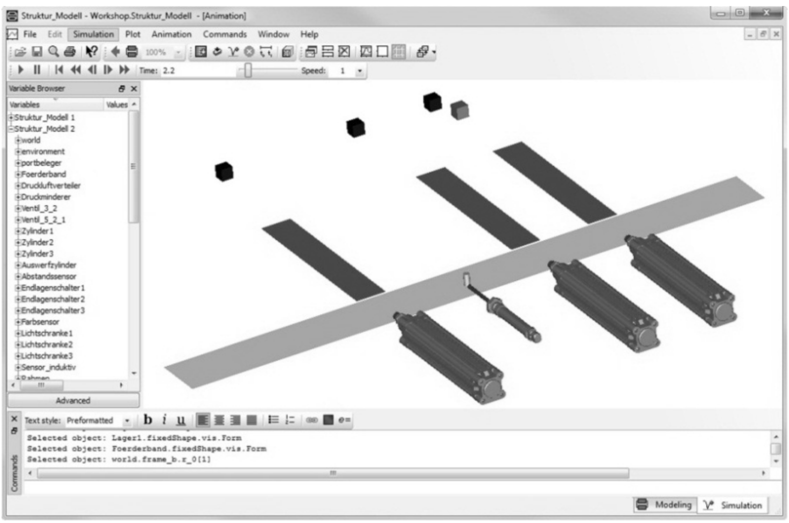

Fig. 5. Screenshot of the simulation model in Dymola

4 Simulation and Adjustment of the Principle Solution Models

The use of the simulation environment Dymola allows an easy modification and adjustment of initially created systems. As shown in the previous section the names of the Modelica components match the names of the system elements within the active structure. Due to the graphical representation in the Mechatronic Modeller and in Dymola the developer can model the system similar in both tools. Within the simulation environment, the developer refines the parameters, adjusts the positions of elements or adapts the control. This process continues until the system shows the desired behavior. The obtained results are important for the further development of the system. They have direct influence on the selection of appropriate solution elements as well as the development of the shape model in the CAD system. As the system model is the basis for all involved experts during the concretization phase the results of the simulation have to be transferred back into the partial models.

An example of modifications and adaptations on the sorting station are the positions of the light barriers and the speed of the conveyor. Both parameters are crucial for the accurate sorting of the samples. Since the conveyor belt does not stop immediately when the control signal is set, the light barriers have to detect the sample before they reach the store. The parameters must be aligned to ensure a smooth running of the sorting process. During the simulation the developer can easily modify the speed of the conveyor and reposition the light barriers to test different combinations. Furthermore, the speed of the belt impacts on the stand of the samples. Although all samples have the same geometry they are made of different materials. As a result the friction between samples and conveyor belt and the inertia varies. Too rapid acceleration and deceleration ramps can cause an overturn and hence lead to problems during the sorting process. These are a typical problems within a virtual commissioning of a new system.

The mentioned changes and enhancements to the simulation model influence mainly the active structure including the system elements and parameters. Three types of changes can be distinguished. The addition and subtraction of simulation models, the refining or setting parameter values as well as the adaptation of flows relations between elements. Each of these modifications will affect the design of the active structure. So far the changes like position or parameter values have to be transferred back manually into the active structure. The influences on the other partial models like the function hierarchy or the environment are captured in the Mechatronic Modeller. This ensures that the principle of solution is kept consistent.

5 Summary

The presented work shows a way to secure and optimize mechatronic systems within the conceptual design phase. The basic idea is the use of predefined idealized simulation models of subparts. These are automatically combined into a simulation ready Modelica model which allows an early simulation and analysis of the dynamic behavior. Starting point is the active structure of the new system with all system elements and the flow relation between them. Using a converter, the information is extracted, combined and converted to a Modelica model. The automated transfer of information allows developers to test and compare different approaches easily. Detailed knowledge about the simulation models is not required as the idealized models can be seen as a black box. This simplifies the use of simulation models in the early development phase. The secured principle solution improves the development of the system by the involved experts and supports the selection of suitable solution elements.

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Design for Testability for Micro-mechatronic Systems

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Abstract. The development and manufacturing of highly precise micro-mechatronic systems, such as MEMS applications, is a challenging task due to the complexity and variety of their manufacturing technologies, as well as their high quality requirements. Within the context of the product engineering process of micro-mechatronic systems, quality inspection by means of production measurement technology is a crucial factor. This paper presents a survey of the challenges regarding quality inspection of micro-mechatronic systems. Furthermore, a Design for Testability approach for these types of products is described and exemplary applications of its implementation are shown.

Keywords: Design for Testability, Simultaneous Engineering, micro-mechatronics, MEMS, MID, TSV.

1 Introduction

Due to their complexity and their high degree of miniaturization various functions can be realized by manifold micro-mechatronic systems. Smart phones, intelligent sensors for private homes, or micro robots are only a very small selection of possible applications. However, because of their specific characteristics, quality assurance of micro-mechatronic systems and, in particular their testing, is a challenging task.

The goal of this article is the optimization of quality inspections within the production process of micro-mechatronic systems. It is elaborated, how this aim can be achieved most effectively, if the entire product engineering process, including the design phase, is taken into global perspective.

The article is organized as follows. Section 2 introduces micro-mechatronic systems and summarizes the state-of-research regarding their product engineering process. Furthermore, it contains a short introduction into different quality assurance methods. In section 3, the concept of Design for Testability is discussed with regard to micro-electronic and micro-mechatronic systems. In section 4, the latter is further elaborated and a methodological approach for the integration of Design for Testability into the product engineering process of micro-mechatronic systems is presented. Section 5 shows the implementation of this approach for different exemplary systems.

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2 Literature Review

2.1 Micro-mechatronic Systems

The term *mechatronics* describes an interdisciplinary field of engineering sciences which is based on the classic disciplines of mechanical engineering, electrical engineering and information technology (cf. Figure 1) [1]. It is often defined as the synergetic integration of mechanical engineering with electronic and intelligent computer control in the design and manufacturing of industrial products and processes [2].

Isermann emphasizes that mechatronic systems provide the opportunity of functional and spatial system integration, which is more than a mere addition of the different disciplines [3]. Yet, this also leads to a higher complexity of the systems.

The integrative approach of mechatronics can be also applied to miniaturized systems. Most of today's micro systems are based on semiconductor production technologies (layer deposition, lithography, and etching). Besides classical semiconductor technologies, which are used for the production of integrated circuits (ICs) and *micro-electro-mechanical systems* (MEMS) devices, there are various other technologies which are important for 3D micro-mechatronic systems, such as the LIGA technology [4], IC packaging technologies (wire bonding, flip chip) [4], the Through-Silicon-Vias technology for stacked ICs [5], the Molded Interconnect Device (MID) technology [6], and the Flexible Circuit Technology [7].

Typical examples of micro-mechatronic systems are accelerometers and gyroscopes used as motion sensors in e.g. automotive and consumer electronics.

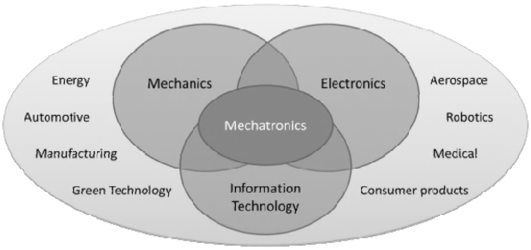

Fig. 1. Definition Mechatronics

2.2 Methods of Integrated Product and Production Design for Mechatronic Systems

Due to their interdisciplinary nature, their cross-functional dependencies, and their high degree of miniaturization, micro-mechatronic systems usually are complex products involving interdisciplinary product engineering processes, which is dealt with by methods providing an integrated view on the product engineering process [8].

A design methodology for mechatronic systems has been standardized in the German guideline VDI 2206. By means of the so called V model, an iterative, cross-domain solution concept is presented (cf. Figure 2) [9]. Within this, first, a system design is developed, which involves the segmentation of the overall function into sub-functions. On this basis domain-specific designs are elaborated and, hereafter, integrated into a common product. This process is repeated in several iteration cycles further concretizing the final product. The guideline suggests the application of the V model also for the design of the production system and comments on the great importance of intermeshing product and production design.

This integration, however, is further elaborated in the Simultaneous Engineering (SE) approach. SE is characterized by a target-oriented, interdisciplinary cooperation and parallel development of product, production and sales with regard to the entire product development process by means of consequent project management [8, 10].

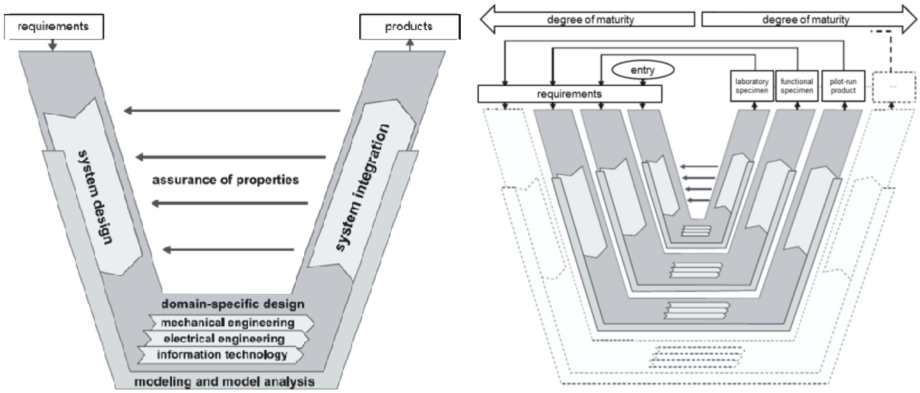

Fig. 2. V model for iterative, cross-domain product development according to VDI 2206 [9]

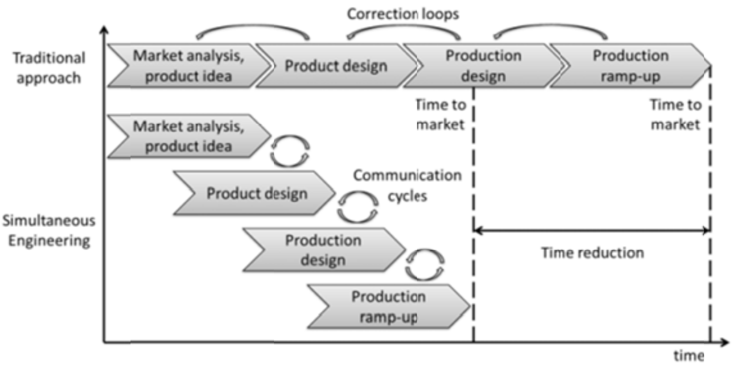

Fig. 3. Parallelization of product and production design by Simultaneous Engineering [10]

2.3 Quality Assurance of Micro-mechatronic Systems

The production quality is a very important characteristic for most micro-mechatronic systems. Nowadays, customers require a 100% quality standard when buying technical products, such as smart phones or video projectors. As the production quality of the respective micro-mechatronic systems is crucial to their functionality, manufacturers have to invest enormous efforts to ensure the quality of their products.

Quality can be defined as the realized condition of a product in relation to the customers' requirements [11]. Quality defects of micro-mechatronic systems can be based either on an inadequate design of the product or a defect within the production process. A zero defects quality level usually can be only achieved by a comprehensive approach such as Total Quality Management (TQM), which involves all steps within the product engineering process [12]

Obviously, it is most advantageous to prevent defects of a technical product before their occurrence. Hence, the application of preventive methods such as Quality Function Deployment (QFD), Product Failure Mode and Effects Analysis (Product FMEA) within the so called Design for Quality approach in the design phase is very effective (cf. Figure 4) [12]. The same accounts for preventive methods during the production process (e.g. Process FMEA, Poka Yoke, Preventive Maintenance) [11].

However, because of the broad variety of production technologies in micro-mechatronics and their complexity, it is particularly difficult to control all the involved production processes of an entire micro-mechatronic system. Therefore, the detection of defects is crucial for the quality of micro-mechatronic systems, which can be only realized by adequate methods of production measurement technology such as optical sensors (e.g. confocal microscopes, interferometers), tactile sensors, atomic force microscopes (AFM), or scanning electron microscopes (SEM).

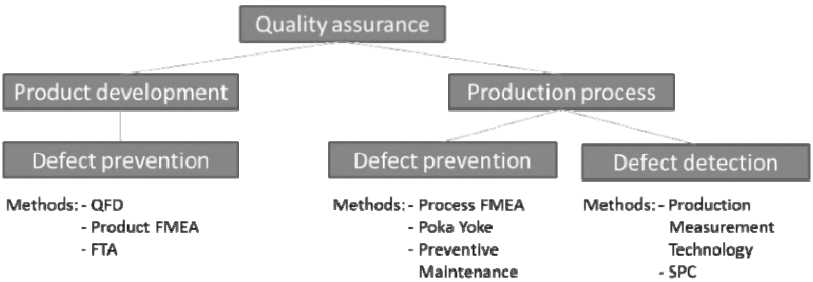

Fig. 4. Quality assurance within product development and the production process

3 Design for Testability

3.1 Design for Testability in Micro-electronics

In the product development process of microelectronic circuits not only the production process is adjusted by the implementation of testing equipment, such as functional test devices (e.g. in-circuit tests), but also certain considerations regarding the product design of the circuit hardware are taken into account.

The objective of these design techniques, which are summarized as Design for Testability (DFT), is to support the application of manufacturing tests in order to make them easier, faster and cheaper [13]. In particular, for microelectronic systems, this became necessary due to the dramatic increase of ICs per hardware module and results in changes to the circuit design on the board.

3.2 Challenges of Micro-mechatronic Products and Possible Applications of Design for Testability

For micro-mechatronic systems, which deal with micro-mechanical functionalities in addition to the aforementioned electrical ones, DFT would also be a suitable approach in order to support quality inspections within the production process. Especially for the micro-mechanical components of these systems, the manufacturing tests are often not taken into account explicitly within the product development process.

Besides, even the electronic design within micro-mechatronic systems can require new approaches for Design for Testability. For instance, 3D-shaped Molded Interconnect Devices (MID) or 3D integrated circuits with through-silicon-vias (TSV) architectures, which are becoming more and more important for the further miniaturization of micro-mechatronic systems, require new considerations to implement DFT [15]. If these technologies are used within micro-mechatronic systems, the complexity for testing and quality assurance is also increased.

4 Methodical Approach

4.1 Principles of Design for Testability for Micro-mechatronic Systems

According to *Weckenmann et al.* the quality of a measurement result is influenced by the measurement object itself, the measurement procedure, the measurement device, the operator of the measurement device and the measurement environment [15]. The latter three of those influences can be optimized within the field of production metrology without crucial dependencies to the development process of the product. On the contrary, the properties of the product as a measurement object highly depend on its design. This, furthermore, has an influence on the choice of the measurement procedure, as well. Therefore, it is advantageous to take the requirements of the testing into account already within the development process of the product. For micro-mechatronic systems, this implies both, the mechanical design and the electrical circuit design.

The degree of how suitable the design of a micro-mechatronic system is for its testing depends on many different aspects, which are specific to the respective application and the involved measurement technologies. However, the following generic principles can be identified, which enhance the testability of various micro-mechatronic systems:

- high accessibility of the measurement attribute
- high stability of the measurement conditions
- high observability of the product condition
- high durability of the product
- low noise interference with the measurement due to the product
- high in-line testability
- high ability for test parallelization
- short testing time

The *accessibility of the measurement attribute* is fulfilled, if the required information of the measurement attribute can be observed easily by means of the measurement device. While, for instance, the contacts of a standard surface-mounted device (SMD) can be inspected without difficulty by AOI, this is impossible for a ball grid array (BGA) with its contact balls face-down.

Stability of the measurement conditions means that all relevant influences to the measurement remain sufficiently constant for a certain period which is necessary to achieve a valid measurement result. If e.g. the length of a very elastic MEMS cantilever, which cannot be fixed in a well-defined condition, was critical to quality, the stability of the measurement conditions would be an issue.

The *observability of the product condition* during the measurement can be defined as the precise knowledge of the current state of the system during the measurement, e.g. the evaluation of the aforementioned MEMS, whether it is exactly straight during an optical measurement.

The *durability of the product* refers to its reaction to the measurement device. E.g. a typical Through-Silicon-Via contact pad with a diameter of approximately 5 µm is easily damaged by the common contact pins of an electric inspection such as ICT.

Noise *interference with the measurement due to the product* occurs, if parts of the product, which are not subject to the measurement, bias the measurement result, e.g. diffused light reflected by the product within an optical inspection.

In-line testability, the ability for test parallelization and the testing time are criteria which determine the efficiency of the test. The total time required for all measurement tasks can be minimized, if the product design allows the inspection to be integrated in the work cycle of the production process, several measurement attributes to be observed simultaneously and short testing periods.

If the product design of a micro-mechatronic system complies with these principles of DFT, the quality of the measurement results can be enhanced significantly.

4.2 Integration of Design for Testability within the Product Engineering Process of Micro-mechatronic Systems

The aforementioned principles of Design for Testability can be easily integrated into the state-of-the-art planning approaches of the product engineering process of micro-mechatronic systems. In the following a methodology for their integration into the V model and the SE approach is presented.

Within the V model, for an iterative development of the product design, the DFT principles serve as additional guidelines in the phase of the system design (cf. Figure 2). The criteria build additional requirements, which have to be considered within the definition process of domain-specific sub-functions. By means of the derived sub-functions they are incorporated into the domain-specific co-design of mechanical engineering, electrical engineering, and computer science. Finally, these developments are integrated into the total product and the next cycle for further refinement starts.

In parallel to the product design, the design of the production system is developed. As an iterative approach, the V model can be applied similarly. As the conception and installation of the required production measurement technology is also part of the production system, these are integrated within this process.

According to the Simultaneous Engineering approach, the production system design starts as early as possible to enable a strong cooperation between product and production design (cf. Figure 3). Within this process, the product design according to the DFT principles and the composition of the production measurement technology are matched and adapted to each other in order so finally select an optimal configuration for testing purposes. Considerations regarding preventive methods of quality assurance are combined within this process to determine which degree of testing is necessary (cf. Figure 4).

Thus, in total, a TQM system covering the entire product engineering process of micro-mechatronic systems can be realized which smoothly integrates the Design for Testability approach.

5 Exemplary Applications of the Methodical Approach

Currently, the Institute of Production Science (wbk) and the Institute for Data Processing and Electronics (IPE) at the Karlsruhe Institute of Technology (KIT) are working on possible implementations of the presented methodical approach. As a first demonstrator a micro vibration switch was realized at IPE, which is presented in the following. For further illustration, two additional commonly available systems are describes, which also comply with the aforementioned DFT principles.

5.1 Micro Vibration Switch

A micro vibration switch is a low-cost micro sensing device to detect motion (cf. Figure 5) [16]. It is integrated in battery operated, movable system, to activate (or deactivate) the device, while the system is agitated. Typical applications are bicycle backlights, remote controls, GPS tracking systems and illuminated dog collars. The sensor is realized as a functional element in a PCB. By integrating a movable microball inside the PCB a resistance change can be detected, if the sensor is in motion. For efficient production, 1300 single sensors are arranged on a single production lot (cf. Figure 6).

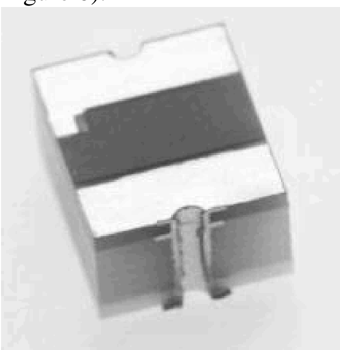

Fig. 5. Micro vibration switch, single sensor (with friendly admission of Sensolute GmbH)

Fig. 6. Production lot of micro vibration switches

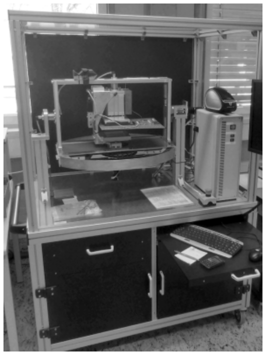

Fig. 7. Test station for micro vibration switches

In order to optimize the testing of the sensors within the production process, a test system was concurrently developed with the production layout of the sensor (cf. Figure 7).

The co-design and co-development process lead to a patented sensor arrangement on wafer level, where multiple sensors are electrically connected in series and parallel to each other. Thus, DFT could be realized very effectively for the micro vibration switches. In particular, it was possible to find an optimized solution with regard to the DFT criteria of high ability for test parallelization and short testing time. Due to this design, 50 % of conductive through holes could be saved and the testing time could be reduced by a factor of 150. 1300 sensors are tested in less than 10 seconds [17].

5.2 Bosch Pressure Sensor with MID Technology

The pressure sensor DS8 by Bosch for an automotive application is a 3D MID system, which is produced by 2-component injection molding (cf. Figure 8) [18]. One of the two polymers can be metallized after molding, thus forming a 3D circuit board which connects the actual measuring cell and a printed circuit board (PCB) to the main automotive system. By means of the MID technology a miniaturization of the system was achieved by Bosch.

Despite the miniaturization, DFT is realized very sufficiently. For MID systems mainly the criterion of the accessibility of the measurement attributes is the bottleneck. Quality inspection typically is carried out by AOI and contact testing. Both can be easily realized, as test pads have been designed that are all on the same plane for AOI and that can be contacted from the outside. This also qualifies for parallel and inline testing.

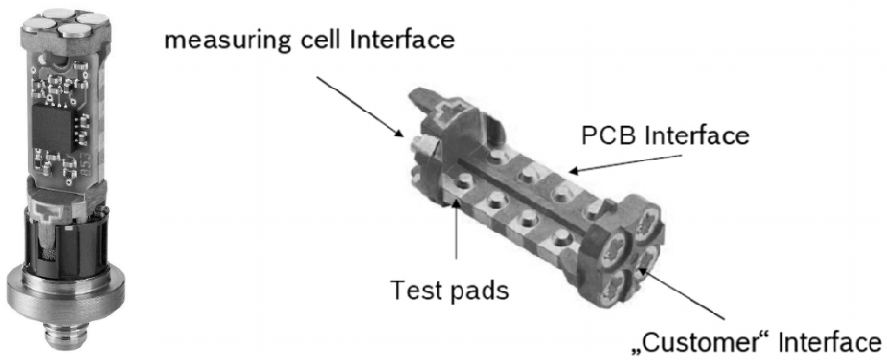

Fig. 8. Design for Testability of Bosch pressure sensor DS8 with MID technology [16]

5.3 3D Stacked ICs with Through-Silicon-Vias

Through-Silicon-Via (TSV) is a very capable technology for stacking and connecting ICs in a space-efficient manner (cf. Figure 9) [19]. TSVs are very thin connections (diameter 5 µm, pitch 10 µm) which are drilled through silicon chips. Thus, if ICs are stacked on each other, contact pads of both sides of adjacent chips can be connected within very limited space.

For a complex system consisting of stacked ICs modular contact testing is essential, which means that first each chip has to be tested by pre-bond testing, before the system is iteratively combined and tested by post-bond testing [19, 20].

However, because of the fine pitches and the fragile contacts of TSVs, common contact testing equipment such as ICT is not applicable. The small contacts cannot be accessed precisely and are easily damaged. Hence, the DFT criteria of accessibility and durability are not fulfilled.

Yet, a DFT-conform configuration can be achieved by the implementation of larger probe pads and the adaption of DFT techniques (Boundary Scan Test including Build-In-Self-Test) to the 3D circuit [19]. Only a limited number of contacts of the IC stack can be selected for larger probe pads that can be accessed by the available test equipment. This selection is made in accordance with a suitable DFT algorithm.

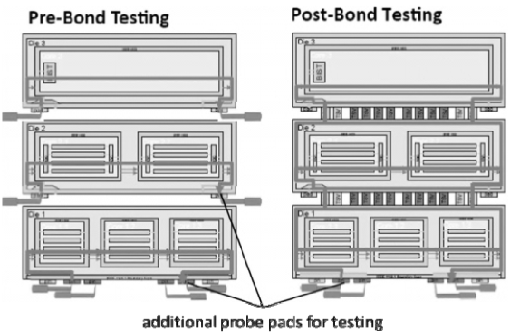

Fig. 9. Design for Testability of Bosch pressure sensor DS8 with MID technology [20]

6 Summary

In conclusion, in this article the difficulty of quality assurance for micro-mechatronic systems with a focus in defect detection is described.

As a solution concept, Design for Testability considering both mechanical and electrical properties of micro-mechatronic systems is proposed. A methodical approach consisting of generic principles of Design for Testability for micro-mechatronic systems, as well as a methodology for the integration of DFT into their product engineering process is presented. The implementation of the DFT approach is illustrated by three exemplary micro-mechatronic systems: a micro vibration switch realized by the Institute for Data Processing and Electronics (IPE), a Bosch 3D MID system, and a typical 3D Stacked ICs with TSVs.

Based on the experiences with these applications, the main advantages of the new approach can be summarized by its high impact on difficult quality inspection tasks, as it enables testing in cases, where this has been impossible before, and by its easy and universal applicability combined with standard engineering tools such as the V model and SE. However, as the approach requires design changes to the product, which typically involves significant effort, from an economic viewpoint, it is only useful, if a new product is developed or if there are crucial reasons for its redesign.

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A Reference Framework for Manual Assembly Simulation

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Abstract. This paper starts highlighting the importance of simulating manual assembly processes in the automotive industry and shortly presenting current available modeling possibilities. It then introduces a reference framework for modeling and simulation in the context of manual assembly process verification and presents a set of available simulation approaches. It concludes by proposing a methodology to assess the quality of different methods and technologies to verify planned manual assembly processes without using the classical physical prototype based approach.

Keywords: assembly simulation, manual assembly, automotive assembly.

1 Motivation

1.1 Increasing Product Variety and Manual Assembly

Seeking to acquire key market shares, original equipment manufacturers in the automotive industry are moving from mass production to mass customization offering more customized vehicles and more model variants. For instance, while in 1993 Mercedes-Benz was offering nine models, by 2015 it is planning to add at least 10 new models to the 22 of its 2012 portfolio. Increasing product variety, the need to include more model variants into existing production lines and shorter production planning cycles, make faster and more secure ramp-up processes —which are demanded by modern automotive assembly systems— more difficult to achieve and affect the way in which automobiles are developed and verified [1-2].

Although product variety impacts all production departments, it must be noted that product customization is mostly handled at the final assembly stage where manual labor is mainly used [1]. Manual assembly enables model variety by e.g. allowing installation of different interior trimmings for sedan and station wagon, and customization by e.g. adding optional features like driver assistance systems without any changeover of the assembly system. Since in the foreseeable future it is not expected that any mechanical assembly system will have the flexibility of the human being [3], the human ability to work in a number of different workstations and to perform several assembly tasks is probably the best way of handling the increasing demand for larger product variability and efficiently using available assembly capacities [1] [3].

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1.2 Reducing Physical Prototypes

Prototype building serves as an opportunity to evaluate, verify and optimize planned manual assembly processes. The assembly planning team conducts several prototype build workshops before the start of production using digital models, as well as early, confirmation, and preseries physical prototypes. The goal of these workshops is to achieve an optimal manual assembly process, through which efficient, stable and robust processes are defined, product quality is guaranteed, ergonomic conditions are optimal, and production ramp-up can be completed faster. Physical prototype building and testing is one of the major cost factors in vehicle development [4-5]. Reducing or completely eliminating these prototypes is in line with the goal and trend of producing more with less, i.e. less material and energy consumption, as well as less time and money [6-7].

In spite of the increasingly accurate digital models, and analysis and simulation tools used during product design and development, real tests on physical prototypes are still required at least for final product validation. Nevertheless, the increasing number of errors corrected using digital models has made the development process more cost and time efficient [5][7], e.g. in areas such as passive safety, the use of digital models and simulations has significantly reduced the use of physical prototypes [4]. In vehicle assembly, digital buildability workshops are a well established process to check vehicle assembly feasibility before any physical prototypes are built [4-5]. As physical prototypes continue to be reduced, an increasing number of verifications and evaluations of manual assembly processes could no longer take place using these prototypes. Alternatives to efficiently and effectively evaluate and verify manual assembly processes as early as possible must be sought and evaluated [2], since waiting for the next available prototype will entail identifying assembly process issues on a later stage, cause ramp-up delays and increase development costs.

2 Reference Framework

2.1 Modeling Manual Assembly Processes

So as to further reduce the number of physical prototypes, it is necessary to explore what possibilities exist to model and simulate manual assembly processes. Manual assembly processes comprise all assembly related operations carried out by a human worker without the use of automatic machines to bring assembly parts onto a base part in order to create a final product. The area where assembly takes place includes the space required for equipment and workers, as well as the space required for the storage of components and finished products [8].

The worker can be abstracted as a human representation. All other elements can be abstracted as objects. For modeling the worker it is possible to use a real human, a digital human model (DHM) controlled by digitalized real human movements, i.e. motion capture see e.g. [9], or a DHM whose movements are mainly computer generated, e.g. [10-11]. Motion capture allows depicting the movements of an actual human through a DHM, in this case the DHM becomes an avatar, i.e. a virtual human representation controlled by a human. In contrast, following the manual or automatic approach the DHM becomes an agent, i.e. a human representation controlled by an algorithm [12]. To model the assembly relevant objects it is possible to use physical prototypes, physical mock-ups (PMU) or digital mock-ups (DMU). See Figure 1.

2.2 Reference Framework for Product Assessment

The use of prototypes for product assessment is an established process in industry. Some applications include the evaluation of product design for usability, aesthetics, maintenance and ergonomics [13]. In [13] a reference framework for product assessment considering physical and digital approaches is presented. At first two dimensions are introduced, i.e. user and prototype, each dimension having the possibility to be real or virtual, thus yielding four possible approaches, i.e. real user–real prototype, real user–virtual prototype, virtual user–virtual prototype and virtual user–real prototype. It is also possible to have a mix of real and virtual prototypes, where an environment is made up of both physical and digital objects. The amount of physical and digital objects present in the environment can vary from purely real to purely virtual.

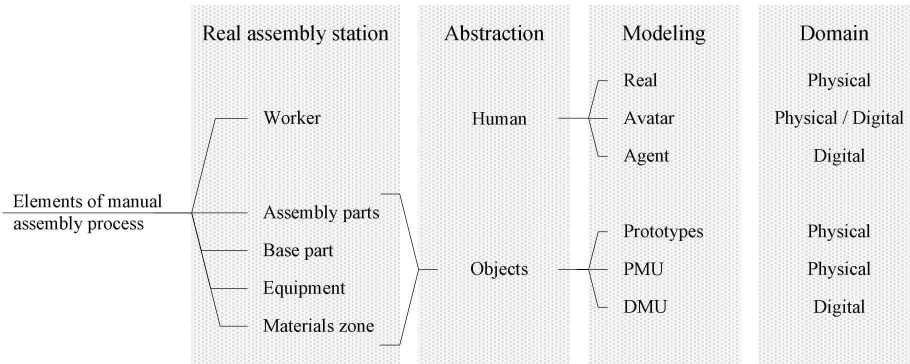

Fig. 1. Elements of manual assembly processes, abstraction, modeling possibilities and domain of action

To further differentiate possible approaches, a third dimension, i.e. interaction, is also introduced. According to [13], the interaction of the real users with the prototypes can either be direct or indirect. Indirect interaction refers to interaction that is mainly visual, while direct refers to visual interaction enriched by the possibility of touching the models. Mixed prototype scenarios based on interaction devices allowing the user to directly interact with mixed objects are also possible.

Vision is the primary source of information about the outside world and it is commonly used to double-check the accuracy of other senses. Visual feedback from the virtual domain is possible through different devices like head-mounted displays, CAVE systems, large projection screens or high resolution monitors with or without stereoscopic eyeglasses, just to name a few [9].

Haptic feedback will enhance interaction by simulating touch and force and feeding them back to the user via an input/output device which tracks the user's intentions and provides a proper response [9]. Lindeman et al. [14] further differentiate between passive and active haptic feedback. Passive haptic devices are physical objects that provide feedback simply by their shape, weight, or other inherent properties, while in active devices the feedback is computer generated.

2.3 Reference Framework for Manual Assembly Process Simulation

Analogously to [13], three dimensions, i.e. the worker, the objects and the interaction, are defined for the reference framework for manual assembly process simulation. The objects and the worker in this case can take on three different levels, i.e. real, digital or mixed, and the interaction can either be visual or visual and haptic. Figure 2 shows the two basic dimensions, i.e. objects and worker.

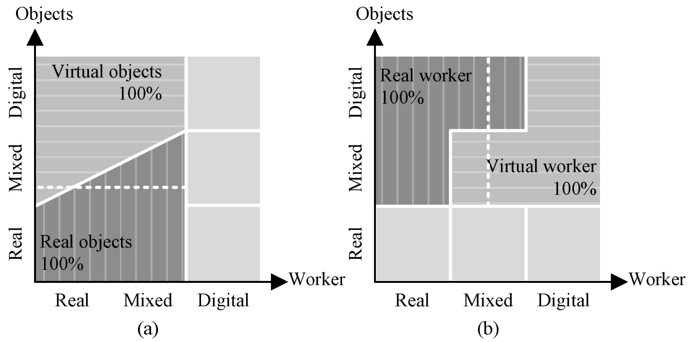

Fig. 2. Objects and worker dimension of the reference framework for manual assembly process simulation, (a) mixed objects and (b) mixed worker

For the objects it is possible to take on three different levels, i.e. purely real objects like prototypes or PMUs, purely digital objects in the form of DMUs and a mix of both, in which e.g. dummy parts are tracked and visualized in a digital environment. As Figure 2 (a) shows, it is possible to have different levels of real and digital objects in the mixed scenario. Once manual assembly process verification begins, detailed digital models of the assembly parts and the base parts, as well as standard and carry over tools, equipment and elements of the materials zone are available. Detailed digital models of some special purpose tools like handling devices, or customized bins and racks might not be available, since these are usually the consequence of the assembly verification process.

During assembly simulation it will be possible to e.g. physically have a cardboard box representing the assembly part being investigated and a table depicting the racks on the material disposition zone, while all assembly relevant objects will be available as DMUs in the digital domain. In this case the mix of assembly relevant objects will be mostly made up of digital objects. If on the other hand, mostly physical objects are available and a few elements are digitally visualized and used during assembly simulation, the mix will be made up of mostly physical objects, the dotted line in Figure 2 (a) would depict such a situation.

To represent the worker it is possible to use a real worker, who carries out the planned processes, a DHM in the form of an agent in the digital domain, or a DHM in the form of an avatar. Unlike in the objects dimension, the mixed worker in this case only takes on one mix level, see the dotted line in Figure 2 (b), which for the sake of simplicity will be 50% digital, i.e. the DHM, and 50% real, i.e. the real worker being tracked through motion capture. Nonetheless, it must be noted that it would also be possible to have other worker mix levels, e.g. if only a digital model of the hands is available in the digital domain, while a real worker is being tracked, this will be a mix made up of mostly a physical worker. The focus will be on complete DHMs, because not including the complete DHM will limit the verification possibilities of the mixed worker modelling approach.

As in [13] two interaction modes are available, i.e. visual, and visual and haptic. Visual interaction occurs when e.g. a real worker interacts by means of a pointing device with DMU objects projected on a screen. If on the other hand, the worker handles e.g. PMU or prototype parts, the interaction will be visual and haptic.

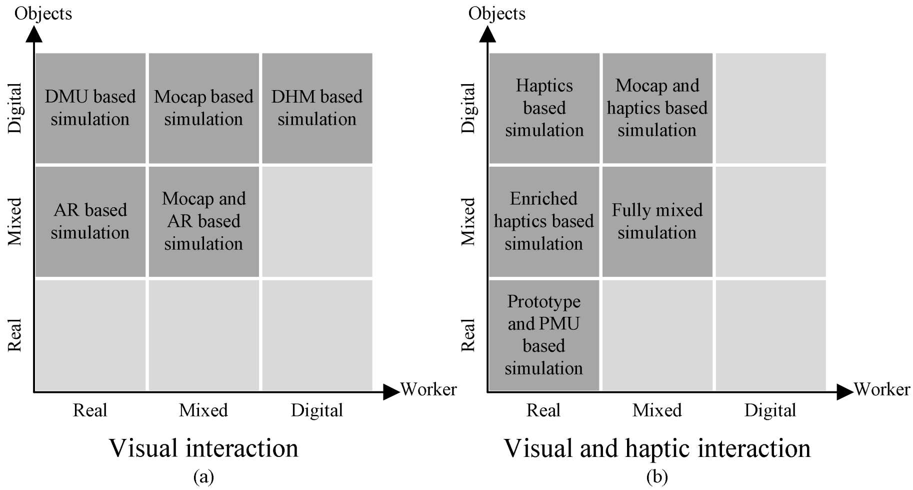

Fig. 3. Manual assembly process simulation approaches with (a) visual interaction and (b) visual and haptic interaction

As can be seen, it is possible to experiment with the models of the worker and the objects in combination with different technologies to simulate the manual assembly process. The domain where the simulation takes place could be physical, like in the current verification process, digital where digital models of the elements are used to depict the worker and its interactions with the objects, or a combination of both where actions/interactions of/with real objects are mapped to the digital models of the elements. Based on the points mentioned at the beginning of this section a framework depicting the possible manual simulation approaches is proposed, see Figure 3. These approaches are briefly described below in sections 2.4 and 2.5.

2.4 Visual Interaction Approaches

Digital worker–digital objects. Currently, manual workstations can be designed, visualized and evaluated by means of DHMs, which can be used alongside the digital models of the workstation and the product to perform product interaction, posture, reachability, visibility, as well as assemblability analysis [10]. In practice such simulations are static and mainly used for critical cases. Dynamic simulations require defining key frames and letting the tools create the in betweens, which is very time consuming and could result in implausible or unnatural movements of the DHM. Available tools are complex and using them requires expertise in ergonomics, CAD skills and also detailed knowledge of the processes and products being evaluated [15]. Although solutions for the automated generation of dynamic simulations have been implemented [11], time consuming preparation, flexibility of the model, lack of realism, lack of interactivity and lack of acceptance are the most prominent weaknesses of this approach.

Mixed worker–digital objects. This is the case of motion capture based simulations, in which the interaction mainly occurs through visual feedback. This approach is based on the possibility of using motion capture technology to directly map human motion onto a DHM, and pointing devices to select and manipulate DMU objects. The motion capture driven DHM will interact with DMU objects in the digital domain according to the input given by the worker being tracked. This approach has the advantage of not requiring any modeling of the DHM movements, thus being faster and generating more confidence about the correctness of the results. Different technologies ranging from easy to use low cost markerless motion capture —the authors are working on solutions based on consumer electronics hardware— to more complex multi camera optical marker based motion capture systems can be used.

Real worker–digital objects. In this case a real user interacts with the DMU objects without the mediation of any DHM mainly using visual feedback to perform the verification and usually a mouse, or other pointing device, to manipulate the objects. This is typical of, e.g. the digital buildability workshop, in which the assembly is digitally evaluated without specifically taking the human aspects into consideration.

Real worker–mixed objects. In [16] an example of an augmented reality based system is presented in which hand gestures are identified and used to manipulate virtual tools and parts that are projected on a work table in order to complete and evaluate an assembly task. In this case the interaction with the objects can be more intuitive and human factors aspects could be considered.

Mixed worker-mixed objects. This is the case of the mixed worker–digital objects approach enriched with physical objects, i.e. the real worker–mixed objects approach. Since physical objects will provide cues about the virtual environment in the real world, the worker being tracked could concentrate more on the task at hand and less on orientating itself in the virtual environment.

2.5 Visual and Haptic Interaction Approaches

Mixed worker–digital objects. This is the same case as the mixed worker–digital objects with visual interaction presented in 2.4 above, but enriched with haptic feedback from the virtual environment. Haptic interaction occurs through active haptic devices, like e.g. the Virtuose6D [17], which allow controlling the hand of a DHM to directly manipulate an object in the virtual environment.

Real worker–digital objects. In contrast to the approach with only visual interaction, here it is possible to manipulate the DMU objects using haptic interfaces. As in the case immediately presented above active haptic devices are used, but no DHM is present in the digital domain.

Real worker–mixed objects. Having a mix of virtual and real objects allows enriching haptic interaction through prototype and PMU parts. Active haptic interfaces can be used, e.g. the smart hybrid prototyping approach for product design presented in [18] can be adapted to be used for manual assembly verification. Passive haptic approaches are also possible in which prototype or PMU parts depicting the form and/or weight of the digital objects are tracked.

Mixed worker–mixed objects. This can be seen as the combination of the mixed worker–digital objects and the real worker–mixed objects approaches. It enriches the virtual environment and the motion capture with physical objects, thus making interaction with the digital domain more intuitive and allowing the real worker to concentrate more on the tasks to be verified and less on orienting themselves in the virtual environment.

Real worker–real objects. This is the case of the current assembly process verification workshops. In this case the simulation is carried out building a prototype under simulated, i.e. non-series, conditions.

2.6 Not Relevant Approaches

Digital worker-real objects/mixed objects. Although physical agents could be used along real objects for product assessment [13], in the case of manual assembly it will not be practical.

Mixed worker-real objects. Depicting the movements of a worker through a DHM while performing assembly tasks with real objects, if not accompanied by the DMU representations, will not immediately add any value to the manual assembly process verification workshop.

3 Evaluating the Different Approaches

Since the purpose of a simulation is to reproduce some of the characteristics of a situation or a system, e.g. manual assembly processes, without reproducing others, e.g. the costs of prototypes, the simulation cannot duplicate the system it simulates, i.e. the stimulus on the simulator will never be identical to those of the simulated system. In order to evaluate stimulus fidelity it is possible to split it into two categories, i.e. fidelity of subjective experience or experiential fidelity also referred as presence, and fidelity of performance or action fidelity. Metrics of action fidelity are more useful as constraints on the design and evaluation of simulators. Action fidelity exists when performance in the simulator transfers to behavior in the simulated system and is measured in terms of task performance. Since transfer of skills from the simulator to the simulated system may occur despite departures from stimulus fidelity, it is expected that a valid simulation does not necessarily need to occur inside a high end fully immersive virtual environment [19].

So as to evaluate how well a simulation approach represents the system, it will be possible to set up different manual assembly scenarios with known issues related to the manual assembly process verification requirements. The focus will be on process description and ergonomics. For process description two critical issues will be evaluated, i.e. process completeness and assembly order. For ergonomics reachability will be the main focus. Addressing process completeness and assembly order assesses how well the given simulation approach depicts the assembly task allowing the worker and the observers to identify the completeness of the process and the feasibility of the assembly order. On the other hand, a reachability issue directly affects the ergonomic wellness of an assembly operation and could indirectly affect process description. For instance, if an operation is planned to be completed without needing to step inside the vehicle, but this is not possible, the result will be an incomplete process description as well as a critical ergonomic assessment. In this case the ability of the simulator to correctly depict the assembly situation allowing or not the worker and the observers to identify the reachability issue is assessed.

These scenarios will be then modeled in different forms and simulated with different approaches. If the focus falls on action fidelity, i.e. task performance, it can be said that the more issues that are identified on a manual assembly process simulator, the better the approach can address the verification requirements. Other task performance indicators such as time to completion might as well be considered. It must be noted that in practice assembly planners tend to favor simple and easy to use solutions allowing them to achieve their objectives in the most efficient way, hence the importance of understanding what elements of the simulator play a key role in addressing the manual assembly verification goals. Therefore, the focus will be on comparing *low cost – low fidelity* and *high end – high fidelity* simulators and in understanding how much value different experiential fidelity levels deliver to the end user, i.e. the assembly planning team, so as to establish the most relevant aspects to consider when designing manual assembly simulators.

4 Conclusions

There are many possibilities to address the reduction of physical prototypes for manual assembly process verification. As can be seen in Figure 4, these possibilities cover a substantial portion of the proposed reference framework. It is worth noting that 100% coverage of the topics addressed during the prototype based verification is not possible using the alternative methods and technologies. These alternative approaches have their limitations and cannot fully simulate all the interactions and effects arising during assembly [10] [19]. Some technologies and methods are more adequate to address a certain type of evaluation or verification task. For instance, an undesired posture during material collection is relatively easy to spot by manually modeling a DHM. Using motion capture to evaluate if getting inside the car is required to complete a task is faster and more accepted than modeling the DHM by hand.

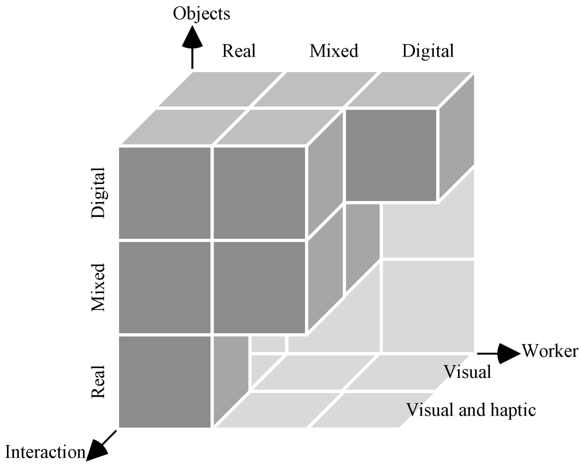

Fig. 4. Possible approaches for manual assembly process simulation according to the proposed reference framework

As it has been presented, there are many ways in which such a simulation can be built as well as technologies that could be used to evaluate and verify the planned assembly processes. They range from purely digital simulation of the assembly process modeling DHMs by hand to e.g. the use of high fidelity PMUs of the entire assembly in a fully immersive virtual environment with active haptic interaction capabilities. Therefore, from all the probable ways in which the digital and physical models could be used to simulate the manual assembly processes, it is not possible to establish a priori which combination will best suit the challenges and requirements of the assembly planning teams during manual assembly process verification. Careful exploration of available alternatives needs to be addressed so as to better understand the effects of different alternatives —e.g. the fidelity of PMUs or active vs. passive haptic feedback— on the value the simulation delivers to the user, as well as on the efficiency of the verification process.

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Product Assembly Information to Improve Virtual Product Development

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Abstract. Integrating product engineering and process planning (e. g. assembly process planning) is a relevant research theme of the last years. Primary objective is the reduction of costs and time-to-market in modern product engineering processes. In this paper the concept of Product Assembly Information is presented to support the assembly-oriented product engineering and to reinforce the integration of product development and assembly process planning. Product Assembly Information contains assembly time-relevant product criteria and is an essential part of continuous data exchange between product development and process planning.

Keywords: Product Assembly Information, Assembly Feature, Connecting Element, Improvement of CAD, Virtual Product Development.

1 Introduction

Within the last few years research activities in the field of virtual product engineering are focusing on a stronger parallelization of product development and process planning. Main aim is the reduction of total planning time and therefore of time-to-market for new products. For this purpose a lot of methods and concepts such as Concurrent or Simultaneous Engineering, Frontloading, Rapid Prototyping or Design for X approaches were developed and practically applied [1-3].

In order to realize a significant reduction of time-to-market methods and tools of information technology are used to enforce the integration of different planning tasks within the product engineering process (PEP). Especially crucial in this context is the integration of product development and assembly process planning [4], [5]. The production costs are mainly determined during the early phases of the PEP where a lot of far reaching strategic decisions have to be made. Therefore it is of primary importance to develop decision and planning support for those early planning stages [6]. One concept to integrate assembly planning aspects in product development was developed in the late 1980s and is known as “Design for Assembly” [2], [7]. It provides

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product development with some general recommendations for an assembly-oriented design. A complete and data-based integration of this concept is still often missing.

Therefore this paper presents aims and potentials for the integration of assembly-relevant knowledge in the product development process by defining and implementing Product Assembly Information (PAI). In order to illustrate the scope of the paper Section 2 surveys the state of the art and identifies need for research. Section 3 presents the concept of PAI, including its definition, application and implementation. In Section 4 the case study for connecting elements is realized. Finally, Section 5 summarizes the results and gives a scientific outlook for further developments.

2 State of the Art and Motivation

2.1 Current Integration Gaps within PEP

Currently existing gaps between product development and assembly planning are caused not only by conceptual weak points, but also by the two-part IT infrastructure in manufacturing industry. On the one hand, Computer Aided Design (CAD) and Product Data Management (PDM) systems provide support to product development processes. On the other hand, e. g. Enterprise Resource Planning (ERP) systems administrate the continuously increasing amount of production-related data and support operative production processes (see Figure 1).

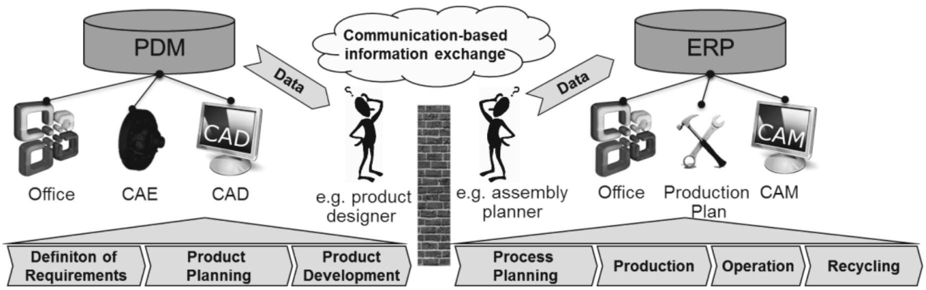

Fig. 1. Two-part IT infrastructure in manufacturing industry [8]

Due to the integration of product and process planning the concepts of Product Lifecycle Management (PLM) and Digital Factory (DF) were developed and are of high relevance nowadays [9], [10]. Thus, PLM and DF solutions represent the current approaches to provide integrated IT infrastructure in the context of Simultaneous Engineering. In spite of their high acceptance and wide dissemination in manufacturing companies the utilization of assembly-relevant knowledge, e. g. in form of assembly features, is not often realized in a structured way [11]. A typical example for an integrated utilization of directly represented (explicit), manufacturing-relevant knowledge is the creation of a numerical control (NC) work plan based on a CAD model [12], [13]. Due to the complexity of the application field assembly process planning, a uniform representation of assembly-relevant information and its consistent usage along the PEP are not established yet.

2.2 Initial Approaches in Product Development

The classical tasks of assembly planning, the creation of a Manufacturing Bill of Materials (MBOM) based on an Engineering Bill of Materials (EBOM), is much more focused on using assembly process planning expert know-how. An explicit description of the planning procedures and the planning logic is often not available. As a consequence, this planning knowledge remains personalized and therefore implicit.

Nevertheless, some approaches for an explicit documentation of assembly-relevant parameters in CAD systems for example in features exist [14], [15]. However their consistent usage in practical application is still limited [11]. For example Siemens - Solid Edge ST 4 contains the assembly feature “screw connection” to select the required nuts, washers, bolts, etc. After the joint is completed and the feature assistant is closed, Solid Edge creates a new node in CAD according to the new joint, which contains all participant parts (see Figure 2).

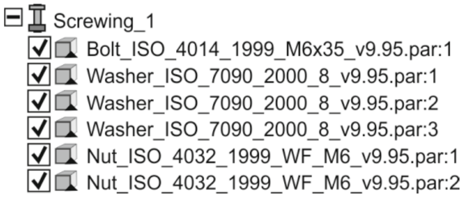

Fig. 2. Screw connection in Solid Edge ST4

The main weakness of CAD assembly features is their rare utilization in the ongoing PEP. In most cases feature information is not consistently used in assembly process planning. This is caused by system interfaces and consequential information loss during data exchange e. g. between CAD and PDM system. In this example, the information transferred is often limited to a pure Bill of Materials (BOM) without detailed assembly specification.

2.3 Information Content within PEP

The illustrated problem of maintaining information available in early stages of product development for downstream planning processes (e. g. assembly planning) is not exclusively caused by the two-part IT infrastructure. Product development cannot gather all important information which is required for assembly planning. A certain set of information can only be added during the assembly planning process. This enrichment of assembly planning information on the basis of product development data is the primary task of assembly planning departments. The know-how gap of determined and required information cannot be bridged only by IT systems themselves.

Additionally this gap between required and available information is often enlarged by insufficient utilization of already existing information, not only on the system boundary, but even within product development and process planning. For example assembly-relevant product development information is often not explicitly stored in IT systems (e. g. CAD, PDM) or saved unstructured and hence not locatable. This results in a non-ideal behavior of the information curves in Figure 3. This effect is enforced by the already mentioned two-part IT infrastructure and herewith a “wall” between product development and (assembly) planning departments. This leads to a growing lack of planning information which has to be added by the assembly planning under steadily increasing time and cost pressure.

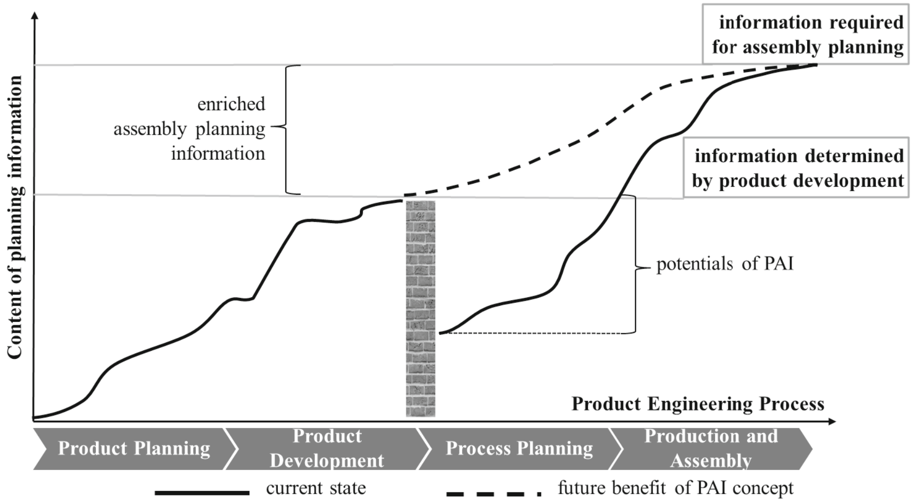

Fig. 3. Information contents of product development and assembly planning

To face the described challenges, gathering and storing of assembly-relevant information within PEP has to be supported. On the one hand, the concept of PAI (as detailed later on in this paper) will offer the opportunity of conserving and structuring assembly-relevant information, as it is already available in product development. On the other hand, it will structure the enrichment of this information in downstream planning processes in close collaboration between product development and assembly planning. The current state of information content development along the PEP and anticipated improvements realized by PAI concept in future are illustrated in Figure 3.

2.4 Requirements Specification for PAI Conception

To summarize the identified need for research methodical requirements (primarily the essential content and organizational integration) and technical requirements (issues of IT supported PAI realization and implementation) for the development of PAI are detailed in following. Methodical requirements are:

- Providing the fundamental opportunity for additional input and exchange of assembly-relevant (in part implicit).
- Minimizing the effort for the enrichment of planning information.
- Defining assembly-relevant information in structured and standardized way.
- Enabling both standard contents of PAI and company-specific adjustments.

Following technical requirements can be identified on this stage of PAI development:

- Dealing with machine-readable, standard data formats to be stored and applied in different IT systems.
- Allowing information transfer across the variety of PEP-relevant IT systems.
- Enabling context-based and problem-related representation of planning information along the PEP.
- Creating a basis for the application of Data mining on assembly-relevant data.

3 Concept of Product Assembly Information (PAI)

As described in Section 2, the transfer of information within PEP is still a key challenge for manufacturing industry. To address this issue, it is necessary to create a methodical and systemic way to store assembly-relevant information. Therefore, the Institute for Virtual Product Engineering (VPE, TU Kaiserslautern) in collaboration with the Chair of Industrial Engineering (APS, TU Dortmund) developed the concept of PAI in order to extend existing PDM data models. PAI contains and structures all assembly-relevant information of an assembly or a part (analog to the idea of Product Manufacturing Information [16]). This information can vary depending on the functional behavior of the part or its hierarchical position in the product structure.

3.1 Definition of PAI Content

There are two different general approaches to define the information content which has to be represented within PAI (see Figure 4). The first one is to develop PAI based on know-how from product development and assembly process planning, the so called knowledge-based compilation of PAI. For this aim all assembly-relevant aspects and their typical values have to be defined and aggregated in attributes beforehand. Deriving specific values for the predefined attributes can be automatically detected from CAD system, selected or added by product designer.

The second approach follows the data-based definition of relevant attributes and their value classes. Therefore, the application of machine learning techniques is required for analyzing digital databases of different IT systems in order to identify and adjust relevant attributes.

Both ways to define the required PAI can lead to one and the same or two different PAI contents (attributes and value classes) depending on their data- or knowledge-based creation. To get valid and usable PAI both approaches have to be combined. The comparison of the results will lead to a PAI content meeting the requirements of both planning processes and their data-based support within the PEP.

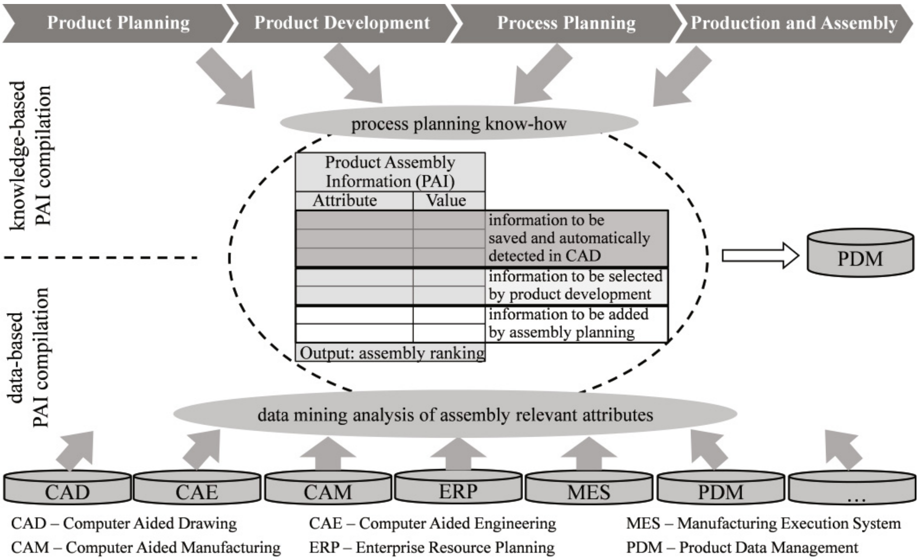

Fig. 4. Concept of Product Assembly Information (PAI)

3.2 Application of PAI

To transfer assembly-relevant information from product development to assembly process planning, the concept of PAI is utilized. Thereby PAI contains and structures assembly information of a joint or a connecting element.

A PAI consists of one or more triple of attribute, unit and value. For example, relevant information about a screw torque has the following content: *data name:* torque; *data unit:* Nm; *data value:* 19. Nowadays, product designers often paste assembly-relevant data as a comment on engineering drawings. Later in PEP assembly process planers e. g. determine the assembly time by searching and analyzing these comments which are sometimes only accessible as non-digital engineering drawings in hard copy. This disadvantage can be eliminated by application of PAI. As soon as information about connecting elements is available, it can be extracted from the PDM system by process planers (see Figure 5).

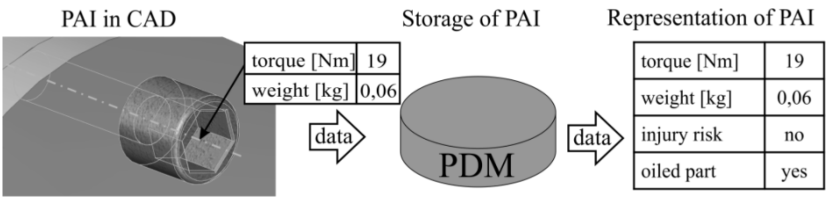

Fig. 5. Improved information transfer via PAI

3.3 Implementation of PAI in CAD

For the implementation of PAI, PDM and CAD data model extensions are essential. Therefore, relevant attributes can be attached as an assistant function in CAD.

The example in Figure 6 shows the assembly of motor block and cylinder head in CAD. Thereby, assembly assistant function is represented as a dialog checking defined attributes and highlighting problems. In this example, the weight of the cylinder head is very high, so the assistant function of CAD suggests weight reduction to achieve an assembly improvement. In addition, parameters e. g. *number of screws* and *controlled torque* are defined and their values traced (marked with a check). The exclamation mark in the line *additional elements* indicates a missing washer in the assembly. Combining and visualizing all assembly-relevant information in one single window (see Figure 6) allows the identification of potentials for improvement. This could be a reduction of weight and an accomplishment of washers.

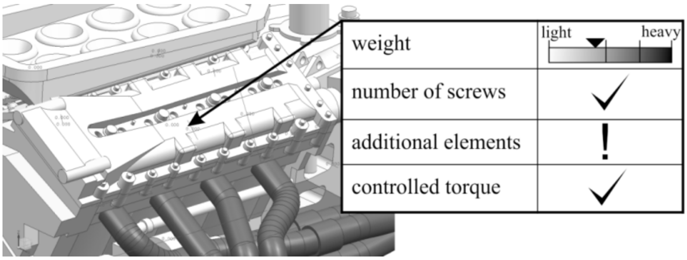

Fig. 6. PAI-based assistant function in CAD

4 Case Study for Connecting Elements

Section 3.1 presented two alternatives for detecting PAI-relevant information. In this case study a knowledge-based definition of attributes is realized. For this purpose, connecting elements are examined regarding their assembly-relevant characteristics and their suitability for the development of PAI. Thereby connecting elements are selected, because they are frequently applied during the design of manufacturing products and often specified in a standardized way.

4.1 Classification of Connecting Elements

Connecting elements can be classified according to the detachment and operating principle in a not-detachable and a detachable category (see Figure 7). Thereby detachable connecting elements are subdivided in two classes: non-destructive and

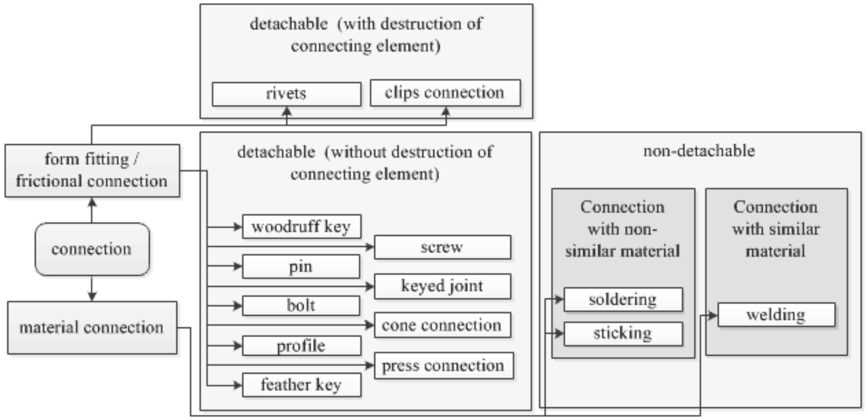

Fig. 7. Classification of connecting elements [17]

destructive detachable ones. The first class of connection can be reused after disassembly. Destructive connections in contrast are developed for only one-time assembly and are destroyed during a disassembly process. A rivet connection e. g. cannot be reused, because it must be drilled during the disassembly process.

The most frequently used connecting elements in mechanical engineering are bolts and screws [17]. Therefore, assembly-relevant information of screw connection is analyzed in the following to build a basis for the development of screw-PAI. The aim of analysis is to detect attributes, which describe a screw connection from both engineering and assembly planning view.

4.2 Attributes and Values of Screw Connections

Table 1 illustrates an extract of assembly-relevant attributes of a screw connection which have been identified knowledge-based considering the rules of Methods-Time Measurement (MTM). MTM is a Predetermined Motion Time System (PMTS) and offers a standard time data catalogue for manual assembly operations depending on different product and process attributes.

First assembly-relevant attributes and values of screw elements (see first two columns in Table 1) are gathered based on product development and process planning know-how. Secondly identified attributes are analyzed concerning their information sources. According to Figure 4, the identified attributes are categorized (see Table 1) in information which can be automatically extracted from a CAD-Part (column 3); needs product engineering know-how to be extracted (column 4) or needs to be defined by assembly planning (column 5).

Table 1. Example of attributes and values of a screw connection

Attributes	Values	Source of information		
		CAD	Product engineering	Assembly planning
additional elements	washer, nut	x		x
automatic screwing	automatic/drill screwdriver			x
controlled torque	yes/no	x		
glove used	yes/no			x
lack of space	yes/no		x	x
magnetic screw	yes/no		x	
manual screwing	cross recess; open-end spanner; …			x
material	metal sheet, wood…	x		
obstructed view	yes/no			x
oiled parts/ lock Tide	yes/no		x	x
screw head diameter	mm	x		
screw type	tapping screw, metric screw	x		x
thread pitch search	yes/no			x
thread type	fine thread / coarse thread	x		x

5 Summary, Further Development and Scientific Outlook

The concept of PAI is a standardized and aggregated way to describe and store assembly-relevant information within PEP. PAI will scale down the "wall" still existing between product development and assembly process planning. The uniform representation of PAI is not limited to the use within CAD systems for product design support. It is supposed to be an adequate extension for current PDM systems as connector to further downstream planning solutions as well. The paper presents connecting elements, their classification and standardized description as a possible key structure for an applicable assembly planning support by PAI. An exemplary case study identifies assembly-relevant parameters for screw connections. The classification of these parameters gives an idea of further potentials of PAI-usage within PEP.

The technical feasibility of the proposed solution has to be shown by implementation of the PAI concept in CAD and PDM systems. As a scientific addition, the possibilities of modern machine learning applications have to be implemented within the concept. In the future Data Mining for example could help to overcome the disadvantages of high initial efforts in defining relevant PAI content. It can also reduce insufficient company-specific planning support, leading to a more flexible and adoptable concept for the usage of PAI. Especially important in this context is the data-based identification and standardized representation of assembly-relevant information within the huge amount of digital data. For an improved utilization of the PAI concept new methods for analyzing assembly-relevant information stored in existing PAI should be developed and applied. This will raise the final scientific question of a standardized representation and seamless usage of information in following planning processes as realized in DF or PLM solutions.

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Assisted Decision-Making for Assembly Technique Selection and Geometrical Tolerance Allocation

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Abstract. Assembly process planning involves many aspects from geometrical matters to operational research. Though, the literature shows very few works about assembly technique selection.

This paper deals with an original method to select assembly techniques and to allocate component geometrical tolerances in order to minimize the product cost and to maximize the conformity rate associated with the assembly plan.

The data structures used to define a parametric assembly plan is detailed. This data structure is used to formulate a multi-objective optimization problem reflecting the concerns of the study.

The entire method is illustrated trough a case study. The results obtained are presented and followed by a discussion about the potential benefits of its application in an industrial context. The useful support that this method can provide to decision-making is highlighted. Its shared point of view from product designers to manufacturing process designers makes it an efficient tool for concurrent engineering.

Keywords: Assembly process planning, assembly technique selection, geometrical tolerance allocation, multi-objective optimization, concurrent engineering.

1 Introduction

1.1 Design of an Assembly Process Plan

The assembly of large mechanical structures, such as aeronautical ones, may account for a large share of their total delivery cost. Boothroyd and Dewhurst stressed out the importance for manufacturing companies to assess a product's design by designing assembly process plan as soon as [1] in order to reach the maximum performance [1]. Computer-aided assembly process planning has been the subject of many research works generally aiming at finding the minimum lead time and/or cost. The performance of the assembly process plans is evaluated according to several indicators such as, for example, tooling needs, reorientations of sub-assemblies, technological similarities in consecutive operations and so on [2].

[1] What is called design for manufacturing and assembly (DFMA).

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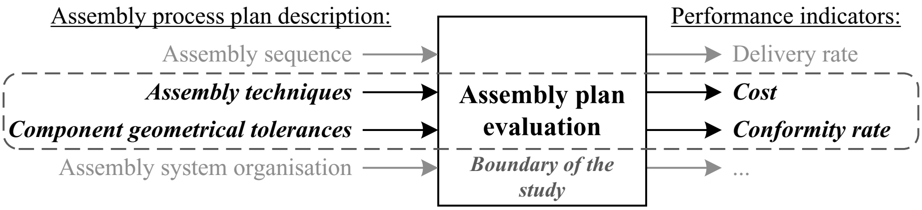


Fig. 1. Schematic view of the description and evaluation of an assembly process plan with the proposed approach boundary

As summarized in Fig. 1, the description of an assembly process plan can be split into an assembly sequence, the assembly technique selected to make each attachment of the product, the geometrical tolerances allocated to each component and the description of the assembly system[2]. Most of the works presented in the literature only focus on specific aspects of the problem.

Assembly sequence planning, either defined as the part introduction ordering [3–5] or as the joint realization ordering [6, 7], has been widely studied in the literature [2]. The joint-based approach is close to the activity-based approach proposed by Cao and Sanderson [8], and reflects some of the issues considered for the organisation of the assembly system commonly treated in operational research [9].

But the generation of assembly sequences and the organisation of the assembly system are not the only activities encapsulated in assembly process planning. Assembly technique[3] selection [10] is seldom addressed in the literature even though it may have the greatest impact on production cost, according to Abdullah et al. [11].

Selecting assembly techniques implies setting the associated geometrical capabilities. The concern of geometrical quality of the assembled product (commonly called tolerancing) is therefore coupled with the assembly process planning. Up to this point, the geometrical tolerances allocated to the components to be assembled may be part of the information contained in a comprehensive assembly process plan [7, 12, 13].

1.2 Proposed Approach

Massive automation has been the key solution to answer the need for decreasing manufacturing cost and increasing delivery rate in many manufacturing domains. But in the field of aeronautical structure assembly, the complexity of some attachments, the high level of geometrical requirements and the high working area required are several hurdles to an efficient use of automation with respect to manual assembly. Trades-off have to be made.

This paper aims at proposing an original method to select assembly techniques and to allocate component geometrical tolerances in order to minimize the product cost and to maximize the conformity rate associated with the assembly plan. The assembly

[2] Either spatial or temporal.

[3] Also called *assembly process* by some authors.

sequence is assumed to be already defined and the organisation of the assembly system is not considered.

Section 2 details how an assembly process plan can be described according to a set of decision variables and how it can be evaluated according to several performance indicators. This formal view of the problem serves the definition and the resolution of a multi objective optimization problem.

A simple use case is presented in Sect. 3 and the results obtained are detailed in Sect. 4. Section 5 concludes on the potential benefits of this approach in a concurrent engineering context.

2 Optimization Problem

2.1 Multi-objective Optimization

Considering a given product and a given assembly sequence, the purpose of the presented work is to propose a method to find a set of assembly techniques and a set of geometrical tolerances that minimize the non-conformity rate and the delivery cost of a product at the same time.

A mathematical expression of this problem is given in (1), where $\boldsymbol{x}$ is a decision variable vector representing an assembly plan, X is the set of feasible assembly plans and f is a function associating a fitness to an assembly plan. The construction of the decision variable vector $\boldsymbol{x} \in X$ is later described in Sect. 2.2.

$$\inf\{f(\boldsymbol{x}) : \boldsymbol{x} \in X\} \tag{1}$$

In the present case, the fitness function f must cope with several objectives (non-conformity and cost). Moreover, these objectives are likely to conflict with each other. A common solution to this issue is to combine the objectives in a single-valued fitness function. But it can prove complicated to model the actual objectives into a single performance indicator, which results in making trades-off a priori.

Solving a multi objective optimization problem seems to be more appropriate within the industrial context. From the assembly process planner point of view, an *interesting* point $\boldsymbol{x}^*$ describes an assembly process plan for which one can not find a solution that provides both lower non-conformity rate and lower cost at the same time, as pictured in Fig. 2.

Assuming $f = [\mathrm{NCR}(\boldsymbol{x}), \mathrm{C}(\boldsymbol{x})]$, non-conformity rate function and delivery cost function described in Sect. 2.3, a solution of the problem given in (1) is a point $\boldsymbol{x}^*$ satisfying (2), $\boldsymbol{x}^*$ is called a non-dominated point.

$$\nexists\, \boldsymbol{x} \in X,\ \ \mathrm{NCR}(\boldsymbol{x}) < \mathrm{NCR}(\boldsymbol{x}^*) \text{ and } \mathrm{C}(\boldsymbol{x}) < \mathrm{C}(\boldsymbol{x}^*) \tag{2}$$

The underlying mathematical problem of this work consists in finding the set of non-dominated points (or a sufficient amount of points if this set is not finite). The assembly process planner finally has to select the plan that provides the best trade-off among the set of non-dominated points a posteriori. The high level, difficult-to-make, decision appears with the rough results in hand instead of during the modelling phase required to build a black-box optimizer. Modelling every single actual objective of the problem alone is likely to be an easier task.

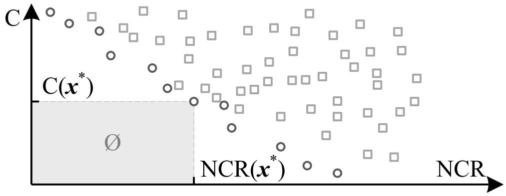


Fig. 2. Non-dominated assembly process plans (circles) among a population (squares) considering the simultaneous minimization of the non-conformity rate and the minimization of the delivery cost

2.2 Parametric Assembly Plan

Generalities. Running the optimization problem presented in (1) requires to convert the assembly process plan description known in technical terms into a mathematical vector $\boldsymbol{x}$ called *assembly plan vector* in the paper.

A product is a set of components linked together through joints during the assembly process. Each component is subject to geometrical variations bounded by geometrical tolerances. Each joint is made using an assembly technique. The requirement on the assembly plan vector $\boldsymbol{x}$ can be deduced out of those three assertions. It must include elements representing the technique selected for each joint of the product and elements representing the components geometrical deviations.

Assembly Techniques. Considering a product with N_{j} joints, the N_{j} first elements of $\boldsymbol{x}$ are dedicated to describe which assembly technique is associated to each of the N_{j} joints. Assembly techniques are stored and indexed in a library with several attributes: index, associated list of assembly operations, list of costing information, geometrical capabilities, etc.

The technique assigned to the joint j is the one the index of which equals the value of the jth element of $\boldsymbol{x}$, as pictured in Fig. 3.

The assembly process planner has to define the list of techniques suitable to make each joint of the product. Some additional constraints can be set among those N_{j} first elements: two joints can be forced to be made with the same technique for example. This reduces the set X of feasible assembly plans to the technically admissible ones.

Geometrical Variations and Geometrical Tolerances. Assuming that the probability distribution of each geometrical variation is known, allocating tolerances amounts to setting these distribution parameters, e.g. the lower bound and upper bound for a uniform probability distribution or the mean value and the standard deviation for a normal distribution. This is illustrated in Fig. 3. If the product's components have N_{gv} geometrical variations, and each of them has k distribution parameters, then the assembly plan vector $\boldsymbol{x}$ also has $N_{\mathrm{vp}} = \sum_{i=1}^{N_{\mathrm{gv}}} k_i$ elements to describe the geometrical tolerances allocated.

Intrinsic constraints exist among those N_{vp} elements, such as a lower bound smaller than an upper bound for instance. Extrinsic constraints can also be declared by the user to define other technical limits, such as the minimum size of a tolerance zone. This also reduces the set X of feasible assembly plans.

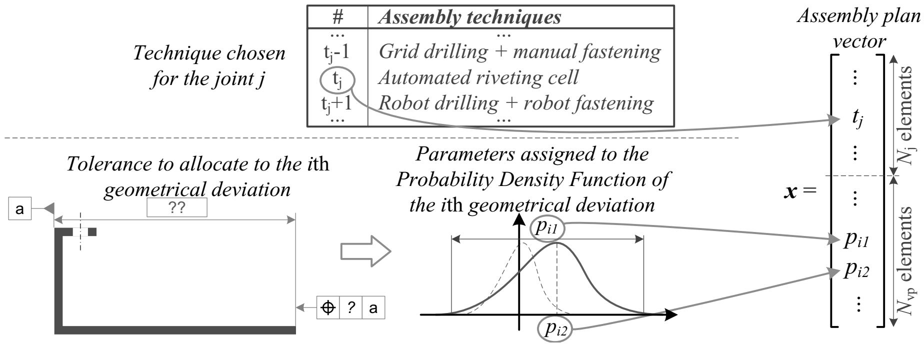


Fig. 3. Translation of an assembly process plan into a decision variable vector $\boldsymbol{x}$

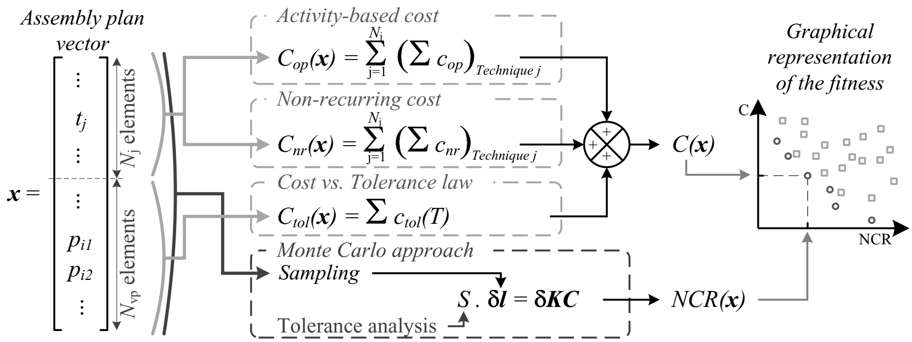


Fig. 4. Evaluation scheme and fitness representation of an assembly plan defined by its mathematical representation $\boldsymbol{x}$

2.3 Assembly Plan Evaluation

Non-conformity Rate. The conformity of a product can be assessed by verifying that some of its characteristics – called key characteristics (KC) in [7] – are kept within a requirement domain defined during the functional analysis. The Non-Conformity Rate of a product is defined as the probability for a product to have at least one of its KC outside of its requirement domain. In this work, only geometrical KC are considered. Tolerancing studies commonly provide a sensitivity matrix S to link the geometrical deviations $\boldsymbol{\delta l}$[4] to the KC deviations $\boldsymbol{\delta KC}$ as in (3) [12, 14, 13].

$$S \cdot \boldsymbol{\delta l} = \boldsymbol{\delta KC} \tag{3}$$

Samples of $\boldsymbol{\delta l}$ vectors can be associated to an assembly plan vector using both PDFs of the component geometrical variations and assembly technique capabilities. A Monte

[4] Gathering both geometrical deviations of the components and deviations due to the assembly techniques employed.

Carlo approach is finally used to associate the non-conformity rate $NCR(\boldsymbol{x})$ to the assembly plan described by $\boldsymbol{x}$.

Delivery Cost. The delivery cost can be split into two cost sources: the cost associated to the assembly operations and the cost resulting from the allocation of geometrical tolerances.

Each assembly technique is characterized by an interdependent list of assembly operations (an example is given in Table 3). Each operation has a fixed cost c_{f} representing consumables and unitary tool wear for example. It also uses several resources (of hourly rate hr_i) during a certain amount of time t_{op}. The elementary cost of an assembly operation is defined in (4):

$$c_{\mathrm{op}} = c_{\mathrm{f}} + t_{\mathrm{op}} \times \sum_i hr_i \tag{4}$$

The total activity-based cost C_{op} is the sum of the elementary cost of each operation, the list of which is derived from the list of selected assembly techniques given by $\boldsymbol{x}$.

The non-recurring cost per product C_{nr}, due to the acquisition cost of all the resources required for the assembly divided by the presumable amount of product to be assembled, is also included to the total delivery cost. As the list of the resources required to assemble the product depends on the assembly technique selection, C_{nr} is a function of $\boldsymbol{x}$.

The cost associated to a geometrical tolerance allocated is modelled by (5) (adapted from [15]). T is the size of the tolerance interval allocated, T_{lim}, a, b, m and k are function parameters identified according to experimental data.

$$c_{\mathrm{tol}}(T) = a + b \cdot \mathrm{e}^{-m(T-T_{\mathrm{lim}})} \cdot (T - T_{\mathrm{lim}})^{-k} \tag{5}$$

The total cost C_{tol} associated to the geometrical tolerances allocated to the product's components is the sum of all the elementary costs evaluated thanks to (5) according to the tolerances described by the vector $\boldsymbol{x}$.

Finally, the sum of C_{op}, C_{nr} and C_{tol} provides the delivery cost $C(\boldsymbol{x})$ associated to an assembly plan, as depicted in Fig. 4.

3 Use case

3.1 Product to Be Assembled

The method described in the previous section is applied to the assembly of a simple mechanical structure composed of four components (see Fig. 5). Three additional temporary components are also used during the assembly, as exposed in Fig. 6 in which the assembly sequence is also given (as the order in which the joints are made).

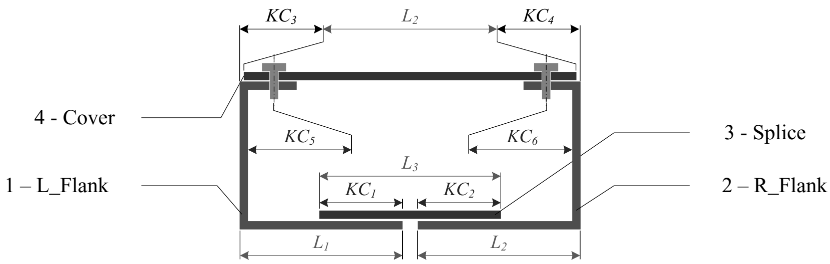
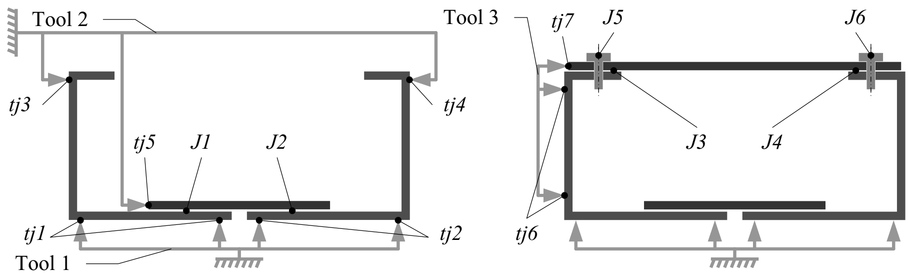


Fig. 5. Details of the product's key characteristics (KC_i), components and their characteristics considered as subject to geometrical variation (L_j)



Assembly sequence: *tj1*, *tj3*, *tj2*, *tj4*, *tj5*, *J1-J2*, *tj6*, *tj7*, *J3-J4*, *J5*, *J6*

Fig. 6. Temporary components used during assembly (referred to as *Tool k*), joints of the product and assembly sequence

Table 1. Parameters of the Cost vs. Tolerance law defined by (5)

	T_{lim} (mm)	a (cost unit)	b (cost unit / mm)	m (mm^{-1})	k
L_1 and L_2	0.01	0	200	1	1
L_3 and L_4	0.01	0	200	1	1

The geometrical variation propagation problem is reduced to a one-dimensional study with six key characteristics and four component's dimensions subject to geometrical variations. The capabilities of the technique selected for the joints *tj3* to *tj7* are also impacting the conformity rate as these joints are positioning joints involved in the KC values. Deviations on KC_1 and KC_2 must be kept within ± 0.6 mm. The value for KC_4 to KC_6 is ± 0.3 mm.

The parameters of the cost vs. tolerance law defined by (5) are given in Table 1. The sensitivity matrix S defined in (3) is not detailed in the paper.

3.2 Assembly Technique Library

The assembly technique library is not entirely described in this paper but the Table 2 presents the techniques considered. The Table 3 details the information stored in the

Table 2. List of the assembly techniques available associated to the joints they can be used for

Index	Name	Feasible joints
1	Positioning with tool	$tj3$ to $tj7$
2	Positioning with adjustable tool	$tj3$ to $tj7$
3	Positioning with a robot as tool	$tj3$ to $tj7$
4	Positioning with a specific automated station	$tj3$ to $tj7$
5	Back-to-back positioning	$tj1$ and $tj2$
6	Back-to-back positioning with splitting	$J3$ and $J5$
7	Traditional bonding	$J1$ and $J2$
8	Rapid bonding	$J1$ and $J2$
9	Drilling with grid and Manual fastening	$J4$ and $J6$
10	Drilling and Fastening with robot	$J4$ and $J6$
11	Drilling and Fastening with a specific station	$J4$ and $J6$

Table 3. Details of the technique *Positioning with a robot as tool*

Technique name:	Positioning with a robot as tool				
Operations	*Fixed cost*	*Duration*	*Resource(s)*	*Quantity(ies)*	*Capabilities*
Robot referencing	0	1	Robot	1	
Component Grabbing	0	0.5	Robot	1	
Component Positioning	0	0.5	Robot	1	$\mathcal{U}(-0.07, 0.07)$

Resource hourly rate: Robot, 0.7 cost unit / mn
Resource acquisition cost: Robot, c_{nr} *=50000 cost units*

library for the *Positioning with a robot as tool* technique. In addition to the feasibility constraints detailed in Table 2, the joints $tj3$ to $tj5$ must be done with the same technique. So do the joints $tj6$ and $tj7$.

4 Results

The optimization problem defined in (1) is solved using the Non-Sorting Genetic Algorithm II (implemented in the *Inspyred* Python library [16]) with a population composed of 200 individuals evolving during 20 generations. The sensitivity matrix S is obtained using the tolerance analysis software AnaTole [14] and the non-conformity rate is evaluated with a Monte Carlo method implemented in OpenTURNS [17].

The non-dominated points obtained are displayed in Fig. 7. The assembly process plan corresponding to the square point in Fig. 7 is detailed in Table 4.

The results illustrate the interest of a multi objective optimization. Considering a single objective for the fitness and the other one as constraint would give an arbitrary boundary between acceptable and non-acceptable solution, leading to an *optimal* point not necessarily better than other ones. Here, a decision-making team can adapt the final choice with more information in hand.

A deeper analysis of the results displayed in Fig. 7 shows that the points can be classified into four zones for this use case. In each zone, the assembly techniques selected are identical and only tolerances allocated are varying. It is therefore possible to

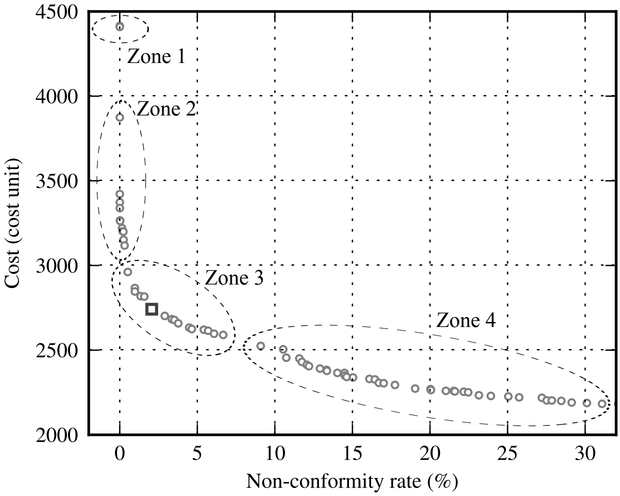


Fig. 7. Non-dominated points obtained after optimization, with four separate zones of iso-technique and varying allocated tolerances.

Table 4. Assembly process plan corresponding to the square point in Fig. 7

Joint	Assembly technique selected	Dimension	Allocated tolerance
$tj1$ and $tj2$	Back-to-back positioning	L_1	$\mathcal{U}(-0.40, 0.30)$
$tj3$ to $tj7$	Positioning with robot as a tool	L_2	$\mathcal{U}(-0.40, 0.30)$
$J1$ and $J2$	Traditional bonding	L_3	$\mathcal{U}(-0.22, 0.21)$
$J3$ and $J5$	Back-to-back positioning with splitting	L_4	$\mathcal{U}(-0.17, 0.16)$
$J4$ and $J6$	Drilling with grid and Manual Fastening		

identify the most relevant set of assembly techniques early during the design of the product and to refine the tolerance allocation along its design process.

5 Conclusion

Selecting assembly techniques and allocating geometrical tolerances for a product requires making quality vs. cost trades-off. The method proposed in this paper helps the assembly process planner to find a set of *good*[5] solutions among which he can select the one that suits the best his interests.

The method is based on an assembly technique library in which the company know-how can be stored and upon a geometrical variation propagation relation associated to the assembly sequence. A wide range of potential assembly process plans can therefore be investigated and evaluated from an objective point of view. Results can be obtained with various assembly sequence scenarios and even with various product architecture scenarios. Decisions about the product's design and its assembly process plan can be taken from a point of view shared by product designers and manufacturers, enhancing collaborative and concurrent engineering.

[5] The non-dominated points, from the mathematical point of view.

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Automated DHM Modeling for Integrated Alpha-Numeric and Geometric Assembly Planning

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Abstract. Digital Human Model (DHM) simulations are established as alternative to prototype based assembly verification. Prohibitive modeling effort constrains its application to selected tasks. In this work, a novel methodology is introduced to automatically generate DHM assembly simulations from textually planned assembly processes. The methodology is based on the software ema, which employs a human movement database mapped to building blocks. The methodology is evaluated using a model for a car interior pre-assembly station at Daimler AG. It is compared to state of the art process verification with prototypes, classical DHM modeling and manual application of ema. Most of the processes can be identified and half of them are realistically modeled. The presented methodology is a promising approach towards automating DHM modeling for process verification. Such a feature could help integrating today's alpha-numerical process planning to 3D geometric planning because no CAD expertise is required.

Keywords: Assembly planning, digital human model simulation, controlled natural language.

1 Trends in Automotive Assembly Planning

Automotive assembly systems need to adjust to a continuously changing market. Trying to keep up with market demands, automotive OEMs are offering an increasing number of customized vehicles and model variants. The main challenges faced by modern automotive assembly systems are faster and more secure ramp-up processes, which can manage shorter production planning cycles and increasing product variety, as well as the need to include new variants into existing production lines [1].

The availability of accurate digital models and simulation tools has significantly reduced development time and costs by being able to identify and correct problems before any physical prototypes are built. For assembly planning digital buildability check is a well established process, in which digital models of the vehicle's parts are checked for geometric consistency, thus guaranteeing that all parts can be assembled before any prototype parts are manufactured [2]. Geometrical process simulation is mostly used by experts, who address critical issues, because of high modeling effort. Automation has been addressed by e.g. [3] [4].

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The use of computer aided planning systems and the increasing standardization of processes has opened the possibility of documenting production planning from the early stages of product development. In this way, it is possible to have a preliminary assembly plan that is based on a standard process plan at the beginning of assembly planning. In this assembly plan information and performance indicators are initially documented with default values. Once sufficient product and process information is available, these preliminary values are replaced by actual ones. As product development progresses and assembly planning is refined, these indicators start to give a more realistic view of the planned production processes.

2 Concurrent Assembly Planning in Automotive Industry

In order to address high product variety and shorter product development times, techniques like concurrent engineering are employed to achieve early integration of product and process planning [5]. Concurrent engineering, which is common practice in today's automotive development, has led to shorter development times, allowing early problem identification and reducing correction costs [6]. However, in early planning there are uncertainties about product details that complicate communication between development process parties (Figure 1). Considerable research has been conducted in modeling these uncertainties such as Derichs' fuzzy database approach [7].

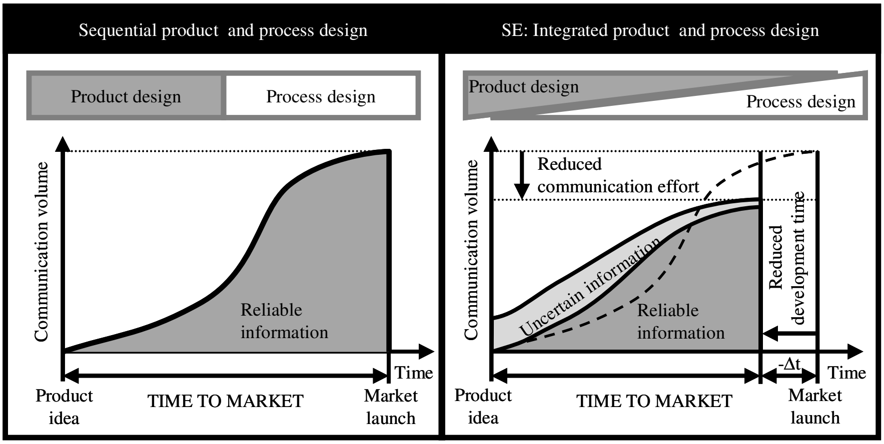

Fig. 1. Information reliability in Simultaneous Engineering (translated from [7])

In practical assembly planning environments, simpler approaches can be found. One is to differentiate levels of detail in each process step and plan as far as possible, i.e. fill out the data fields that are known at the moment, and document possible uncertainties as free text (c. [8]). This common approach has drawbacks. Management normally tries to shorten development times urging planners to fill in uncertain solutions. Uncertainties are documented in an individual text form that cannot automatically be analyzed. Since aggregation is time consuming, uncertainty information stays hidden. Thus, planning documentation tends to give a too optimistic view of the planning progress. In these individual planning and notification texts, uncertainty is mostly described using vague terms. Since there is no vagueness measure, getting an overview of planning progress is time consuming. Additionally, there is no link between a vague term in a textual description and geometric parts that are linked to this description. Thus, tracking if process descriptions are up to date after product design changes is a challenging task.

3 Manual Assembly Process Verification

Prototype building serves as an opportunity to evaluate, verify and optimize production planning [2]. The assembly planning team conducts several prototype builds before the start of production. During these prototype builds, the planner reads the planned processes out loud, and a worker interprets and follows the instructions, while experts from different fields perform different evaluations and verifications. The goal of these builds is to achieve an optimal production process preparation through which efficient, ergonomically optimal, stable and robust processes are defined, product quality is guaranteed, and production ramp-up can be completed faster.

As product variety increases, it becomes more difficult and costly to build physical prototypes of all variants. Reducing prototypes reduces the number of manual assembly process verifications that can be done using prototypes. An established method to address non prototype based manual assembly process verification is the use of digital human model (DHM) tools that are available inside PLM systems, such as Dassault's Delmia. These tools are widely used in automotive industry to simulate manual assembly processes [9]. Unfortunately, these are complex tools, that to be correctly applied require CAD expertise, as well as knowledge of process and product [10].

In practice, mostly static analyses of critical assembly situations are addressed in this way. This is due to time consuming modeling, inflexibility to changes on process and product, and to often occurring unnatural movements of the DHM if dynamic processes are modeled. Typically, key frames, i.e. static postures, are defined and the DHM interpolates between every pair of key frames to generate the so called in betweens depicting the movement of the DHM. Modeling a simple task, e.g. walking to a rack and grabbing a part form a bin, requires to define various key frames, i.e. defining the position of every single joint of the DHM, and any possible interaction with other objects in the scene. If simple changes on the scene occur, e.g. a new position of the rack and a new version of the part, new modeling of the whole process is usually required. Even after carefully modeling the key frames, unnatural behavior of the DHM's movements could arise, e.g. the arms will go through the rack. So as to avoid this issue, usually more key frames need to be defined, thus increasing modeling time.

Alternatives, like imk automotive's ema, address the time consuming and inflexible approach of classical DHM tools by allowing a more abstract modeling of the DHM movements and its interactions. This approach is based on the decomposition of tasks into basic operations and the use of parameterized movement generation. The underlying movements appear more natural due to the fact that these were synthesized by recording and analyzing the movements of real workers executing diverse manual tasks [3]. A DHM simulation with ema is built by dragging and dropping basic operation building blocks onto a time line depicting the process. ema is able to generate DHM key frames that depict the intended action and task. This generation depends on building blocks, parts, location and specific movement information such as the worker model being restricted in moving its upper torso. Thus, it is possible to redefine the position of the rack and the version of the assembly part, and the new required postures of the DHM to reach the part are automatically generated based on the current part information with much less effort than with the traditional approach.

In the following section, a novel DHM assembly simulation methodology is introduced. This methodology directly links the textually planned assembly process with the ema activity building blocks approach just presented above. It is shown, how DHM assembly process simulations could be generated, without a user needing to read, interpret and model the process, thus being faster than in the traditional DHM and the ema approaches.

4 Methodology for Automatically Generating Digital Human Model Simulations from Alpha-Numerical Process Plans

4.1 Controlled Natural Language for Assembly Planning

Since the proposed concepts of systematically storing information about abstraction have not found adoption, a method that is based on a controlled natural language (CNL) has been implemented, the method employs the language that practitioners use today. The CNL is focused on staying as close as possible to today's planning texts. An analysis of 1824 textual process descriptions yielded a basic understanding of how such texts are structured. From these texts, a set of semantic roles has been derived:

- ACTIVITY Main process activity
- THEME Part that is manipulated
- GOAL Part that the THEME is joint to
- SOURCE Part that the THEME is separated from
- FASTENER Part that secures a fastening
- TOOL Part that is used to conduct the ACTIVITY
- INSPECTION Objective of an inspection ACTIVITY

The grammar of the CNL was kept as simple as possible. It consists of one fixed role sequence per activity. The text style closely resembles the style of the process descriptions, which are clearly made to be understandable by experts. The comparatively simple grammar allows simple parsing, so that a parser for the CNL was built and tried out on the process descriptions. At this stage, only 321 process descriptions could be parsed correctly so that no automatic transition to the CNL was considered realistic. In order to reduce migration of legacy process descriptions, an input mask for easy validation of planning input has been developed. In close collaboration with planners, role contents have been optimized. This has led to a CNL that is able to cover between 70% and 90% of the process descriptions depending on the planning domain. This CNL represents the basis of the proposed methodology. In all its roles, several levels of abstraction are available and can be automatically analyzed. In the case of activities, each of the 104 activity terms is mapped onto the respective production task category from DIN 8580ff. [10]. These categories have different levels of abstraction, for example "joining" is considered more abstract than "assembling" (in German *Zusammensetzen*). This mapping allows tracking of each process description's abstraction level.

4.2 Mapping Approach

The methodology of automatically deriving DHM models from textual process descriptions starts with mapping the semantic activity roles of the CNL to basic operation building blocks. Usually, the semantic roles are more abstract than basic operation building block parameters. Therefore, concretization is necessary. Since there are normally several concrete ways of realizing an abstract process description, the objective is to derive a concretization that is plausible for both planners and workers. Parts have to be mapped from their abstract representations, (e. g. "Outside mirror, left") to their names in the CAD tree (e.g. "MIRROR OTR LHD LH ASPH TWA STV 360-DEGREE-VIEW"). First, a set of possible CAD objects is retrieved from the bill of material. This list is filtered using the car variant that is employed for simulation and the process-product mapping from the product process resource tree of the digital planning software. All remaining parts are displayed in a 3D-model so that the correct node of the CAD tree can be selected. Geometric locations are given in abstract ways in the semantic roles. They can incorporate prepositions such as "above" another part, or comprise hints such as cable colors. These descriptions are meant to be understood by a worker who carries out the planned assembly process. Therefore, parts are virtually moved in the scene until the state of the respective process step is reached. Candidates for locations that are relative to parts are derived by projecting the bounding box of the basis part into the given direction and selecting a point on the near side of all parts that collide with the projection. If a color attribute is given, the visibility from the worker position is taken to generate points in the middle of the visible colored area. For movement information, reachability issues are predominant, i.e. it has to be determined whether or not the worker is able to easily grasp an object. Therefore, the DHM simulation is put into the loop. Given that all prior process steps are successfully planned, a series of parameter sets that describes process and ergonomic attributes is provided. Simulation is done for each parameter set until successful. If no simulation is successful, no DHM simulation model is generated.

5 Evaluation

5.1 Scenario

In order to evaluate effectiveness and quality of the presented methodology, a pre-assembly station in automotive end assembly has been modeled for process verification. In the scenario, a center console is taken from a rack and positioned in a fixture.

An antenna is contacted and assembled as well as a cup holder, two cover panels, a control module and a telephone keypad. The process is planned in 11 process tasks. The station consists of a roller conveyor, two racks and a work place with a special fixture. Only hand tools are employed. It does not require any special movements such as kneeling, which should facilitate automatic process creation. Four different models of the station process have been modeled independently for comparison:

- A physical prototype in which a worker assembles prototype parts and process validation experts watch. This represents today's established methodology.
- A digital model that has been created with existing functionality of the software package Delmia V5. This model follows the process that is used for ergonomics analysis of critical situations today.
- A digital model that has been created with the software ema using the proposed methodology of the vendor. This methodology promises reducing modeling time and improving process time predictions.
- A digital model that has been derived from the methodology presented in section 4.

5.2 Evaluation Methodology

For each model, process or simulation results have been reviewed by two experts. Criteria address core issues with integrating DHM into assembly validation: The processes that are validated have to be modeled in a realistic way and the process time that results from simulation should be similar to the time that an average worker in a series production would require. Therefore, two experts assessed each process step according to the following criteria:

- *Modeled tasks*. A task is marked as modeled if both experts have noticed the process step being conducted from watching the worker or the DHM, i.e. it can be marked as not modeled if there is not such a task in a simulated process.
- *Realistic process*. A task is marked as showing a realistic process if both experts consider that the process step is conducted similarly to the future process on the assembly line.
- *Realistic human motions*. A task is marked as showing realistic human motions if both experts consider that the movements of the worker or of the DHM are similar to the future worker movements on the assembly line.
- *Process time*. The process time is measured from the actual process time of the worker or in case of a simulation from the simulated time.

Results of quality measures have been aggregated on the task level. If a criterion is only met for part of a task then the result shows "partial" instead of "yes" or "no". In addition to quality criteria, the four models have been compared for modeling effort. For simulation models, modeling time has been derived from experienced users to reduce impact of the early learning curve. For the physical prototype, modeling time has not been assessed because much of this time was spent producing and acquiring prototype parts.

5.3 Results

The percentage of modeled tasks (see Figure 2) shows that the prototype based approach has deficiencies in depicting all processes. This limitation is mostly caused by missing parts or parts that cannot be assembled because of geometric deviations. Furthermore, the currently planned sequence could not be replicated because some parts had been outdated at the time of verification.

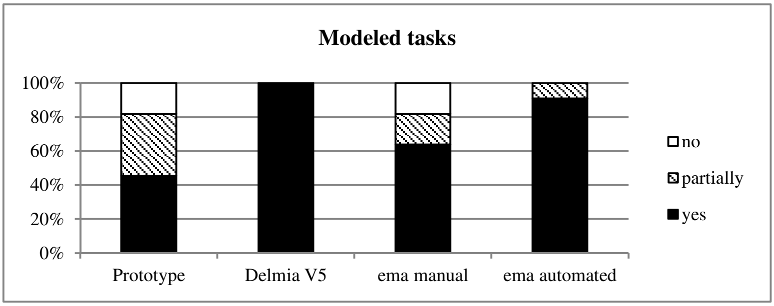

Fig. 2. Ratio of visibly modeled tasks for the four verification models

In the manually modeled Delmia V5 and the fully automated ema simulation, all tasks were visible. The 100% coverage of Delmia V5 resulted from manually adjusting each required joint angle, which means prohibitive effort for large and complex scenarios. Good coverage of the ema automated approach stems from a methodological inaccuracy, i.e. a movement artifact that is visible whenever a new task is conducted. This artifact makes the worker movement less realistic but strongly hints at some action being part of a new task. In the manually modeled ema simulation, only seven tasks could be clearly identified. The simulation does not show the artifact of the automated ema simulation.

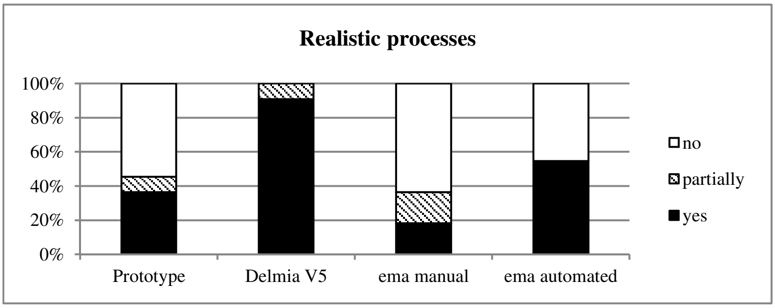

Fig. 3. Process realism for the four verification models

Regarding process realism (see Figure 3), 91% of the processes are evaluated as realistic in the manually created Delmia V5 model, 54% in the automatically generated ema simulation, 36% in the physical prototype approach, while only 18% of the processes follow the plan in the manually created ema simulation. Most process deviations of the worker with the physical prototype result from parts that are missing or difficult to assemble due to tolerance issues, as well as from assembly problems. Both ema models deviate considerably because fine motor skills are not mapped onto worker movements. Therefore, the respective processes may be identified as being present but are not evaluated as realistically following the planned tasks. The ratio of these tasks can be seen in the proposed automatic model generation with ema. If a process is modeled at all then it matches the plan.

Realism of human motions (see Figure 4) is, as expected, best for a real human conducting a task. In the prototype based approach, one process step could only be hinted at, which was evaluated as unrealistic. The Delmia V5 simulation shows almost similar movement realism, while half of the processes of the manually derived ema model include unrealistic human movements. In the proposed methodology, only 18% of the processes have been evaluated as depicting realistic human motions. Most processes deviate considerably from possible human movements due to collisions and overlapping of the DHM with other objects in the scene.

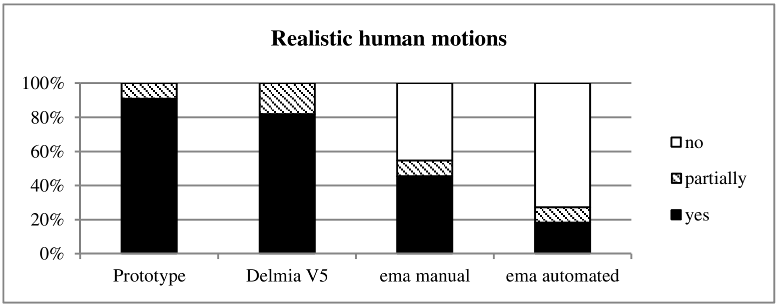

Fig. 4. Human motion realism for the four verification models

Table 1 summarizes differences between MTM expert estimates for process times and the predicted times of the considered approaches. Only the eight tasks modeled by all approaches are considered. Time measurement of the worker shows considerably longer times than the MTM (methods-time measurement) expert estimates. This result is not necessarily wrong because the MTM values refer to a mature process executed on the assembly line after ramp-up rather than prototype building. Considering the median of the process times, the manually generated ema model predicts 90% of the planned time. This may hint at optimization potential because even in processes that are completely modeled, process times are lower than planned. The considerable standard deviation of 0.87s results partly from process steps that were not modeled. Note that two processes are not taken into account for the manual ema model because they were not recognizable and therefore not included in the time assessment. The other models show processing times above the prototype processing times. The Delmia V5 model used Delmia's standard procedure without MTM based optimization. Therefore, considering time predictions, such analyses have to be conducted additionally. The proposed methodology yields the longest time predictions. Correlation of the planned times to the DHM simulated times rank as expected. However, the physical prototype is completely uncorrelated, which emphasizes the little resemblance of assembly time in prototype building to those in mass production. Therefore, none of the investigated simulation approaches should be considered a replacement of MTM analysis.

Table 1. Median and standard deviation for eight ratios of predicted time to MTM expert estimate, and correlation of predicted process times to MTM expert estimates

	Prototype	Delmia V5	ema manual	ema automated
Median [s]	1.25	1.64	0.83	1.72
Std. dev. [s]	1.09	1.37	0.91	0.87
Correlation	-0.02	0.65	0.66	0.55

DHM simulation modeling effort is differentiated into the categories data acquisition and process modeling. Data acquisition mostly consists of gathering CAD models of the respective car variants in their considered assembly state, CAD models of tools, handling equipment and building and process descriptions and their mapping to CAD objects. Data acquisition has been identical for all DHM simulations. For the simulated scenario, data acquisition amounted to 7.15 hours. For the proposed approach process modeling consists of 10.1 minutes of computer processing time on a standard office notebook. Manual modeling with ema took about 10.5 hours. This was mainly due to required tuning of the worker trajectories. The Delmia V5 expert needed 21 hours, because of manual optimization of human movement by explicit entry of worker joint angles. Modeling effort for the physical setup mostly consists of acquiring prototypes and prototype parts, which had been conducted by a range of departments making effort estimation difficult. However, overall cost and effort clearly exceeded those of digital modeling in the considered scenario.

6 Discussion and Outlook

The proposed methodology is a promising approach towards automating DHM modeling for process verification in early stages of assembly planning. Even though human movements are currently rated very unrealistic, a complete process has been automatically modeled. If needed, this process could be an initial point for further manual detailing of the DHM movements.

Shortcomings in movement realism could be overcome by replacing the bounding box based collision model with a more geometrically plausible one. Furthermore, temporary state changes in the 3D model that result from DHM actions should be modeled in an ontology. This ontology may be extended by implicit information that is given from the point of view of the DHM, e.g. a red cable that is mentioned is most probably the one that is at the time visible for the DHM. Such an approach also would allow plausibility checks, which would refine the forced process modeling that is currently done regardless of restrictions and uncertainties. In order to gain consistent motions in the presented approach artificial activities, e.g. turning in direction, have been introduced. These artificial activities should be included into ema's basic operation building blocks, which would increase realism at the cost of reduced visibility of the model tasks.

With sufficient modeling effort realistic human movements in DHM simulations can be achieved. However, modeling effort is prohibitive for systematically simulating the complete process with DHM simulations. The proposed methodology offers DHM modeling from planning texts without the need of CAD expertise. Such a feature could be a first step towards bridging the gap between today's alpha-numerical process planning and 3D geometric planning.

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3DExperiences – Dassault Systèmes Strategy to Support New Processes in Product Development and Early Customer Involvement

A Software Tool Editor's View to Challenge the Smart Product Engineering Revolution

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Abstract. In many industries the market sees a lot of change happening these days; new trends and challenges obviously need to be addressed as part of the product creation process.

Dassault Systèmes (3DS) is introducing a 3DEXPERIENCE PLATFORM to expand the usability of the digital smart product development in an accurate virtual universe beyond Product Lifecycle Management (PLM).

The target is to provide the ability to place the customer at the heart of a system, integrating both company business processes and product development processes. It is a combination of science, art and technology to bring value to our customers by helping them to respond to the needs of their customers and creating 'magnetic' products with strong market appeals.

3DExperiences can be a catalyst for innovation, enabling any enterprise stakeholder to participate in the innovation process, contributing to drive value for the end consumer and create smart products from design to recycling.

This presentation highlights some aspects of the new Dassault Systèmes strategy; shows some of the solution experiences and how customers respond to them. 3DS is a scientific company positioned among the top 10 software companies worldwide and for more than 30 years has been helping companies to transform the way they design and produce their products.

The conclusion is based on an explanation to leverage the virtual product with accuracy through the production of a Probabilistic Certificate of Correctness for complex cyber physical smart product definition.

Keywords: Smart Product, Simulation, Mechatronics, Multi Physics, 3DExperience, SIMULIA, Abaqus, DMU, Functional Mockup Interface, FMI.

1 Why Is Change Necessary?

It is a complex challenge to move from traditional engineering to Smart Product development. Forward-thinking executives are, quite rightly, demanding more and

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better consumer insight and smarter research to measure impacts of potential new innovations. Companies can gain an understanding of their customers which is better, faster, and less expensive by doing four things called the "digital research revolution":

1. Leverage the digital society power to rapidly create and deliver detailed information about what *would be products customer acceptance information*.
2. Recognize the limitations of the measurement systems based on projected past or isolated focus groups.
3. Seek to understand *what customers value the most* and how technologies and innovation can deliver and *enhance the product value*.
4. Link investigations into consumer insights based *on virtual product candidates* that are sorting value very close to their customer relationships management systems and create criteria such as "Cool Feature", "Must Have", etc.

Leverage the Power of the Digital Society

The *Internet is fast*. It enables any type of digital exchange and can leverage data in many forms plus has the ability to *create many more iterations* with a turnaround in a few days, rather than weeks required for traditional methods.

Marketing strategy segmentations for innovation that used to take months can be completed in weeks. *Working digitally is also less expensive than prototyping*/ face-to-face studies and can be conducted with dramatically larger sample sizes.

Finally, customers' online comments, search behavior, and other revelations offer a trove of data.

Decrease Reliance on Traditional Prototypes and Focus Groups

Focus groups were once the default qualitative research approach. Companies gathered *small numbers of consumers* in a facility around *real prototypes* for some hours, promised them a small payment or free products, and asked them to give simple written or oral answers to questions that may or may not have provided real insight. Despite the emergence of better alternatives, little has changed yet.

Full usage of *Virtual Product candidates* now enables leading marketers to create deep immersion experiences with a *large number* of users organized through communities to generate consumer insights and new products; consider values and positioning; and redefine a product's competitive set. These ideas can then be tested quantitatively, either through further research or a market pilot.

Understand How Successful Products are Created

Companies have long focused on what and why people buy. Research data from consulting companies like Oliver Wyman show that this is not sufficient. They clearly show that only few high-quality products are magnetic[1], defining "magnetic" by a simple equation: $M = F \times E$. Magnetic equals best functionality times most powerful emotional connection with customers. Very good functionality is obviously not enough anymore.

Connect What You Know about Consumer Value

Why do consumers disproportionately demand one product over a seemingly similar one, often by a factor of four or five to one? Functionally and technically, products might be close; emotionally, they can be worlds apart. Why do seemingly similar products produce radically different demand curves?

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[1] Magnetic = having a great power of attraction over people.

Demand creators, people who design products that truly excite consumers, are obsessed with understanding customer values, and connecting the dots from multiple value chains to fix it. They don't assume that buying = wanting. They use the value map to recognize the huge gaps between what people buy and what they really value including emotionally — and use those value map as a springboard to see differently. Demand creators crack the mystery of the demand equation by doing a radically better job answering a small set of critical value and differentiation questions very well.

2 The Concept of 3DExperiences by Dassault Systèmes

How can a Software tool vendor support demand creators?

3DS has initialized a large change to apply the power of the Digital Society to help product creators with the new challenges described above: Introduce the ability to create Smart Products from an unified digital representation that are all interacting together to create a "Virtual" Smart Product.

To reach customers but also to ensure that fast development cycles based on value of a product that can actually be produced can be achieved digitally, a "Virtual" Smart Product needs to be digitally accurate. This product accuracy is not sufficient to help creators if it is not also possible to benefit from similar accuracy in the digital modeling of the environment in which the products will be used.

And of course measuring value and making product creators able to deliver the *magnetic* products described above means that ability to interface with large communities and finally partners including suppliers, channels and consumers are requesting *interacting socially* in fast and efficient digital loops.

3DS has started to create a Product Creator Digital Platform that has the ambition to complete the digital landscape compared to other platform technologies

- Facebook as a social platform
- Google as a search platform
- Wikipedia as a knowledge platform
- App stores as a services and applications platform
- Android as a development platform
- YouTube, iTunes and others as a content platform

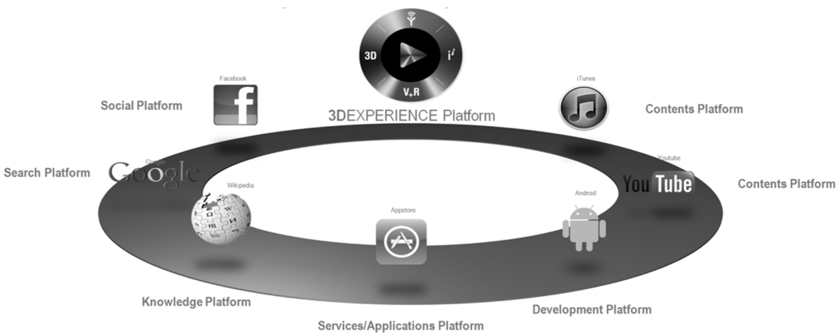

Fig. 1. 3DExperience Platform compared to other platform technologies

This *Product Creator Digital Platform* is named *3DExperience platform* and is designed to socially link the large communities of contributors in product developments required to create Smart Products.

The integration is done around real accurate *Digital Virtual Smart Products* that are leveraging the 3DS 20 + years of experience in creating accurate engineering around 3D based digital engineering.

The target is to provide the same accuracy that was obtained on geometry to the other engineering domains. The target is *not to provide game platforms* but to enable the *magnetic product creation* to be done socially based on the real physics and manufacturability of the products - this can be seen as a natural extension to the Product Lifecycle Management market (PLM).

The representation of this strategy is indicated by a user interface to access the software and data platform in the form of a compass as a synonym for a highly integrated application environment and a platform concept.

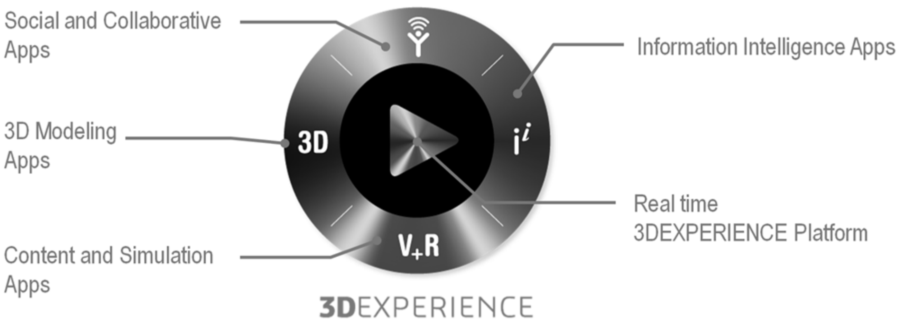

Fig. 2. 3DExperience Platform Compass

3 User Experience by Industries

The 3DS new *3DExperience platform* is to be delivered for 12 industries – that produce Smart Products including the more traditional customers of the company such as Automotive, Aerospace and Industrial Equipment to new customers such as high volume Consumer Packaged Goods, Retail, Energy, Process and Utilities, Financial and Business Services, Life Science and more.

Fig. 3. Dassault Systèmes supports 12 Industries

3.1 PLM Innovation by Engineered Business Experience

Overall the changes, whether it is the market, the consumer buying behavior, new products, changed mobility etc. have a significant impact on the way engineering will work in the future.

From	**Discipline Collaboration**	to	**Social Industry World**
From	**Product**	to	**Business Modeling**
From	**Document Management**	to	**Experience Management**
From	**Search**	to	**Dashboard Intelligence**
From	**Product attributes**	to	**Consumer Experience**

Fig. 4. PLM Innovation

4 Examples of Industry Solution Experience

4.1 Transportation & Mobility (T&M[2]) Solution Experience[3]

As part of the transformation process toward integrated Smart Product delivery the *new 3DExperience platform* is addressing 5 major areas in the T&M domain:

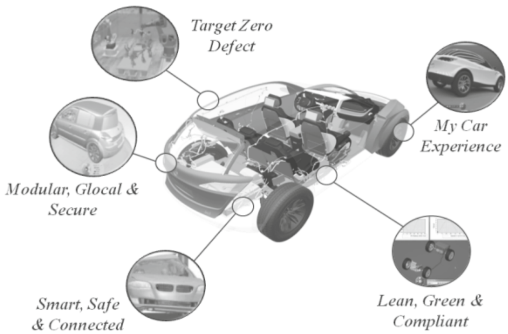

Fig. 5. Transportation and Mobility Industry Solution Experience

My Car Experience
The purpose of this experience is to understand how the customers are expecting the next generation of the mobility services by providing some innovative ways to collect their needs and identify the market trends, to enable crowd-sourcing and co-creation around new concepts and social innovative design. Powerful 3D design tools to boost the industrial innovation process and efficient tools to perform virtual car clinics and showroom, with augmented reality and immersive reality, will be introduced.

A virtual in-car feeling by enabling new in-car experience, including driving experience will lead to new design and engineering front loading experience, thus reducing the time to market and reducing physical prototypes.

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[2] T&M includes automotive, truck, motorcycle, motorsport and transportation industry segments.

[3] Information about other Solution Experiences from other Industries can be obtained from `www.3ds.com`.

Lean, Green and Compliant

The purpose of this experience is to improve vehicle energy efficiency upfront with light weight and green propulsion and to explore new ways of progress by optimizing the energy balance and the weight. Providing an end-to-end solution for EV and HEV propulsion concepts development accompany companies in their will to be more environmentally responsible. An integrated platform for vehicle validation and certification to define, manage and monitor the validation and verification process (physical and virtual test) insures requirements validation. The compliance towards global regulations and certifications (material compliance, FMVSS, CAVA, passive safety, etc.) help to optimize the vehicle performance globally and by providing a multi-physics simulation platform to evaluate and optimize all the performance of the vehicle, increased product quality and satisfying sustainability results can be harvested.

Smart, Safe and Connected

The market today is challenged by a re-invention of the mobility experience as 80% of vehicle innovations are coming from embedded systems and development moves from vehicle attributes to vehicle experience. A huge complexity in the number of ECUs, lines of code of software and an increasing number of functional requirements makes car design error prone, resulting in 20 to 40% of vehicle development cost spent in testing and diagnostics. The market demands to improve quality and safety and decreasing the number of warranty cost and cars recalls. To demonstrate functional safety against class actions lawsuits and to standardize on industry initiatives such as Software re-use (AUTOSAR), Strengthen safety (ISO26262) and early validation are mandatory to support next generation car developments. The concept of *Functional Mock up* that integrates *mechanical, electronics, software and simulation*, is key to design and simulate the car of the Future: *smarter, safer and always connected***.**

Modular, Glocal[4] and Secure

This experience allows defining the technical requirements from a marketing analysis and ideation process done on unstructured data, to define the vehicle portfolio and monitor the program: project dashboards, program 360° and quality plans (incl. suppliers). Platforms and modules, interfaces as well as the vehicle architecture (volumes, technological choices, etc.) are managed along the defined configurations. The management of the EBOM is based on a modular approach and support the Digital Mock-up review processes (Design, Manufacturing and Simulation) in a distributed environment (Suppliers, R&D centers,). The MBOM manages the assembly processes per manufacturing plant and the supply chain, from engineering to after sales, including sourcing, RFQ/Supplier choice process, and the contract and cost management, etc. are integrated as well.

Target Zero Defect

To ensure a zero defect process End-to-End on all the domains, extend the zero geometry defect to the End-to-End, and taking full benefit of new system engineering and collaboration environments is the purpose of this experience.

[4] Glocal = Global and local.

Capitalizing and reusing knowledge globally for design, manufacturing and simulation will promote innovative tools and methodologies in Architecture and Conceptual phases of the processes. Augmented simulation contribution and key differentiators in all steps of the processes will improve productivity and efficiency to reduce cycles by providing Best-of-Class solutions.

5 Complexity of Delivery with Accuracy

Most product transformations towards Smart Products have been done in complexity stages from integration of independent mechatronic systems and intelligent sensors/actuators and interfaces to the current Cyber Physical Systems.

Delivering accurate Cyber Physical Systems in Smart Products requires a tight coupling of computational and physical elements, and therefore the behavior of geometry (deformations, kinematics), physics and controls need to be certified over a very high dimensional space.

Because of the infinite number of potential failure modes of these systems, 3DS has developed new concepts for the systems integration.

The **System Probabilistic Certificate of Correctness (PCC)** quantifies the probability of satisfying requirements with consistent statistical confidence in integration between system components inside a Smart Product. This metric is based on the notion that the fidelity, applicability, tolerances and accuracy of simulation models along with the predicted results are equally important for verification and validation of all the dimension of the product. To compute PCC at every stage of the product lifecycle a large set of technologies has to be deployed, namely virtual prototyping, simulation tolerancing, tiered abstraction modeling and automated simulation frameworks that are available inside the *3DExperience platform.*

PCC can be implemented as a scalable engineering practice for certifying complex system behavior at every milestone in the product lifecycle and provides real improvement over the V-cycle, because verification and validation happens at every stage of the system engineering process thus reducing rework in the more expensive implementation and physical certification phase.

Today's complex systems have to meet hundreds of top level product acceptance requirements which in turn reference numerous standards and sub requirements.

Validation is the process of establishing evidence that the product meets the customer's requirements. A large variety of techniques are used today to certify cyber physical system requirements. Examples are reachability and fault tree analysis, Monte Carlo simulation, virtual prototyping as well as quality assurance processes used in software development based on mean time between failure, defect density and other metrics.

In leveraging the 3DExperience Platform a combination of these concepts for the certification of top level probabilistic requirements is being deployed.

This is done at virtual product certification level rather than physical product certification with the understanding that both are essential parts of the certification process. Especially in the early stages of design, physical prototypes most likely will not be available and the end user will have to rely heavily on simulated behavior. Later in the life cycle, but before product launch relying on simulated behavior is essential because it is not feasible to carry out physical experiments.

Hardware in the loop experiments often involves a physical (electronic) controller and the simulated behavior. The configuration and/or mission of the product may change and it becomes interesting to know if the product can be certified for a new mission. At that point measured operational data for the product which can be used to improve the fidelity of the virtual prototypes is made available.

5.1 Simulation Tolerancing

The process to define system tolerances is called tolerancing.

Tolerances are widely used in engineering to indicate the limits in geometric dimensions, physical properties, and measured values. Tolerances are a powerful concept in terms of contractual agreements as well. Warranties can be issued that certain tolerances are met. Tighter component tolerances are marketed as higher quality products which command a higher price.

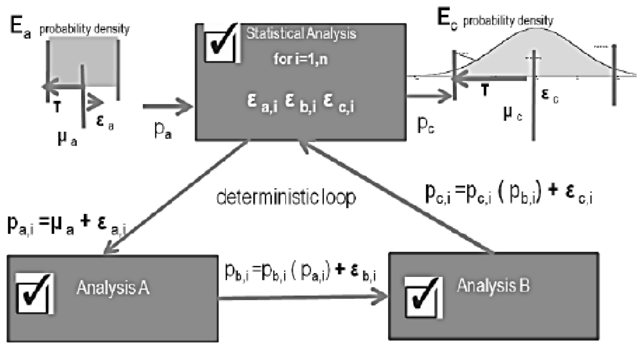

Fig. 6. Confidence Interval

Today there is no accepted practice to deploy tolerances for virtual prototype simulated behavior. Unfortunately, the effect of simulation accuracy on the computed stochastic results is very large and requires the system wide implementation of the use of tolerances for each computed behavior of the virtual prototype. For this to be a scalable and easy to adopt solution, parameter tolerances (both input and output) would have to be implemented as parameter attributes in a PLM implementation and shared between applications. Conservatively it's allowed to assume a uniform maximum entropy probability distribution.

The confidence interval is determined through a quality assurance process of verification of similar models with the same assumptions and the same solver settings.

5.2 Tiered Abstraction Modeling

Tiered abstractions are a key enabler to efficient PCC calculations.

Multi- tier abstraction process can speed up the engineering design process by a factor of five Tiered abstraction modeling processes.

In the functional Tier 1 the focus is on fast modeling of the product behavior as it pertains directly to the customer requirements.

Trading off customer PCC requirements as well as cost and model tolerances to determine the critical behavior models is required. Critical behavior models are those models for which the PCC relevant behavior most efficiently can be influenced by increasing their fidelity. For the critical behavior models high fidelity abstractions based on high fidelity (CAE) virtual prototypes need to be authored. These models are then used as replacements for (initial) critical behavior models in the functional tradeoff. This process is repeated until the product is verified and validated for a given design milestone. This eliminates costly rework as compared to late stage V-cycle.

5.3 Results

Virtual prototypes are mainly used as a replacement of physical prototypes in the V-cycle system engineering process.

3DS targets with 3DExperience platform can show an improvement over the traditional V-cycle because verification and validation happens at every process stage from concept to manufacturing using multi fidelity virtual prototypes. This approach identifies problems early and reduces rework in the more expensive implementation and physical customer or certification phase.

In practice the ability to integrate in a single platform all the requested tools to create a scalable engineering practice for studying complex system behavior can for example enable creation of accurate probabilistic certificate of correctness at every milestone in the product lifecycle by

- Capturing methods by process flow automation
- Making upfront capture of certification methods and implementation of simulation workflows to automate the product design process, thereby enabling rapid loops until the proper results are obtained including in case of user / value change.
- Creating virtual prototypes at different fidelity and abstraction levels
- Enabling efficient simulation and integrating these models into a simulation process flow. Hierarchically nested approximations dramatically reduce simulation process flow execution times while maintaining acceptable model accuracy.
- Verifying requirements in parallel by deploying virtual prototypes across large organizations.
- Scalability by reducing cycle time proportional to additional computational resources.
- Trading off in real time system sizing, modeling accuracy, technology selection and manufacturing tolerances against requirements and costs. This tradeoff process detects (human) modeling errors because of the need to explain the computed trade-offs.

6 Summary

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Data Fusion and 3D Geometric Modeling from Multi-scale Sensors

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Abstract. The past several decades have seen major advances in sensor technologies, including surface scanning at multi-scales. While state-of-the-art research focuses on methods for integrating diverse scanned data into a single geometric model for inspection analysis, these methods still cannot handle multi-scale data. This paper proposes a new approach for data fusion from multi-scale sensors by defining two generic frameworks for data fusion: Single-Level Multi-Sensor (SLMS) for multi-scale data merged on one level and Hierarchical Multi-Sensor (HMS) for hierarchically merged multi-scale data. These frameworks are based on state-of-the-art generic frameworks and use the properties of multi-scale sensors properties. The feasibility of the proposed approach is demonstrated on 2.5D surfaces scanned by CMM touch probes and laser scanners and on 3D multi-scale synthetic data from CAD models.

Keywords: data fusion, multi-sensors, multi-scale, inspection analysis.

1 Introduction

3D inspection analysis has progressed significantly as advanced sensors have evolved from single sensors into multi-sensors [1-3]. Multi-sensors have several advantages: (a) Different inspection technologies can be used; (b) The number and type of sensors are not limited; (c) Diverse data can be added adaptively; and (d) Multi-scale data can be merged into a single multi-scale model. Sensors are classified as contact and non-contact types [3-5] based on the interaction between sensor and inspected part. A typical multi-sensor configuration includes both contact sensors (e.g. touch probes) and non-contact sensors (e.g., video cameras, laser scanners and micro-probes). The multi-sensor head of the Nikon scanning system [6] is depicted in Figure 1.

Contact and non-contact sensors each have their own working principles and properties, simultaneously providing diverse and complementary data that can considerably improve inspection. Contact sensors provide sparse and very accurate high resolution (HR) data, while non-contact sensors provide dense and less accurate low resolution (LR) data. Due to their differing accuracies, these two data sets can be regarded as multi-scale data. The main challenge lies in how to utilize the LR data despite its lower accuracy.

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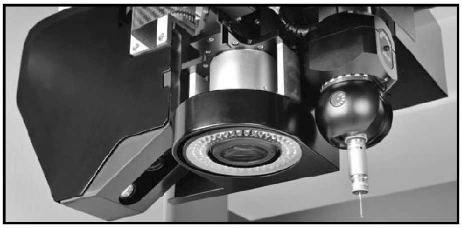


Fig. 1. Multi-sensor head [6] with a laser scanner (left) and a touch probe (right)

Customers continue to demand smaller, faster, cheaper, easier and more precise metric solutions. Multi-sensors can meet these demands more effectively than can multiple single-sensors [6-8].

In the literature, data fusion methods for multi-sensors are characterized by the following parameters [2-3]: (a) data flow: centralized, decentralized, and hierarchical; (b) arrangement: serial, parallel, and combined; (c) configuration: competitive (redundant), complementary, and cooperative; and (d) feedback: without feedback, with feedback only after the final stage, and with feedback after every stage. One of the historical barriers to technology transfer in data fusion has been the lack of uniform terminology that crosses application-specific boundaries.

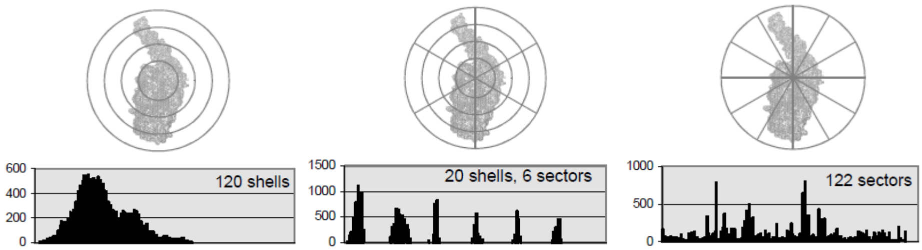
Surface features can be classified into two groups: Regions of Interest (ROIs) and Points of Interest (POIs). A ROI is a region on a model that includes important features, such as edges, corners and holes. A POI is a point that belongs to the ROI and is a part of some feature. POIs are thought to be more unique than ROIs and to carry sufficient information, while being less complex to use and store. In addition, POIs belong to ROIs and can be useful for matching and merging between sampled data. According to [2-3], fusion between geometrical data comprises the following steps: (a) alignment of coordinate systems/references (not within the scope of this paper); (b) feature detection on the data sets; (c) matching data sets; and (d) merging and reconstructing the fused model.

Feature detection: Most feature detection methods are based on curvature analysis [5], [9], [10]. Sipiran and Bustos [11] recently proposed an extension of the Harris Detector [12] for 3D meshes based on calculating local neighborhoods, fitting quadratic surfaces and selecting POIs.

Matching data sets: Feature detection methods usually provide a descriptor of the detected feature that can be compared with descriptors of other features. Shape histograms [13] are descriptors that can be used for matching. First, shells (Figure 2a), spherical sectors (Figure 2c) and their combination (Figure 2b) are constructed around the feature center of mass. Next, histograms are calculated of the surface area distribution, enclosed into shells, sectors and their combination (Figure 2). Finally, a quadratic distance function is used to compare the histograms. This descriptor can be used for POIs [14].

This paper uses an approach combining curvature analysis and geometric descriptors, provided by the multi-scale shape descriptors-based method [9].

Merging and reconstructing the fused model: Since data processing methods [9], [15-16] are usually applied on meshes, a mesh should be reconstructed from the scanned points. The data can be merged into a single model using strategies such as (a) merging all data sets into one cloud of points, (b) stitching different data sets, and (c) correction of one data set according to another. This paper uses a variation of shape histograms in which similarity is calculated according to the physical properties of the data acquisition and then applied on meshes that were reconstructed by the Power Crust method [17].



(a) (b) (c)

Fig. 2. Shape histograms [13]

Framework models can provide data fusion methods with a theoretical base. Among such models in the literature are (a) the JDL data fusion process model [1], (b) the Thomopoulos model [18]; (c) the multi-sensor integration fusion model [19]; (d) the behavioral knowledge-based data fusion model [20]; and (e) the waterfall model [21]. Table 1 compares these models according to data flow, sensor arrangement, sensor configuration and feedback integration. According to the table, the

Table 1. Comparison of models

Model	Data flow	Sensor arrangement	Sensor configuration	Feedback integration
JDL Data Fusion Process Model	Centralized / Decentralized / Hierarchical	Serial / Parallel / Combined	Competitive / Complementary / Cooperative	After every step
Thomopoulos model	Centralized / Decentralized / Hierarchical	Serial / Parallel / Combined	Competitive / Complementary / Cooperative	After every step
Multi-sensor integration fusion model	Hierarchical	Serial / Combined	Complementary / Cooperative	After every step
Behavioral knowledge-based data fusion model	Centralized	Parallel	Competitive / Complementary / Cooperative	-
Waterfall model	Centralized	Serial / Parallel / Combined	Competitive / Complementary / Cooperative	After final step

multi-sensor integration fusion model fits our requirements. It is based on local data fusion from different types of sensors, including contact and laser sensors, works with serial/combined sensor arrangements, and provides feedback after every step. In addition, when global data fusion of all data is needed at every step, the behavioral knowledge-based data fusion model or the waterfall model can be used.

2 Approach

Multi-sensor systems are usually built modularly, with single sensors integrated into a common framework. Each single sensor gives the local data of a measured region, and data from all the sensors is integrated into the complete data set. This integration can also be defined as a hierarchical tree, in which the leaves are the local data sets and the root is the fused model. Thus, basing of the multi-sensor system on the SLMS and HMS generic frameworks is proposed.

In the *Single-Level Multi-Sensor (SLMS)* framework**,** the sensors are arranged on one level (Figure 3). The behavioral knowledge-based data fusion model or the waterfall model can represent SLMS using multi single-sensors that scan simultaneously.

In the *Hierarchical Multi-Sensor (HMS)* framework, the sensors are arranged hierarchically as a binary tree (Figure 4). The multi-sensor integration fusion model can serve as a model for HMS, with every level involving fusion of two different datasets.

A common SLMS and HMS core can be defined (red dotted rectangle in Figure 3 and Figure 4). This core should be flexible enough to deal with all types of diverse scanned data. The basic core comprises six main stages (Figure 5): (a) data acquisition; (b) mesh reconstruction; (c) ROI and POI detection; (d) matching data sets; (e) merging data sets; and (f) reconstructing the multi-scale model.

3 Implementation

The proposed data fusion frameworks were partially implemented using C++ with the OpenGL graphic library and partially using Matlab. Synthetic data was also used for feasibility testing.

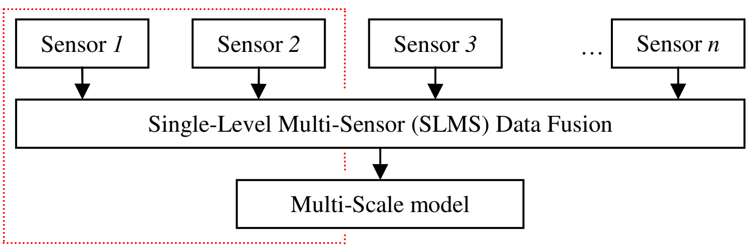


Fig. 3. SLMS data fusion framework – general scheme

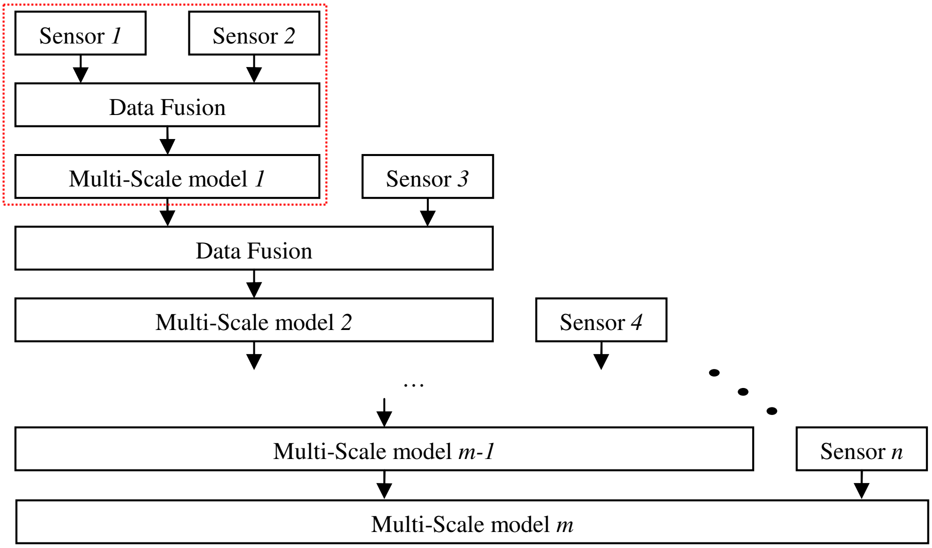


Fig. 4. HMS data fusion framework – general scheme

Data acquisition from multi-sensor system: The sampled data takes the form of point clouds when a CAD model is also available. Some of the models were built with SolidWorks. Triangle meshes at different resolutions were generated and point clouds were extracted. These point clouds are accurate, while sampled data is noisy. Normally distributed noise is therefore added to the synthetic points in the direction of surface normals.

Mesh reconstruction from sampled data: The Power Crust method was used for mesh reconstruction. If the mesh is already provided, this step can be omitted.

ROI and POI detection on sampled data: The ROIs on both sampled data sets are detected, based on Shmukler and Fischer [9]. POIs are then found for each data set. Figure 6 shows a sample with marked ROIs (left) and POIs (right).

Matching between sets of sampled data: The sets of sampled data are matched using Shape Histograms. Shells and spherical sectors are built for the POIs.

Calculation of POIs histograms: For each POI, the surface area of the sub-shells is defined. The histograms are then calculated for each sub-shell.

Correlation map between POIs histograms: Corresponding POIs have similar or approximated histograms. In contrast to the shape histograms method, in this study the physical properties of the data acquisition are also integrated. Every measured surface can be represented as a superposition of surface properties, such as roughness and waviness [22]. Figure 7 shows an example of two measurements of the same area using different sensors. A comparison of Figure 7a and Figure 7b shows that if the observing window is big enough, the similarity between profiles can be detected and corresponding regions identified. For 2D measurements, the similarity will be in the curves, while in 2.5D/3D the surfaces will be similar. Thus, corresponding POIs should have similar histograms, and correlations between these histograms should

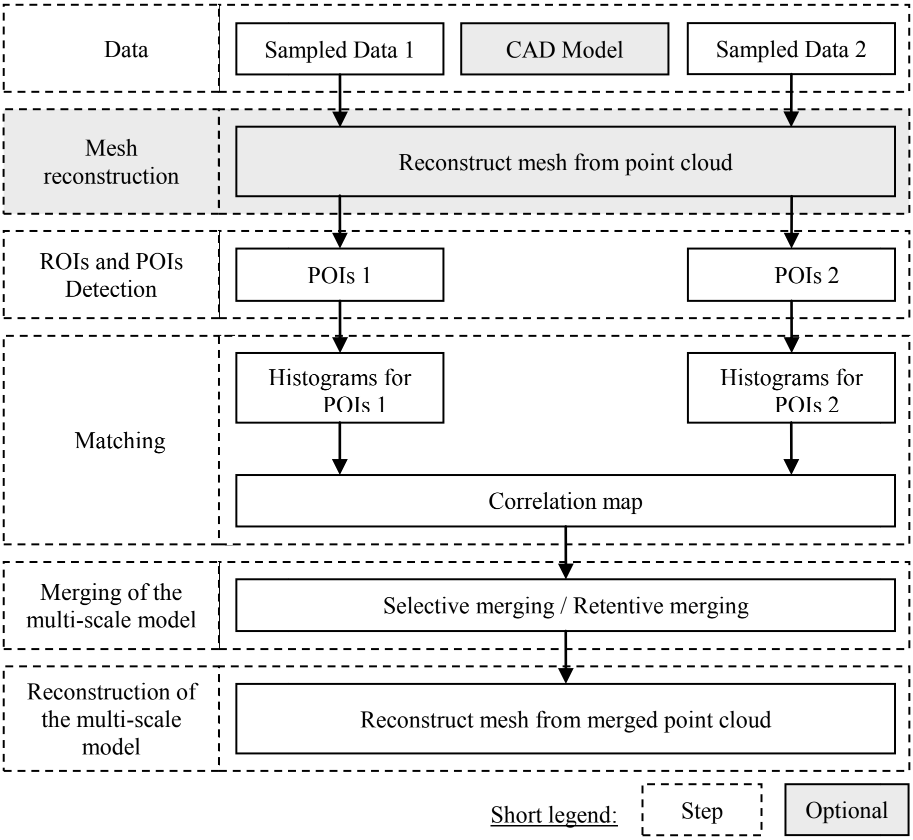


Fig. 5. Proposed approach for basic core

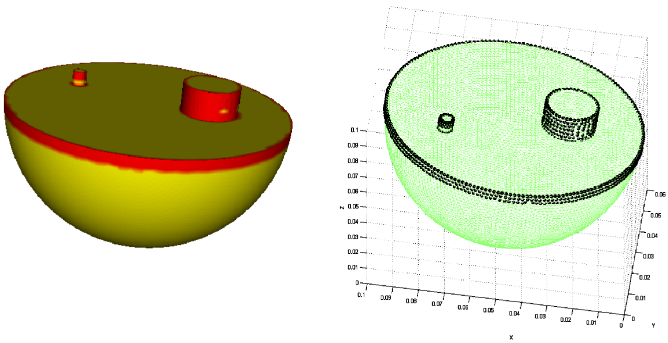
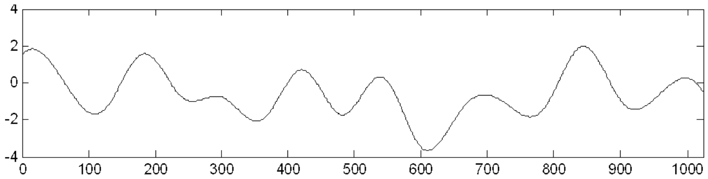
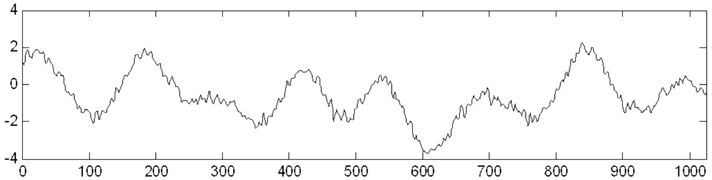


Fig. 6. Model with ROIs (left) and model with POIs (right)

yield relatively high values [23-24]. Correlation maps between two sampled data sets are built for shell and sector histograms. Linear correlation coefficients are then calculated between every pair of vectors for each type of histogram. These coefficients are defined as correlation maps. Based on the threshold value, pairs of POIs with high correlations are chosen as candidates for correspondence. If there is a correlation between matched POIs, the ones with the minimum distance value is chosen to overcome noises and measurement errors. The result is a correlation map with connections between corresponding POIs from sampled data sets.



(a) Example of surface profile, measured by low resolution sensor



(b) Example of surface profile, measured by high resolution sensor

Fig. 7. Example of surface profiles, measured by sensors with different sensitivity

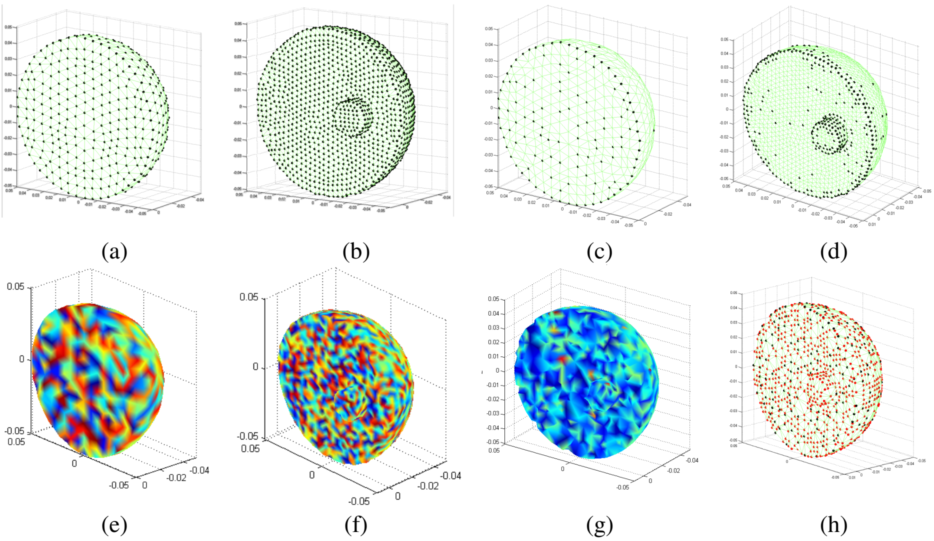
Merging LR dense data with HR sparse data into the multi-scale model: The proposed approach deals with two types of noisy sampled data: (a) high resolution (HR) data that is very accurate but sparse, and (b) low resolution (LR) data that is less accurate but dense. Hence, HR data is much more reliable than LR data. Two types of merging approaches were used: (a) selective merging and (b) retentive merging. In *selective merging*, only some of the points from each set of sampled data are added to the merged model. The error at the measured point, defined as the Euclidian distance between the measured point and the corresponding point on the CAD model, is used as a point selection criterion. Then, a normalized error map of the sampled data is calculated. Finally, the threshold of error value is defined to filter noisy points. In *retentive merging*, all points from each set of sampled data are added to the merged model, and some of the points are corrected using various approaches, for example according to the error map defined by the selective merging. Nevertheless, if the number of points in one set of the sampled data is significantly smaller than in another set, the error map is not effective.

This study used two correction approaches: *Gaussian Processes (GP)* and *B-Spline correction function*. The GP approach of Colosimo and Pacella [25] works with 2.5D surfaces only and refers to data from a pair of contact (HR data) and non-contact (LR data) sensors measured on the same surface. A two-stage model is used to connect LR and HR data and then to correct dense LR data relative to sparse HR data, using scale and location adjustment functions. In the CAD field, a B-Spline is a Spline function with local support with respect to a degree parameter [26-27]. Every polynomial function of a given degree can be uniquely represented as a linear combination of B-Splines of that same degree and smoothness. In fact, a B-Spline function can be considered a low-pass filter [28-29], so that B-Spline curves/surfaces can be used as a correction function for LR data.

Multi-scale model reconstruction: The Power Crust method is used to create the mesh for reconstructing a multi-scale model from the multi-scale cloud of points.

4 Examples

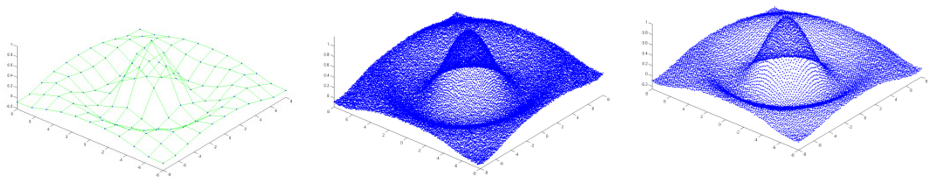
Two examples show different types of merging and data. Figure 8 shows an example of the selective merging of two synthetically sampled 3D data sets, with different densities, noise values and level of details, simulating partial sampling by one sensor.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 8. Example of selective merging

For two data sets (Figure 8a and Figure 8b) POIs were calculated (Figure 8c and Figure 8d), error maps were built for each data set (Figure 8e and Figure 8f), and selective merging was carried out according to the threshold. Figure 8g shows the error map of the multi-scale merged data. Figure 8h depicts the multi-scale merged point cloud with mesh; black points obtained from data set 1 and red points from data set 2. The overall error rate of data set 2 is lower. Figure 9 shows an example of retentive merging using the B-Spline correction function. The merging is done between two synthetically sampled 2.5D data sets with different densities (Figure 9a and Figure 9b). Due to the low density of the data set, in order to visualize shape Figure 9a includes also the mesh. Multi-scale merged data can be seen at Figure 9c.



(a) (b) (c)

Fig. 9. Example of retentive merging

5 Summary

This paper has described the SLMS and HMS frameworks that were developed for data fusion from multi-scale sensors. These frameworks offer the following advantages: (a) integration of advanced and traditional inspection technologies; (b) unlimited number and type of sensors; (c) adaptive addition of diverse data sets; (d) merging multi-scale data into a hierarchical multi-scale model. In the future, performance can be improved by using an Octree-based data structure for efficient storage and fast neighbor searching. Moreover, additional information, such as texture, normals and color from the multi-sensors, can be incorporated.

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Exploiting Service Data of Similar Product Items for the Development of Improved Product Generations by Using Smart Input Devices

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Abstract. State-of-the-art industrial products generate large amounts of data that is not lead back into product development. The use of modern technologies like mobile devices and Auto-ID to identify product items and collect data offers a new, rich data source that can be used by product development. To gain an understanding of the products in practical application, the collected data can be processed by assistant systems for the improvement of products. The assistant system outlined in the paper in hand uses statistical methods and methods derived from risk management to provide a comprehensive analysis. A short overview of the analysis results is presented to the product developer as a preselection of parts worth improving. Based on the preselection, the product developer can choose specific parts and gain further information via the assistant system. The system itself provides that information using different methods of product and information visualization.

Keywords: Data Mining, Information flow, Internet of the things, Knowledge Engineering, Product use information, QR Code, RFID, mobile computing.

1 Introduction

Throughout the lifecycle of industrial products, a large quantity of data is generated. During the early phases of product life (i.e. the design and manufacturing phases) mainly unchanging data is generated. This data includes information about the product itself (e.g. type information, serial number) and it does not change throughout product life. In the later phases of product life, namely the product use phase, different types of changing data are generated. That data can e.g. contain information about the configuration, the condition, or the environment of a particular product item. This data provides a snapshot of the current condition of a given product item. The present use of product use data is limited to the specific purposes it has been generated for. As a matter of fact, with regards to the improvement of maintenance or later product generations, the high potential within that data is currently not considered at all.

The approach presented in the paper in hand employs mobile computing to facilitate the collection of service data that can provide detailed information about the

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usage and maintenance of product items. To gain structured data from different data sources (e.g. in-house services, product manufacturer services, third party services), the approach implies that a service event can be carried out facilitated by mobile devices and using predefined user dialogs (e.g. check boxes) for specific, frequently occurring actions (e.g. the exchange of a component due to a breakdown). The stored information is crucial for the service provider and needs to be lead back to product development, as it shows great potential for product improvement. Comprehensive information about the usage and maintenance of large numbers of product items can be analyzed for a variety of purposes. The aggregation of all product use data of an individual product item allows an improved design of later product generations. Based on this aggregated data, an assistant system is proposed. The proposed system utilizes statistical methods and methods derived from risk management. The introduced approach is versatilely applicable for new product generations in the design phase and also for products in the later lifecycle phases.

2 Related Work

Feedback Data in Product Development

Conventional material and information flows are directed forwards and connected to the lifecycle of material products. Exceptions comprise recycling where products are dismantled and no value or direct benefit is created. For several years, customer feedback also has been established as a backwards directed type of information flow [1]. Customer feedback is lead from the product use phase of a product into product development. The goal is to make products that fulfill customer demands. Customer feedback is considered subjective feedback. Therefore it is not free of personal opinions and feelings. The transformation of subjective feedback into objective information has been addressed frequently in literature [1].

The acquisition of objective feedback is a relatively recent research topic, which has evolved together with the development of smart products and new business models. The latter have lead to a stronger connection between providers and customers, and therefore enable the leading back of product-related information. Objective feedback is data or information derived from sensors of a product, sensors in the environment of a product, data generated by service staff, data generated about service staff, or quality parameters. [2] Objective feedback is free of personal opinions and can be either structured or unstructured.

Structured data has a homogeneous structure as found, for instance, in databases. Unstructured data has no such structure and is e.g. information that is hidden inside a document or texts. Unstructured data cannot be captured without further processing [3]. Methods of extracting information from text are currently under development.

When using objective and structured data, a further processing of that data is more effective due to fewer efforts converting the data into understandable information. Another advantage of objective data is that this data can be generated, collected, and aggregated automatically. Therefore the effort of collecting such data is very low. A basic problem when using objective data is that important information for a correct interpretation of the data may be missing. Hence, comprehensive monitoring of the whole product is favored.

Within different research projects, objective data has been taken into closer consideration. The PROMISE EU research project considers product-embedded information devices for information tracking and tracing. A concept for leading information into product development and production has been created [4] [5].

WiRPro, a further research project, has extended the PLM approach by processing product use information chiefly based on the use of Bayesian Networks [6] [7]. This project has yielded a feedback assistant system that consists of four modules: analysis, diagnosis, decision support, and prediction [8]. These modules have been designed to directly support the product developer in improving existing product generations.

Based on the above-mentioned characteristics and different types of feedback, service data, which is collected by smart input devices, will be used. This data can either be sensor data or generated by service staff. As the input interfaces of the service staffs are expected to be structured, only objective and structured information is gathered.

Use of Automatic Identification Technologies with Smart Input Devices

Throughout the last decade, the number of smart input devices like smartphones and tablet PCs has increased significantly. These devices facilitate mobile computing and mobile communication. Some devices also feature embedded cameras or even near filed communication (NFC) or radio frequency identification (RFID) reader module, and can be used as a reader for automatic identification (Auto-ID) technologies [9].

The term Auto-ID technologies refers to a set of different technologies like barcodes, e.g. QR codes (readable by camera systems), and RFID tags, e.g. NFC tags (readable and rewritable by electromagnetic high frequency transceivers). Auto-ID technologies provide an opportunity for automated identification of physical product items without manual errors like assignment or typing errors, and can provide cross-media references between the physical world and the virtual world inside computers. They thus constitute a basis for the vision of the Internet of things [9]. The use of the Internet of things as a source of information about product items requires marking product items by affixation or embedding of marking technologies like RFID tags or barcodes onto the item, and to store a unique URL or ID within the marking technology. These marking technologies can be read by commonly used mobile devices, to access and alter different data sets of a product item in data bases via the internet.

Summary and Focus of the Research Work

In a literature research, several approaches have been found that deal with leading back data into product development. Still, these approaches are highly specific, as they only consider particular data sources for special use scenarios more closely. The use of mobile devices and Auto-ID technologies has been taken into consideration only rarely, never to gain subjective nor objective feedback information. Moreover, the field of leading data from service staff into product development to improve current product generations has only been treated scarcely.

3 Proposed Approach

3.1 Overview

The presented approach focuses on industrial products, which are cost-intensive and used several years. Throughout the product use phase of such products, maintenance costs exceed investment costs. Thus, a large number of industrial products are equipped with embedded sensors. Due to the sensors and regular servicing, maintenance is the main data source during the product use phase.

Based on the combined service data (e.g. small errors, total failures) of several product items from the same or similar product types, analysis methods can be performed to support the development of further product generations. Product improvement can affect the whole product or just components of the product.

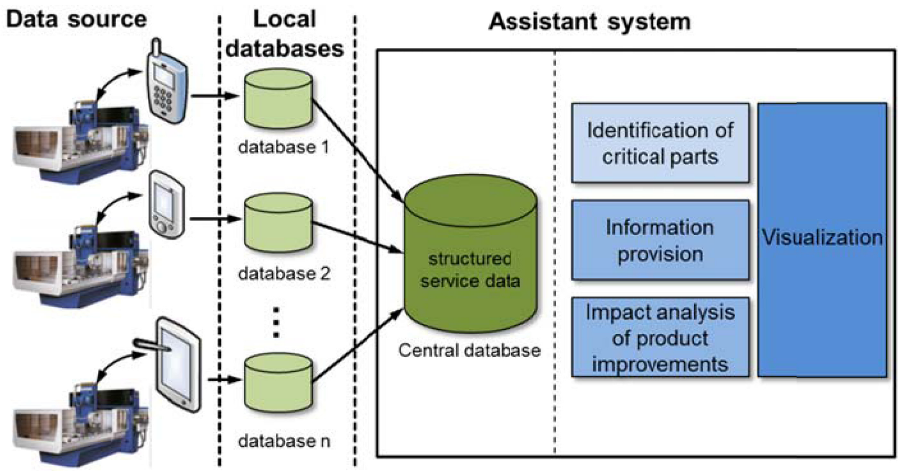

Fig. 1. Concept for the assistant system

An overview of the presented approach is provided by Fig. 1. The left side of Fig. 1 shows the relevant data sources of the approach. The data source can be e.g. maintenance information collected by service staff with smart devices and embedded sensors. The staff uses smart input devices to generate and collect data and information from different product instances. The collection of maintenance information with smart devices is performed in several steps. First, the marking technologies are read to provide an identification of a unique product item. Based on the identification, the smart device can access existing datasets related to this product item via the internet. That information can be displayed on the mobile device and be used to assist the service staff during inspection. The existing dataset can be updated depending on the collected data and the performed actions by the service staff.

Each particular dataset is stored in a local database of the service provider who is in charge of maintenance of the related product item. To provide a sufficiently large number for statistical analysis, the different heterogeneous databases have to be aggregated. The aggregated data is stored in a central database, which is part of the proposed assistant system.

To efficiently support the product developer in improving existing products, the assistant system consists of four interacting modules for the

- identification of critical parts,
- information provision,
- impact analysis of product improvements, and
- visualization.

Based on the aggregated data, the module for the identification of critical parts provides the developer first with condensed information about components that require improvement. The visualization module provides that information in an environment (PLM and CAD system) known to the product developer. To gain further information about a component, the developer can access further information via the information provision module. The module for the impact analysis of product improvements inherits knowledge about components like earlier improvements and their impact. That knowledge is stored as lessons learned.

3.2 Feedback-Relevant Data Sources

The approach presented in this paper can use different kinds of data sources to gain detailed information about the usage and maintenance of product items for the same or a similar product type. These data sources can be data collected by service technicians and product users, as well as sensor-derived data, which are integrated into industrial goods. To make the approach versatilely applicable for a great variety of present product types, the presented approach is mainly focused on data of service technicians and product users. Using service technicians and product users as a source of data makes it possible to consider simple products, without any sensors. That way, the proposed method can be used for products that are in the development phase or in the later lifecycle phases. This data source can provide a great detail even about complex or unforeseen situations, which cannot be fully recorded via sensors e.g. complete breakdowns, disturbing environmental conditions on the installation site, or an interplay among errors.

To assist service technicians and product users in gathering data, the outlined approach suggests the use of mobile devices that can read marks of automatic identification technologies such as barcodes and RFID tags, and can access the data sets, which are related to the ID or URL, that are stored inside the marks via the internet. This information can be used and displayed as a part of guided user dialogs, which can lead through a systematic inspection of the product item. The order of the inspection steps can be based on the structure of the product type and the known errors of the type. Each inspection step can be assisted by short information. The result of the inspection step can be noted in the form of damage codes or check boxes if necessary.

Through the use of chiefly predefined user dialogs on the mobile devices, data gained during the inspections can be considered structured data. The collected, structured data from different data sources (e.g. in-house services, product manufacturer services, third party services) can be integrated into a central database, which contains extensive data about errors that have occurred with a large number of similar product items.

3.3 Modules of the Assistant System

Module for the Identification of Critical Parts

The presented approach uses consolidated, structured data of different data sources (e.g. in-house services, product manufacturer services, third party services) to gain comprehensive information about the errors of a vast number of similar product items, which is derived from the same or similar product types. The information about the usage and maintenance of larger quantities of product items can be analyzed for a variety of purposes. The main focus of the introduced module is the automated identification of critical parts of product components that need to be improved and considered for redesigning or a new design.

To provide an adequate selection of components, which needs to be reviewed by a product designer, the module for the identification of critical parts uses simple but effective methods. The basic idea of these methods lies in a comparison between the actual and the target performance of the considered product items. One of these methods uses statistical methods to analyze the achievement of target performance characteristics. Another method is based risk management to analyze the occurrence of minor errors and total failures.

The method based on statistical methods analyzes the achievement of target performance characteristics by using average values and statistical frequency analyses. These target performance characteristics are provided by the values that are listed in the specifications, regulations and manufacturer's quality requirements. The relevant regulations can be listed in standards, legislative regulations, or obligations of treaties. The manufacturer's quality requirements are not necessarily documented in the product specifications but should be orientated towards customary business practice in the related sector and the expected customer requirements. As a first step of the method, the module for the identification of critical parts uses data collected form a large number of similar product items to calculate average values of different product characteristics. In a second step, the module for the identification of critical parts performs a statistical frequency analysis and calculates how many product items have reached certain percentages of an estimated value. Fig. 2 shows a visual example of a result of the statistical method based on the meantime between failures (MTBF).

The method based on risk management analyzes the occurrence of negative effects like minor errors and total failures by using a risk matrix. The risk matrix is a method that is used in risk management approaches like ISO 31000 or ISO27005 to provide an overview of all considered risks, and it also shows the importance of the various

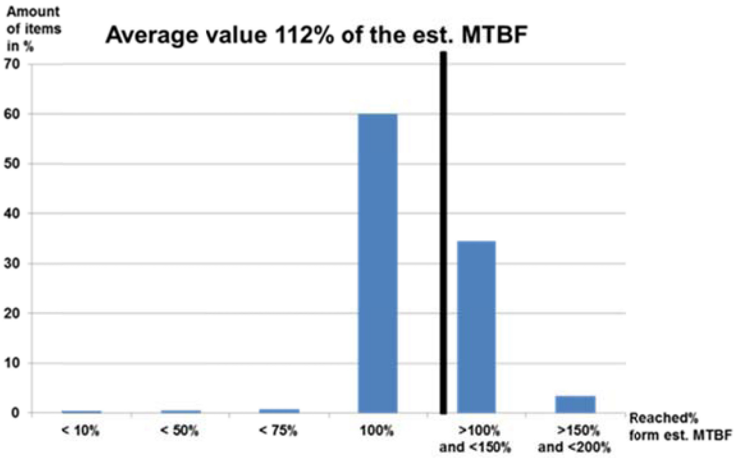

Fig. 2. Example for the MTBF assessment of one component

risks. Since risk is often defined as to equal the product of the likelihood of the negative incident multiplied with the impact of the unwanted incident, the risk matrix uses these dimensions as axes (cf. Fig. 3). The likelihood of errors and total failures, which is represented on the horizontal axis, can be calculated statistically. The impact of an incident shown on the vertical axis can be measured based on repair efforts and follow-up costs. Fig. 3 shows a visual example of a result from the proposed method regarding the risk of component errors and total failures of a machine.

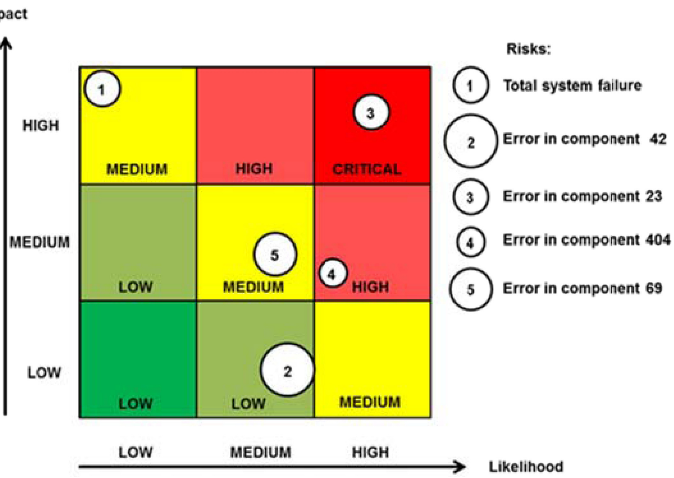

Fig. 3. Example for the risk analysis of different components

The first result of the two proposed methods is a classification of the product and its components into three different categories. Depending on the results of the two methods, a product and its components can be classified as "sufficient no review", "review is advisable" or "review is crucial". This classification is used by the visualization module to offer product designers a preselection of products and components, which require improvement. Detailed graphical output as presented in Fig. 2 and Fig. 3 is given to the module for information provision.

Module for Information Provision

The main function of the module for information provision is to provide additional information to preselected products and components. To gain the additional information, the product developer has to choose preselected parts, which are classified as "review is advisable" or "review is crucial" of the product and need to be considered in more detail. Examples for additional information can be the output generated by the two preselection methods (cf. Fig. 2 and Fig. 3) and the collected and aggregated data itself.

To display the information in a context that is customary to product developers, the module for information provision processes the additional information for a presentation via the visualization module. To depict all additional information in a comprehensive overview, the visualization module uses methods of data and information visualization (e.g. area charts, hyperbolic trees).

Module for the Impact Analysis of Product Improvements

A major task of the module for the impact analysis of product improvements is to assist product developers in checking and analyzing the effectiveness and efficiency of already performed improvements. To enable a deeper analysis, the module for the impact analysis of product improvements provides the possibility of tracing back the impact of modifications made on parts or components over many changes and product generations. The discoveries are stored as "lessons learned" and provided to the product developer in later product changes.

Another task of the module for the impact analysis of product improvements is the management of dependencies and interactions between positive and negative impacts of changes made, which have been detected by the product developers. That kind of knowledge also enriches the "lessons learned".

For an effective knowledge provision, knowledge visualization methods are used (e.g. decision maps).

Visualization Module

The visualization module supports the product developer in improving existing products by displaying crucial information in a simple and easy to understand way. The information and knowledge for the identification of critical parts gained in the modules, the information provision, and the impact analysis of product improvements will be presented within the working environment of the product developer. For this task digital engineering visualization methods are used in combination with the information and knowledge visualization methods of the modules for information provision and impact analyses of product improvements. These methods have to be combined and adapted in the approach as a whole.

The example of the visualization module presents an early outlook on a possible later implementation of the visualization module. The visualization module displays the results of the modules for the identification of critical parts, information, and impact analyses of product improvements.

Often JT technology is used to generate small sized 3D models. In this particular case, the 3D pdf technology has been used to create the model (cf. Fig. 4). Next to the visualization of the 3D model, the product structure is presented.

The product developer can interact with the 3D model and the product structure. By double clicking a part in the 3D model, that part will be highlighted in the product structure and additional information or a dialog open up. The product developer then has the opportunity to choose the information he wishes to see.

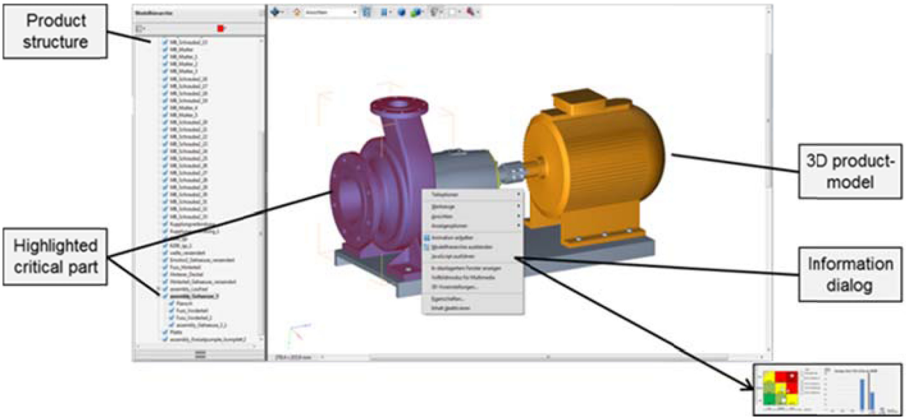

Fig. 4. Visualization example

4 Outlook and Future Work

The presented concept provides an approach for the analysis of structured service data for the purpose of product improvement. That data can be collected by the use of mobile devices and Auto-ID technologies. The data from different sources can be aggregated in one central database, which provides the possibility for a detailed analysis using statistical methods and such derived from risk management. This analysis assists product developers in identifying critical products and components with the most need for improvement. For enhanced integration into product development, the visualization of this analysis can be integrated into existing tools like PLM and CAD systems.

Future research work will also explore unstructured data like texts for the enhancement of the product development process. Further research will feature the integration of the approach into the WiRPro research project, which mainly considers structured sensor data collected from industrial products.

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Design of a Clip Product Based on Customer Needs for Playing Acoustic Music

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Abstract. Inclusion of uses and users in product design remains a challenge to take up; especially when their characterizations are very specific (it's the case with disabled persons). In the musical domain, a lot of adapted interfaces are manufactured to enable users with disabilities to play music from digital audio. But few of them allow the music practice on acoustic instruments, which is one of the goal identified by the AE2M non-profit association (Ergonomic Adaptation of the Musical Material). In this specific context, this paper presents the design of a universal product which transforms any user environment object to a personalized interface, to play percussion instruments.

Keywords: user environment, design, disabled people, acoustic music, robotic musical.

1 Introduction

Traditionally, designers create products or interfaces for able-bodied users, assumed to have normal motor skills [1]. Atypical users, including people with disabilities, remain outside of these skills and capabilities standards. They must adapt to with existing systems, using technical aids. Unfortunately, these technologies are unusable for people with temporary impairments. They are also not adapted to users whose abilities change over time. The data, detailed in a research report conducted by INSEE (France's National Institute of Statistics and Economic Studies), show a significant need of assistance in handling (only 35.3% satisfaction for remote handling) [2]. Nevertheless, these means are often abandoned because of their price and complex use. The main reasons for giving up are due to a minimum consideration of future users in design activities.

There are two main groups among system designers for disabled people [3]:

- The first which go to certain well-defined needs and seek a technological solution (social pull). These proponents generally have a good knowledge of disabilities. They are looking primarily practical systems, efficient and robust, sometimes ignoring the more advanced technologies. The risk here might be to focus too much on obsolete technology, unusable or too expensive.

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- The second which go to a technology they have mastered and are looking for applications in the field of disabilities (technology push). The risk here might be to propose solutions for imaginary or non-priority needs.

Integrate multidisciplinary teams in the design process can avoid these risks.

Our research work consists to the development and the manufacture of physical interfaces facilitating access to instrumental music for children with heavy physical disabilities. Currently, disabled user environment are not adapted to their needs and human machine interface. One solution is a custom design of products for each user motor skills. But this process can be lengthy and difficult because of the myriad of user profiles. Moreover, one of the most objectives is to reach low cost production and the large diffusion for disabled customers.

The research question can be written as below: How to design a universal product which would transform any user environment to a personalized interface?
To answer this question, our methodology is the following:

Section 2 presents an identification of needs in our context thanks to a literature review. Three main parts are exposed: future user characteristics, existing adapted system to play music, human machine interaction in musical practice. Thanks to the needs list defined previously, section 3 offers a first prototype based on piezoelectric sensors technology. Its structure is defined with a representation of human machine interaction in our specific context. Its architecture is described in functional component decomposition. After a presentation of test methods, section 4 shows the first results when using this interface for a musical playing.

2 Identification of Needs

As the NF EN ISO 9241-210 UCD Process[1] recommends, designers take into account the contextual factors as well as the requirements of the future users before producing design solutions.

2.1 User with Disability

User characteristics define the context in which the product is used. The futures users are children with disability. We are focused on the disability ICF-CY definition (International Classification of Functioning, Disability and Health for Children and Youth), proposed by the WHO (World Health Organization) to understand the terminology of disability [4]. This definition provides a common language that can record the problems occurring during infancy, childhood and adolescence. It is based on body functions and body structures, activity limitations, restrictions participation and environmental factors significant for children and youth (Figure 1).

1. NF EN ISO 9241-210: 'Human-Centred Design Processes for Interactive Systems' Genève, Switzerland, International Organization for Standardization, January, 2011.

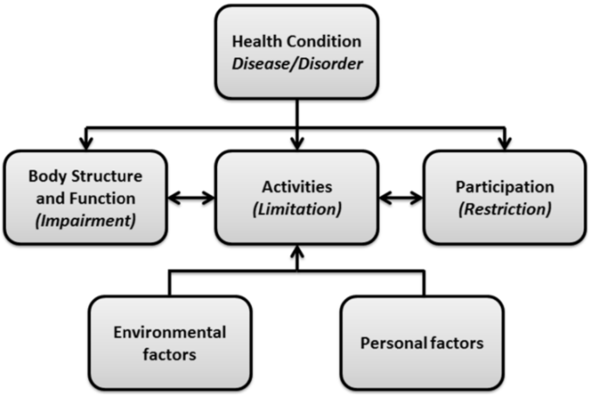

Fig. 1. ICF-CY definition: International Classification of Functioning, Disability and Health for Child and Youth

Disability therefore results from the interaction between a person with health problems and contextual factors (personal and environmental). Impairments refer to modifications of body functions or anatomical structures, such as paralysis. Activity Limitations are difficulties an individual may experience in these activities (walking, eating, playing etc...). Participation restrictions are problems a person may meet to participate in a situation of daily life, such as transportation inaccessibility.

2.2 Existing Adapted System

This section analyzes existing systems for the practice of music. This analysis can reveal needs, problems and constraints that have not been taken into account.

2.2.1 To play Music with Digital Audio

Interfaces designed for disabled people allow musical practice from digital audio:

- The BAO-PAO fits perfectly with the computer-assisted music because it needs to operate a computer and special software. It consists of four rigid steel arches, each terminated by two spheres at the ends. A laser beam passes between the upper sphere and the lower sphere. It generates a sound when the musician crossed it with a drumstick or hand [5].
- TouchTone is an electronic musical instrument. Its goal is to develop musical ability, to develop bimanual coordination and to increase social participation of children with hemiplegic cerebral palsy [6].
- The GUI//RO is a stylus controlled instrument, augmented with resistive force feedback. The system is manufactured through an electromagnetic coil controlled by Arduino board. Sounds and haptic effects are generated by the position on the stylus in touch-sensitive screen [7].

With these solutions, users can play any instrument thanks to synthesize sound. Nerveless, the musical instrument is dematerialized. Indeed, the user doesn't visualize a real musical instrument for the music game. Moreover, transportation and equipment installation can be difficult and not adapted with the environment of disabled people.

2.2.2 To Play Acoustic Music with AE2M Project

Few systems allow the music practice on acoustic instruments. This is the goal of the AE2M non-profit association (Ergonomic Adaptation of the Musical Material) [8]. It provides access to instrumental music for children with disabilities, with the same autonomy level as non-disabled. It's a multidisciplinary team which is surrounded by three main applications specialties (Figure 2): Musicians (by specialized professors in instrumental music and musical manufactory), Paramedical specialists (by doctors, specialist therapists) and Engineers (principally by teachers and engineering students).

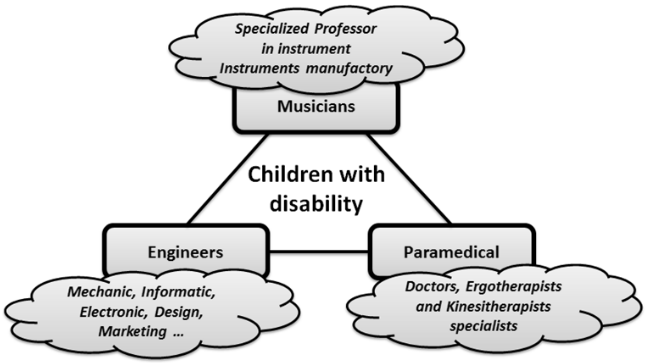

Fig. 2. Competencies triangle of AE2M project

For a better understanding of this competencies triangle, it is necessary to develop the roles and the work of these specialties in the project. Engineers should be familiar with the properties of the musical instrument which children would try to play. So they consult the music specialists of the project. Moreover, engineers have to discuss with the paramedical specialists who spend all their times with disabled children. They know some physical capacities of these children, those needed for the project development.

Generally, interfaces manufactured by the association AE2M allow children to play percussion instruments A specific solution realized is an electromechanical system to allow a strike of the drumstick on percussion instruments (Figure 3). The user activates the system by the means of accessories (push button, pressure effort, etc.) positioned around him according to his ability to perform body motions. With this system, the musician couldn't perform different strike velocity on the instrument and the preparation of musical activities could be long because of the myriad of user profiles. Depending on motor skills (movement, strength ...) and the user environment (wheelchair, tablet ...), this system may have difficulty to be integrated naturally.

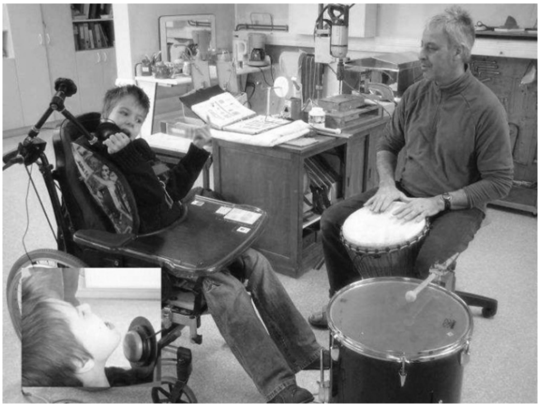

Fig. 3. Use of electromechanical magnet for a playing game

2.3 Human Machine Interaction for Musical Practice

To define the user tasks, it is important to design the user-system interaction. Metois proposes a generic definition that considers the "musical gesture" as anything that fills the space between the musical intentions (cognition, psychology, and musicology) and musical sounds (waveforms physical) [9]. "Musical gesture" includes the "instrumental gesture" concept. Cadoz defines "Gestural Canal" as a means of acting on the physical world and as a means of two way communication: sending and receiving information. Then, his definition considers the Instrumental Gesture as a communication modality specific at "Gestural Canal" as follow [10]:

- It applies to a material object and there is physical interaction with it,
- In this context of interaction, it will occur physical phenomena,
- These phenomena can then become communicational messages.

2.4 Synthesis

These different parts allow describing the needs as well as requirements of our interface realization. In our musical context, we must offer to disabled child with particular health condition, a product which would allow them to enjoy musical play (activities) and even to participate in concert (participation) with the same autonomy level as non-disabled (body structure and function). For musicians and paramedical team, the system must be easy to install and must be integrated naturally to the environment of the user. In addition, the delay between the musical intention of the user and the system response must be transparent. The musician recommends a delay time less than ten milliseconds (between the action of the children and the action of mechanical system). The system must also perform different strike velocity on the instrument. For engineers, the interface must contain a minimum of electronic equipment. If maintenance must be performed, it should be easy. Our proposition is to transform any object in the user environment as an action unit on electromechanical systems.

3 Concept Solution Proposition

This section offers a concept solution using the previous synthesis. The product structure is defined with a representation of human machine interaction in our specific context. Its architecture is described in functional component decomposition.

3.1 Product Structure

The product structure is based on our proper representation of human machine interaction using the definition of "musical and instrumental gesture". In our context, the user has a musical intention (Figure 4). He will perform an action on an object environment. This interaction will produce physical phenomena (force, pressure or vibration) that can be controlled by the user (duration, amplitude). These phenomena can thus become communicational messages to the electromechanical system for the strike of the drumstick on the percussion instrument. The essential elements in designing of our future product are:

- A clip sensor for the physical phenomena detection.
- An electronic board to transform these phenomena in action message for actuator positioned on the musical instruments.

The development is inspired from the different work realize by the LEMUR (League of Electronic Musical Urban Robots) which is the producer of the famous Pat Metheny's Orchestrion composed of forty robotic musical instruments. It uses principally stepper motor, hobby servo and solenoids as actuator. They are controlled by a Pulse Width Modulation Signal (PWM) [11][12].

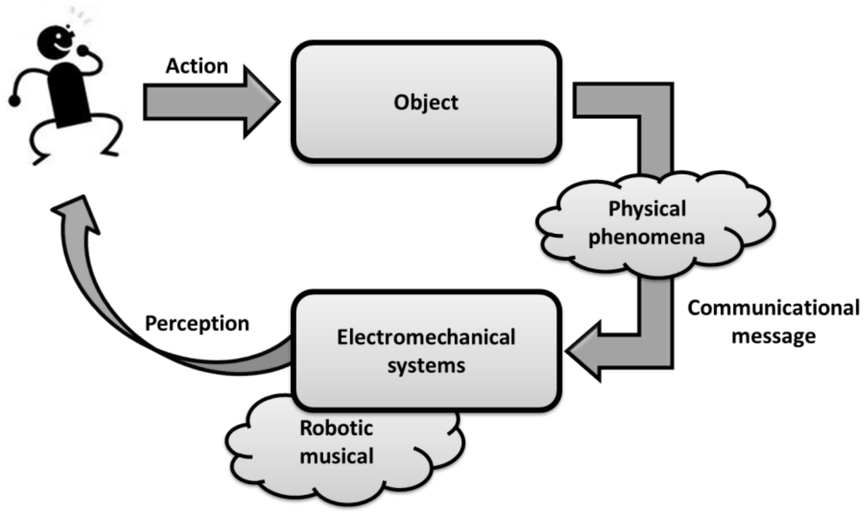

Fig. 4. Human Machine interaction of our interface

3.2 Product Architecture

From this previous definition as well as the identification of needs, this part describes the product architecture. It's divided principally in two parts (Figure 5):

- Control part with sensor clip, electronic board and microcontroller input
- Actuator part with microcontroller output, electronic board and mechanical system

The sensor emits a signal. It is interpreted by a microcontroller to control a mechanical system placed on the instrument. These control actions are based on the musical intentions of the user. In our case, the Arduino board corresponds to our expectations. This material is open source, free and easy for everyone to use. After this interpretation, Arduino can generate PWM signals to control a solenoid. But the output current is too weak to command this system. A power signal processing is therefore necessary. All this process must be realized in less than 10 milliseconds.

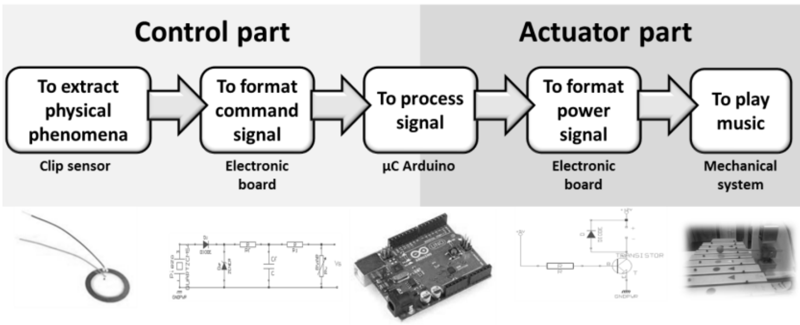

Fig. 5. Architecture of the smart clip sensor

4 Evaluation of the Solution

This section shows an evaluation of the design solution against user needs and requirements. Test methods are presented for the sensor choice and the study of the strike velocity.

4.1 Tests Methods

The sensor choice will be based on the following main criteria: accuracy, sensitivity, size and of price. Three different sensors performances are studied. They are different in size and form: two circular (Multicomp and Murata) and one rectangular (Prowave). They are arranged in a circular arc at an equal distance (d) from a disturbance area where it will be throw, at the same height, different weights. Sensitivity is measure by an oscilloscope (Figure 6). To study the strike velocity, Musician asks to the user to perform three different strikes (Piano, Mezzo, and Forte) on a plastic box where the clip sensor is located (n°1 on Figure 7). After signal processing (n°2 on

Figure 7), the drumstick movement (n°3 on Figure 7) on the instrument (n°4 on Figure 7) is filmed. Speed strike is analyzed with the Kinovea software, a free and open source solution for video analysis. It is mostly used by sports coaches, animation artists and ergonomics engineers.

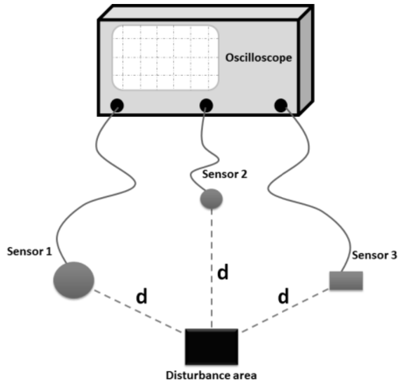

Fig. 6. Test for sensor choice

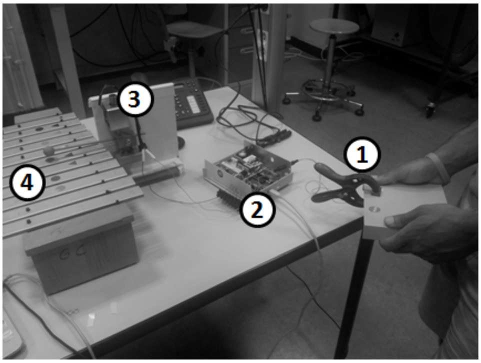

Fig. 7. Test for signal processing and velocity

4.2 Sensor Choice

Figure 8 shows the sensitivity analyzes of piezoelectric sensors Murata, Multicomp and Prowave. The signal amplitude is measured when the weight is throwing in the disturbance area. For a 500 grams weight, Murata gives a signal of 30.2 volts, Multicomp 9.8 volts and Prowave 2.9 volts. Multicomp exceeds 5 volts for weight greater than 120 grams, Murata for few grams. However, Prowave never exceed this value. For the next experimentation, the strike velocity is analyzed with Murata.

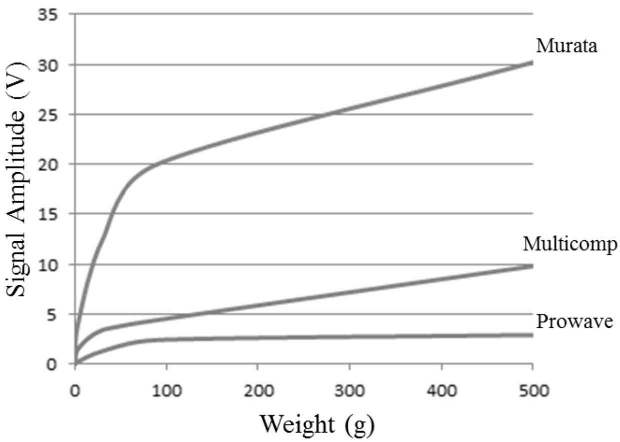

Fig. 8. Sensitivity analyze of piezoelectric sensors

4.3 Strike Velocity

Figure 9 shows the strike speed of the drumstick controlled by the mechanical system. Three strike speeds are saved: the first at 0.4 m/s, the second at 0.7 m/s and the third at 1.9 m/s.

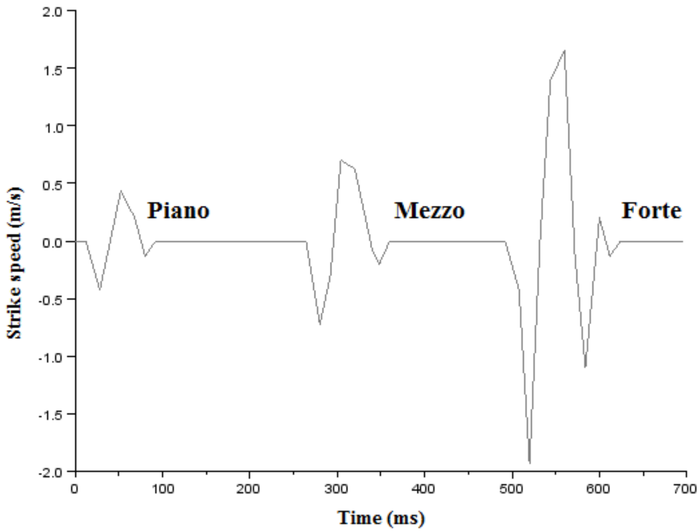

Fig. 9. Strike velocity study with Murata sensor

5 Discussion

Our interface allows transforming any user environment object to a percussion musical instrument. Its architecture is simple with low-cost and easy system Arduino, little electronic equipment to facilitate maintenance. Our system is integrated more naturally to the environment of user. For the sensor choice, Murata sensitivity is more efficient. Indeed, a child with low motion disabilities could control musical instrument. The response time of the system is less than two milliseconds (inferior at ten milliseconds recommended by the musician). It's possible to adjust the strike velocity on the instrument with different actions on an object.

6 Conclusion

Identification of needs and collaboration with the AE2M multidisciplinary team has allows to generate uses specifications of a product. These specifications have been destined to a team of Research and Development, expert in new technology. Thus, this methodology has led to the design of a universal product which would transform any user environment to a personalized interface. The product structure has defined by a representation of human machine interaction in our context. The product architecture is described in functional component decomposition. After these first encouraging results, this system facilities access to instrumental music for users with heavy physical disabilities, but also to increase the uses performance by musicians. The perspectives are focused by the clip design, the increase of the performance of the mechanical system and the "intelligence" of this system (the actuator part is able to adapt to user motor skills).

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Technology Roadmapping Based on Key Performance Indicators

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Abstract. In this paper a new technology roadmapping method, based on the stochastic simulation of key performance indicators, is presented. Initially the specific challenges and the system model associated with the introduction of an innovative electric bus systems are worked out. The future behavior of this complex technological system is forecasted based on a Monte Carlo simulation method with stochastic input to take uncertainties into account and a deterministic model which is derived from the structure of the technological system. Stochastic outputs are obtained for technology readiness, economic feasibility and environmental sustainability. The data are evaluated with a technology information management system to generate technology roadmaps and to support decision making on development strategy and planning of time to market. The method is exemplary illustrated for an urban electric bus system with a special focus on the technology readiness level as a performance indicator.

Keywords: Roadmapping, Systems Simulation, Monte Carlo Method, Key Performance Indicators, Electric Bus System.

1 Introduction

Today's technological innovations typically comprise different integrated subsystems. Examples for such systems innovations are the emerging electric mobility in private and public transportation and the smart electricity grids.

The proper planning of research and development (R&D) efforts to develop the underlying technologies depends on many influencing parameters and it has to consider technological and economic forecasts. Therefore finding the right timing for a successful market launch of systems innovations and starting the necessary R&D activities accordingly is a major challenge of innovation management.

An example is the development of a new urban public bus transportation system with electric buses and inductive charging infrastructure at certain waypoints. Here the technology readiness levels (TRL) of the electric drive train, the charging system and the battery have to match the requirements. Besides the TRL of the subsystems other key performance indicators (KPI) are for example life cycle cost (LCC) or the specific emissions factor per output unit (SEF).

KPIs are an important instrument for fact based technology decision and in this context the method of technology roadmapping (TRM) is widely used. TRM is

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usually based on workshops to define market needs, product specifications, technologies and resources required. However the quality of the resulting roadmap depends on the specific knowledge, availability and skills of the workshop participants. Additionally the results of such a workshop may be biased by personal attitudes and erroneous estimations.

In this paper a new method is presented, which combines data derived from workshops with quantitative system simulation. The input parameters of the system are stochastically modeled to take uncertainties in the system environment into account. Based on a Monte Carlo simulation different technologies can be evaluated in their system context. The KPI mean values give a measure of the expected system performance while the standard deviations represent the forecast uncertainty. These indicators are computed over the considered time span and compiled in a management information system which serves as a tool for decision making regarding the right timing for systems innovations market launch. Furthermore this information system supports the planning of the different product development processes.

The applicability of this method is demonstrated for a new electric urban bus system. The TRL-levels of the different subsystems, fuel cost, price of electricity, carbon dioxide emissions and performance of battery system are considered as stochastic inputs. Based on the predicted TRL, generated by the system simulation, different stakeholders can derive their specific TRM.

2 Background and Objectives

2.1 Systems Innovations

A technological system is a set of interdependent components that are delimited by a system boundary. The system objective is achieved by an interaction of the components and well defined input-output relations. Weiss and Wettengl define systems innovations as the implementation of a system of compatible and complementary components and their commercialization by an industrial consortium [1]. Systems innovations consist of product and process innovations and initiate a change from one socio-economic system to another [2].

An example is the introduction of electric vehicles, also known as electromobility. This systems innovation is based on product innovations like new batteries as well as process innovations like charging management or smartphone based energy payment. All sub-components are strongly interdependent as for example the value of an electric vehicle is limited if compatible charging stations are not available. An electric car only pitches its value added, in comparison to conventional cars, if all necessary sub-systems like charging infrastructure, power plants, energy storages, cars and regulatory framework are compatible and complementary.

2.2 Electric Bus System Innovation

Electrical bus systems meet rising emission reduction targets, because they do not produce any local CO_2, CO, NO_x or particle emissions. Furthermore their noise emissions are quite low. Electric trolley bus systems have been around for many decades but the installation of overhead wires is not possible or desirable in a lot of cities and furthermore the trolley concept doesn't allow flexible alternative routing. Storing the energy for the operation of a complete day will reduce the payload (number of passengers) due to extensive weight of the very large batteries. Hence a systems innovation - roadside charging - is needed which comprises several new sub-systems (figure 1).

Electric busses can only replace conventional diesel buses, if all its components have a sufficient technology readiness level (TRL) and it is crucial for OEMs and suppliers to have sound information about the TRL landscape. If for example the battery technology isn't ready, it's useless to bring an inductive charging system on the market.

This paper presents an approach to forecast future technology readiness as well as ecological and financial performance of a new electric bus system by applying technology roadmapping.

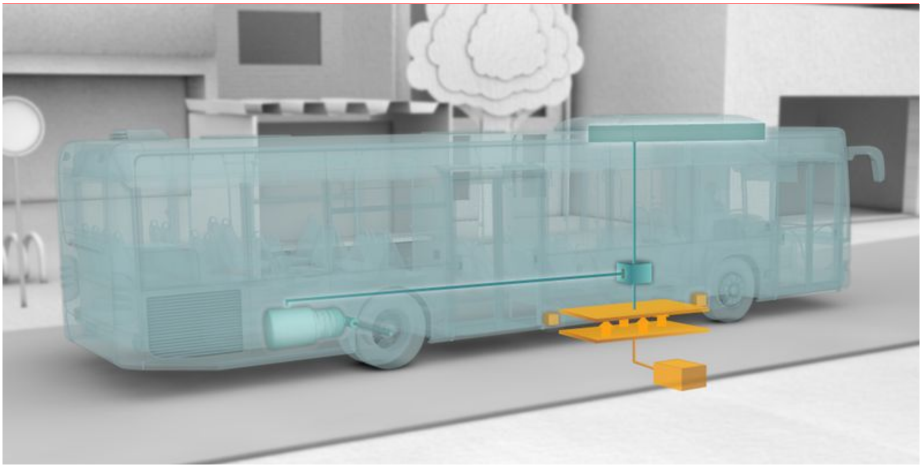

Fig. 1. New urban public bus transportation system [3]

2.3 Technology Roadmapping

Typically technology roadmapping is based on a qualitative methodology and identifies the relationship between technology and time. Recently quantitative techniques have been introduced into technology roadmapping as well.

Qualitative techniques are often based on structured workshops where a group of ex-perts identifies the relevant elements of the TRM. The contents are derived in a subjective form from the know-how and expertise of experts. A good example of such an approach is the T-Plan method [4].

The quantitative approach is based on objective data and mathematical algorithms rather than subjective judgments. However, data generation and data processing are not free from errors due to misinterpretations and false estimates.

Hence an approach, which combines the positive aspects of both approaches, is favorable [5-6]. In this Paper a combined simulation based method, customized for the challenges of systems innovations like the electric bus, is presented.

3 Simulation Based TRM

3.1 Methodology

Simulation based TRM allows forecasting the future system behavior and provides indications about future requirements for technological solutions. Based on the findings, the right time for a market entry can be estimated, which provides a base to plan the product development processes.

By modeling the system with its elements, relationships and boundaries in a system model [7], the structure of a system becomes more transparent and manageable. It allows finding interdependences, sensitivities and possible threshold values. A major advantage over classic workshop based approaches is a higher degree of objectivity and reproducibility of the results.

The structure of the technological system defines the stochastic model of the simulation (as shown in figure 2). Hence the systems structure needed for a simulation based TRM depends on the elements of the system, their relationship and input/output relationships. System engineering provides a set of tools that support an analysis of the system structure. One exemplary tool is the design structure matrix method, which provides a methodology for the structuring of complex systems into interrelated subsystems and components [8].

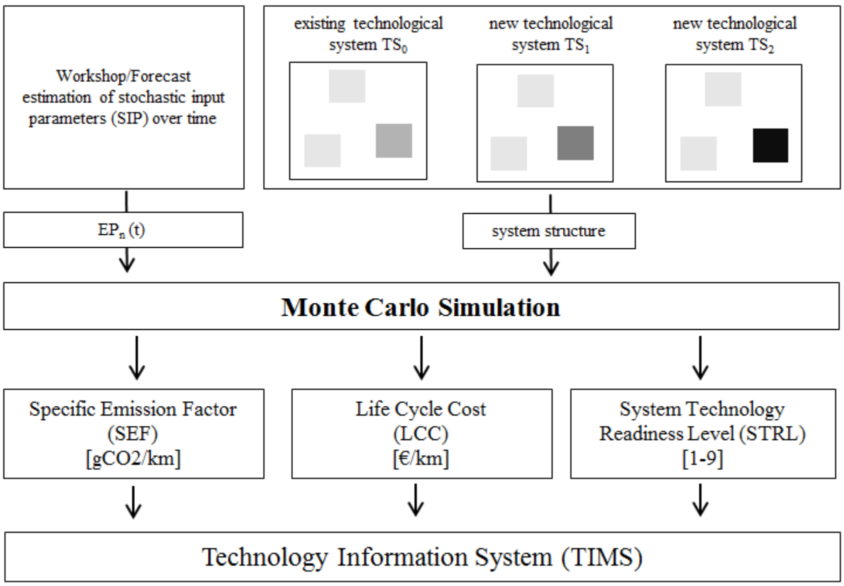

Fig. 2. Key Performance Indicator System

For the electric bus system three KPIs are evaluated. The first performance indicator measures the LCC as an economic objective. The second indicator is the SEF, which measures CO_2-emissions per output unit as an environmental objective. The third indicator is the system technology readiness level (STRL), which is an indicator for the maturity of technologies and possible technical problems associated with system integration.

Based on the system structure a deterministic model for the Monte Carlo simulation can be defined. Input parameters are stochastically modeled variables which are driven by out-side influences. Based on stochastic input data the Monte Carlo simulation iteratively computes the stochastic distribution of the KPIs.

For the modeling of the input parameters, the project evaluated and review technique (PERT) [9] is used. PERT has its origin in the military network planning. This technique is widely used to plan projects under uncertainty which is normally the case in R&D programs. As an input for the PERT distribution estimations of the optimistic (o), most likely (m) and pessimistic (p) value of an input parameter are carried out. With these three parameters and the factor k, which represents the weight of the most likely scenario, a beta-distribution is derived [10].

The expected mean value of the Beta-PERT distribution can be easily obtained from:

$$\mu = \frac{o+km+p}{k+2} \qquad (1)$$

With the standard deviation of a Beta-PERT distribution:

$$\sigma = \frac{p-o}{k+2} \qquad (2)$$

Input data can be obtained from internal or external studies, as well as subjective expert estimations. Specialized internal or external experts with specific knowledge in a particular field (e. g. battery technology) can estimate certain input parameters even if they do not have a grasp of the entire system. This is an important enabler for an effective information search.

For every input parameter specific values for the variables a, o and p are estimated. The focus on only three values makes the methodology manageable and convenient for the application in industry practice. If the experts involved can not agree about the input values the arithmetic average of the expert's estimations is taken.

The readiness of components technologies is an important indicator, for the risk associated with the development of a technological system. Therefore the STRL should be one of the three KPIs.

The STRL methodology is based on the TRL scheme, developed by the National Aeronautics and Space Administration (NASA) which is based on a 1-9 scale. TRL 1 represents the level of basic research whereas TRL 9 stands for field tested (figure 3).

TRL 9	Actual system flight proven through successful mission operations
TRL 8	Actual System completed and flight qualified through test and demonstration (ground and flight)
TRL 7	System prototype demonstration in a space environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 5	Component and/or breadboard validation in relevant environment
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 2	Technology concept and/or application formulated
TRL 1	Basic principles observed and reported

Fig. 3. TRL levels proposed by NASA [11]

The estimation of a TRL at the system level requires more than just single TRLs. The criticality of the various components must also be considered. Therefore it's proposed to weight the TRLs according to its criticality if they are aggregated to a system technology level. The criticality value of the components should be measured as proposed by Hicks and Larsson (see figure 4).

Criticality Value	Definition
3	Technology is 'enabling' to the core functionality of the product. No work-around or substitution possible.
2	Bold Technology fulfills a vital role in the product's functionality. However, a work-around may be possible using substitute technologies that will incur an acceptable penalty.
1	Technology is 'enhancing' to the product's performance, cost etc. Several alternative technologies exist that could be substituted and incur a minimal penalty.

Fig. 4. Definition of the criticality value according to Hicks and Larsson [12]

The STRL value is computed from:

$$STRL = \frac{\sum(TRLxCriticality)}{\sum(Criticality)} \tag{3}$$

In this paper the concept of Hicks and Larsson is extended to a multi-layer concept, which also considers subsystems. The criticality of a superior system should be defined as the arithmetic average of it included subsystems respectively components.

The deterministic model for the STRL calculation in the case of an electric bus system is shown in figure 5.

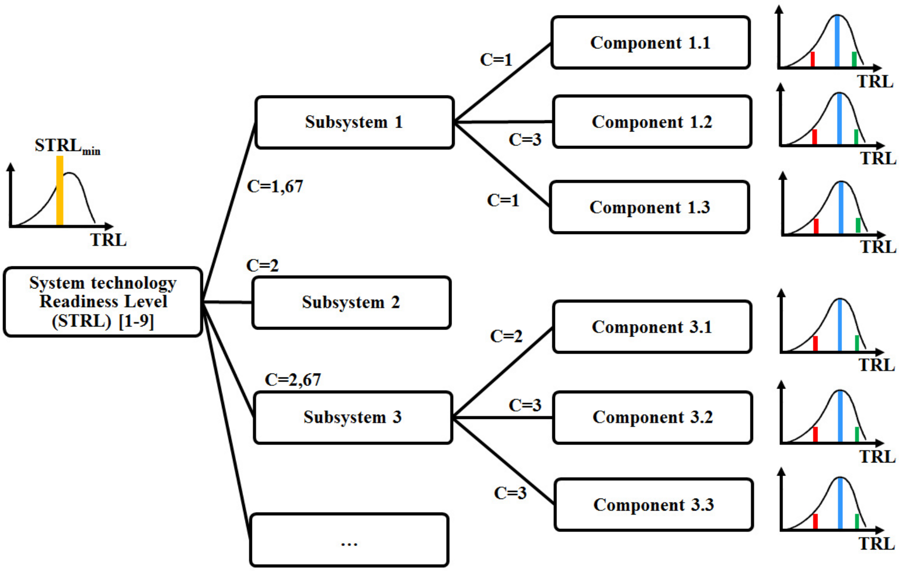

Fig. 5. Structure of the system simulation in the case of an electric bus (excerpt)

The stochastic modeling and simulation of the other KPIs (SEF and LCC) has been described in more detail by Spangenberg and Goehlich [13].

3.2 Technology Information Management System

For the Interpretation of the calculated KPI distributions a transparent and manageable method has to be provided.

All single KPIs like LCC, TRL and SFE [CO_2/km] could be weighted and aggregated to one high level KPI, which represents the overall performance of the technological system [14]. However this leads to the problem of finding reasonable weights for each KPI. Furthermore there is a danger of not recognizing a critical single KPI because it is compensated by others. Therefore it is expedient to define specific minimum values for each KPI and to monitor the KPIs with respect to mean value and standard deviation over time.

The evaluation is carried out with the following comprehensible traffic light logic:

A traffic light is “green” if for the new technological system the KPI mean value is better and the standard deviation is smaller than the existing system. It’s “yellow” if either the mean value or the standard deviation is better. Naturally it’s red, if both characteristics are worse [13].

In the specific case of the TRL KPI the traffic light becomes green, if the mean value of the TRL forecast exceeds TRL_{min} and the p-value lies above a predefined threshold (e. g. 0.95). At that point, the technology is ready enough to shift its development from scientific institutions like universities to the corporate R&D departments, which integrates it into the system context.

The stochastic simulation is executed, based on different input parameters, for different years so that the probability distribution of the system performance over time is generated. Figure 6 shows the simulated TRLs of an urban bus system for the years 2012, 2016 and 2020.

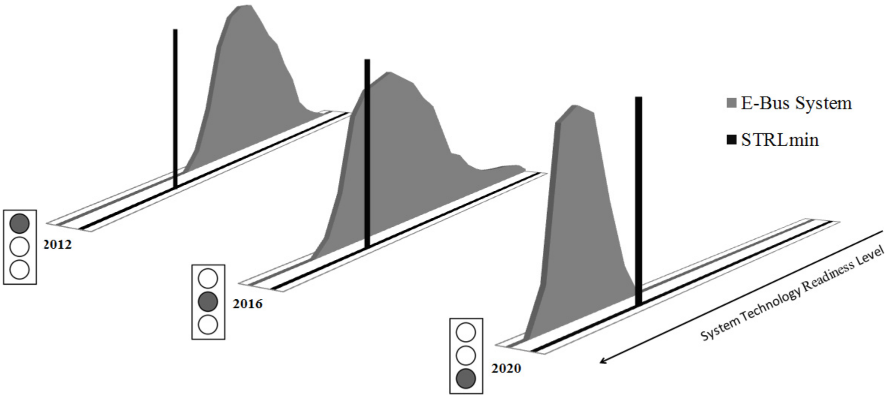

Fig. 6. Exemplary results of the stochastic TRL simulation

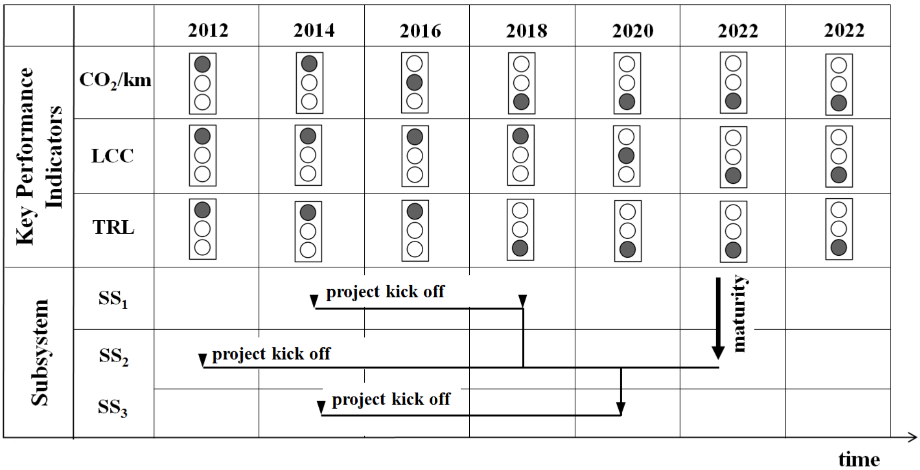

Fig. 7. "Technology Information Management System" (TIMS) as an decision tool

When the TRM is constructed, all three KPIs have to be considered. Therefore a Technology Information Management System (TIMS) like in figure 7 can give substantial support. This TIMS displays the traffic light forecast for every KPI over time. If all traffic lights are green, the new system is favorable in contrast to the consisting system, so that it makes sense to switch to the new technology.

From that point of time the R&D roadmap is planned backwards. The project kick-off for the separate subsystem development projects is planed top down from the time to market point, based on the estimated project time and the interdependencies between the projects. In the example in figure 7 the R&D project for subsystem SS_2 starts in 2012 whereas project SS_1 in 2014.

4 Conclusions

The new TRM method presented in this paper could successfully be applied to an electric bus system innovation. The concept of stochastically modeled KPIs allows a forecast of the expected system performance and takes uncertainties of the system parameters into account. Through the use of a consistently structured model and identical input parameters for the simulation of the different KPIs valid results are ensured. The proposed technology information management system provides a suitable decision making tool. Since TIMS can be easily updated, continuous information about the best time to market can be provided. Furthermore this information system supports the planning of the different product development processes.

A bus manufacturer can obtain a suitable TRM for the electromobility R&D strategy while a public transport authority can use the results to plan the introduction of electric busses in its fleet.

The adaption of the presented approach to systems innovations in other industries is currently under investigation.

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Technical Risk Management for an Ensured and Efficient Product Development on the Example of Medical Engineering

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Abstract. Nowadays, industry and trading companies are facing a lot of risks. These risks occur in a variety of different fields such as in the corporate strategy, the development of new products or in the introduction of new business and production processes. Due to external influences in particular technical risks are increasing, e. g. by regulations, increasing price and quality competition or shorter product life cycles, reasoned by innovative products. Therefore, an effective and efficient technical risk management system is crucial, to keep competitive advantages. A survey of the FRAUNHOFER INSTITUTE FOR PRODUCTION TECHNOLOGY IPT, regarding technical risk management (TRM) in manufacturing companies, confirms the described importance, because 75% of the companies assign TRM a very high importance within the product and process development. Against the background of shown challenges, the FRAUNHOFER IPT developed an approach to make the assessment and control of technical risks more efficient.

Keywords: Risk management, risk assessment, risk control, quality management.

1 Introduction

In a survey conducted by the FRAUNHOFER INSTITUTE FOR PRODUCTION TECHNOLOGY in 2011, 180 manufacturing companies were asked what methods they use for assessment of technical risks and what challenges they face by assessing and controlling technical risks. The results show that the Failure Mode and Effects Analysis (FMEA) with 60.3% is the most utilized method. Also highly widespread is risk assessment in workshops and team meetings (52.5%). The methods DRBFM (9.5%) and FTA (7.3%) are less utilized within risk analysis.

When asked about the biggest challenges within analysis and evaluation of risks (see Figure 1), the lack of clarity and precision of the methods becomes apparent. One

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reason for this is, for example, that often subjective assessments do not lead to a common risk definition and do not deliver enough objective bases of valuation by appropriate scales. The reason for the lack of quantification is reasoned by difficult surveyable data and therefore only partially applicable statistical models. An immediately following problem is the dissatisfaction of employees by conducting risk analysis and assessments, because the results are not clear enough (for example same values of Risk Priority Number RPN). In addition, employees are frustrated by the lack of implementation or tracking of measures to treat risks. Another reason for the lack of precision may lie in the universal character of the methods. The methods are not individual enough to specific industries and products, for example in medical engineering, where risks for the patient have to be evaluated. So individualized concepts that regard organization, corporate culture as well as deployable resources of a company are required.

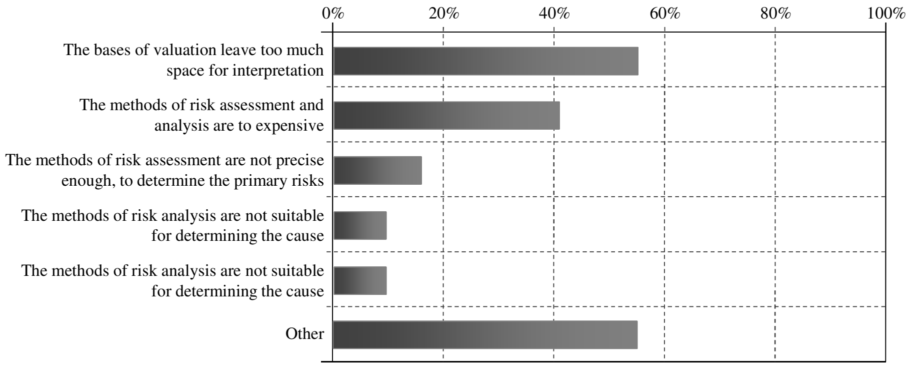

Fig. 1. Challenges related to risk analysis and assessment

The sustained success of risk management is possible only through the control of risks. Therefore it is important to assess the effectiveness and to draw conclusions from the risk assessment for future projects. The high costs (time, money, personnel) are criticized as a challenge related to the control of risks. From the fact that 38.6% of the enterprises consider the benefits of risk control as too low, can be concluded that the potential of risk management is not yet fully recognized and exploited. Concerning the acceptance of risk management 33.5% of the participants of the survey fear personal consequences in the analysis and assessment of risks.

The following paper treats this problem by introducing an integrated model for assessment and control of technical risks. Therefore existing approaches for risk assessment and control as well as their central deficits are illustrated. On this basis a method for technical risk assessment and a model for technical risk control are described. The paper closes with the illustration of the model validation results in the medical industry.

2 Current Approaches to Assess and Control Technical Risks

2.1 Methods to Assess Technical Risks

As the results of the survey show, FMEA is the most utilized method. Amongst others the reason for this are different normative requirements (e. g. ISO 14971 in medical engineering or ISO TS 16949 in automotive sector etc.). Along the product development process different tools supporting risk management exist. The methods are introduced in the following.

FMEA. The goal of a Failure Mode and Effects Analysis FMEA is the analysis of products and processes during the early stages of development concerning potential failures and initiating measures for failure prevention through an integrated risk analysis [1-6]. In effect, an FMEA reduces development time and costs, while increasing the quality by avoiding product defects [3]. Therefore FMEA is a valuable tool for risk management [6]. The most common arguments against FMEA are the high costs of implementation, the influence of subjective perceptions and the difficult interpretation of the risk priority number RPN that is not to be considered as an absolute degree for risk [5-7]. The monetary quantification of risk on the basis of the risk priority number is not possible either. Thus, the sole application of FMEA does not lead to an objective quantification of risk and solutions to eliminate the causes of failures, but it allows a systematic and structured collection of explicit and implicit knowledge about possible failures [6, 8-9].

QRC. The QuickRiskCheck QRC is a simple method for the identification of critical process risks. It was developed at the FRAUNHOFER IPT. In the first step a process is mapped, divided into process steps and the main risks of these steps – in form of failures occurred in the past – are identified. Afterwards the most risky process steps are identified through pairwise comparison. The risks of these process steps are analyzed in detail. The occurrence probability and effect of every identified risk is aggregated and assessed by a 3-stage scale. In the following, measures are defined and their effect on every single risk is evaluated on a 4-stage scale. Through this evaluation of the aggregated benefit of the measure, a ranking of all measures is developed. Furthermore the possibility of determination of the costs of each measure exists. [10-13]

FTA. The Failure Tree Analysis FTA is a method for systematic identification of failures in complex and safety related systems [14-16]. The starting point is an analysis of the technical system under consideration (product / manufacturing process) for which an undesirable event is to be defined and a failure tree will be developed. For this failure all possible combinations of malfunctions are identified and displayed in a tree structure. [14-15] As all single causes of a failure respectively damage have to be identified, the costs rise over proportional to the complexity of the system, so that the construction of the failure tree is very challenging [16-17].

ETA. The Event Tree Analysis ETA was first used in the atomic energy field and gradually extended to other fields such as chemical engineering and mechanical engineering [18]. ETA is an inductive logic and diagrammatic method for identifying the various possible outcomes of a given initiating event such as the malfunctioning of a system, process or construction [19]. This bottom-up method leads to a tree consisting of an initiating event, probable subsequent events and final results caused by the sequence of events. Probable subsequent events are independent to each other and the specific final result depends only on the initiating event and the subsequent events following [20]. In this way failure initiation and escalation are represented by a series of trees based on binary logic trees [21-22].

DRBFM. A method that has a very close connection to FMEA, as it was derived in large parts from her, is the Design Review Based on Failure Mode DRBFM. Both methods – DRBFM and FMEA – identify and eliminate product and process inherent risks systematically. While FMEA analyzes potential risks of an entire product or process, the DRBFM concentrates on changes to existing developments and designs. The DRBFM emerged from the realization that changes contain the highest potential for failure and are often implemented without a structured examination of the influences on functions. The goal of DRBFM is to identify potential risks in the development that are aroused by changes on existing products through systematic procedure and to minimize these risks through changes within the product design. [23-25]

2.2 Methods to Control Technical Risks

Risk control as the last phase of the risk management process is a continuous task that concentrates on monitoring the risk situation in the organization [26-28]. The function of risk control is not limited only to monitoring alone, but extends to the review and improvement of existing approaches as lessons learned are fed back into the risk management system [28-29].

With the fulfillment of the tasks of risk control the risk management process is a repetitive closed loop (see figure 2). The information feedback from the phase after development and production allows a steady examination of the current relative to the desired risk position and the derivation of appropriate measures in the preliminary phases of the risk management process. [29-31]

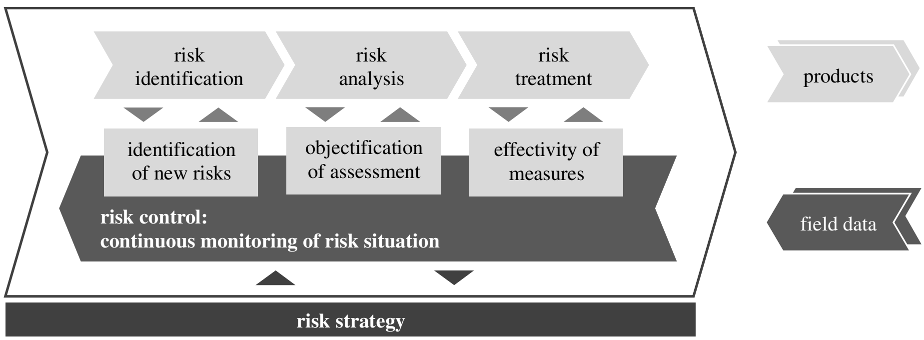

Fig. 2. Tasks of risk control in the risk management system

Flawless Startup. A method for continuous monitoring and controlling risks, developed at FRAUNHOFER IPT in cooperation with MAN DIESEL&TURBO SE is Flawless Startup. The methods defines a structure in which all risks and problems (so called Flaws), for example in a design project, are collected and structured, including all existing information. Within the systematic all necessary information is requested and the necessary measures for treatment determined. Through continuous review-meetings, the status of every flaw is monitored and problems within treatment are documented. The use of Flawless Startup provides a learning effect for new design projects. [32-33]

2.3 Central Deficits and Need for Action

Existing approaches for risk assessment only provide a qualitative rating, for example by using risk portfolios. These methods provide an insufficient image of the probability of occurrence and monetary consequences of risks. Reasons for this are the difficulty of predicting events without historic data and the combination of a risk with its financial consequences because of the delay of some consequences, for example warranty claims or loss of image. Reasoned by the lack of methods for quantification the value of risk management is often considered too low, as the consequences of risks cannot be described and quantified on a monetary scale while decisions are based on costs and benefits in many industries. Another deficit is the simulation of probability of occurrence and monetary consequences of risks, as the existing models of simulation and approaches are too complicated or necessary data can only be received with high costs.

Risk control sustainably ensures the success of technical risk management. The most existing approaches only provide general process models without practical help. With the feedback of data relevant to risk management from field data, the risk management process of an organization becomes a repeating closed loop. Along this closed loop exists a deficit on practice-oriented methods.

3 Methodical Approach

In order to amend the existing methods of risk assessment and control the FRAUNHOFER IPT developed a model for technical risk assessment as well as a process model for risk control.

Goal of the method and the model is the elimination of deficits within the assessment of interdependencies in risk consequences and the efficient control of technical risks. The control of technical risks completes the closed loop of risk management that contains the process phases identification, analysis and assessment and control. This way the overall gain of knowledge in form of a validation of risk assessments is realized. The module of risk inventory and its use in medical industry is illustrated in extracts. The application shows how relevant data can be collected and used in future activities of risk management. Thus, the benefit of risk management is increased sustainably – in the opinion of the companies surveyed.

In the following the method for assessment of the interdependencies in risk consequences is described at first. Afterwards the model for control of technical risks, which completes the closed loop of risk management, is illustrated. In this closed loop the method of risk assessment introduced before as well as the methods of controlling, e. g. the risk inventory are located.

3.1 Method for Technical Risk Assessment

As basis for the method, an event tree is developed in the first step. In the style of a failure tree, used to determine the causes of a risk, the event tree systematically identifies potential risk consequences. The goal is the transparent illustration of all risk consequences, which then will be assessed qualitatively and quantitatively. The selection of the risk to be assessed is based on the knowledge about its consequences, so that expert's opinions are often consulted. The effort of the methods varies with the possible risk consequences. In order to simplify the method and reduce the effort, assessments can be standardized based on the results of former detailed assessments.

The goal of the qualitative assessment is in particular the illustration and evaluation of interaction between risk consequences. For this, the RISK STRUCTURE MATRIX RSM is developed that identifies risk consequences with the highest potential negative influence on other risk consequences and for this reason should be avoided. The developed RSM can be used for risk assessment in product and process development as well as in production.

Development of Potential Risk Consequences by Event Trees. Goal of the development and assessment of potential risk consequences is, to systematically determine the most critical consequences of a risk. Critical means that the consequence with the highest expected damage and probability of occurrence become transparent to allow a decision concerning the treatment of the risk. For the identification of risk consequences, existing approaches of visualizing risk consequences, in form of event tree analysis, are used. [34]

The choice which risk has to be assessed is reasoned on the basis of risk analysis executed in the process step before. For the chosen risk an event tree is designed with the help of methods mentioned before under the use of the Boolean algebra. The illustration is done as detail-oriented as possible, i. e. risk consequences are divided into their smallest logical sequences. Figure 3 shows the schematic illustration of an event tree and the risk consequences contained. After the tree structure is finalized, the probabilities and monetary consequences of the single branches have to be determined. In contrast to the FTA, the probability of detection of the potential failure and the predicted monetary damage is assigned to the branches besides the probability of occurrence. These key figures match the RPN of FMEA and can be used in a subsequent detailed analysis of ETA. In case of unknown consequences this can be the initiating point for the execution of further analysis, for example in form of Design of Experiments DoE.

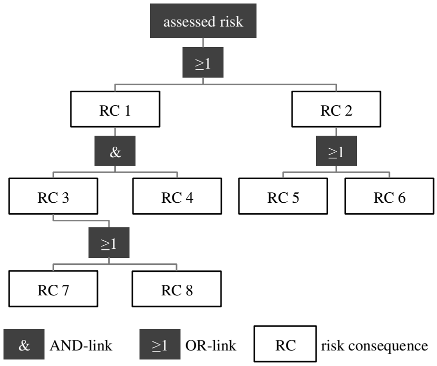

Fig. 3. Schematic illustration of an Event Tree

Determination of the Critical Path through Minimal Cut Sets. After the tree structure has been developed and the necessary input data has been determined, the analysis can be started by determination of the minimal cut sets of the tree. A minimal cut set contains the minimum amount of risk consequences that result from the assessed risk. The goal is the identification of the critical path or the minimal cut set that contains the risk consequence with the highest probability occurrence or damage, or the lowest probability of detection. Cut sets can be derived from the structure of the Event Tree in which the logic element "and" can be interpreted as conjunction and the logic element "or" as disjunction. [35]

On the basis of the derived cut sets, risk consequences that are most likely to occur and least likely to be detected can be derived. These consequences represent the most critical consequences and have to be assessed on basis of existing risk tolerance intervals with the highest priority. The total probability of occurrence of a cut set is determined through multiplication of the probabilities of each contained risk consequence. The resulting probability of the assessed risk is determined trough addition of the probabilities of all minimal cut sets.

Risk Structure Matrix for Assessment of Interactions between Risk Consequences
The created Event Trees, including the determined minimal cut sets can be input of a systematic approach for transparent visualization and assessment of interaction between risks. Starting point are cut sets, that can be transferred in the so called Risk Structure Matrix RSM. The goal of the RSM is to assess risk consequences within the cut sets, concerning their interaction on risk consequences in other cut sets, i. e. increase or diminish the risk or have no effect.

The RSM is a continuative method to the ETA and the quantitative assessment. It allows the qualitative assessment within risk consequences to identify the greatest risk drivers. On the basis of the results a direct risk treatment of the critical risk consequences is possible. The results of the method are integrated into the risk inventory and serve the continuous risk assessment to its final elimination.

3.2 Concept of a Process Model for Risk Control

The following chapter contains the introduction of a process model for risk control. The process model can be divided into an event-driven part, with relation to the collection of field data and a part for continuous review of the risk situation within the organization. The model completes the aforementioned closed loop of risk management.

In the event-driven part field data are analyzed regarding potential risks. The identification of risks after receiving field data is necessary as single risks can demand immediate action because of their possible damage. Furthermore data are analyzed regarding to content and formal aspects, to ensure a high quality of information. Central challenge is the focus on data that pictures product or process risks adequately. Result of this process step is the determination what data has to be gathered in which way. As risks that have not been identified are not considered in the further progress, this step is highly relevant for the complete visualization of the organization's risk situation.

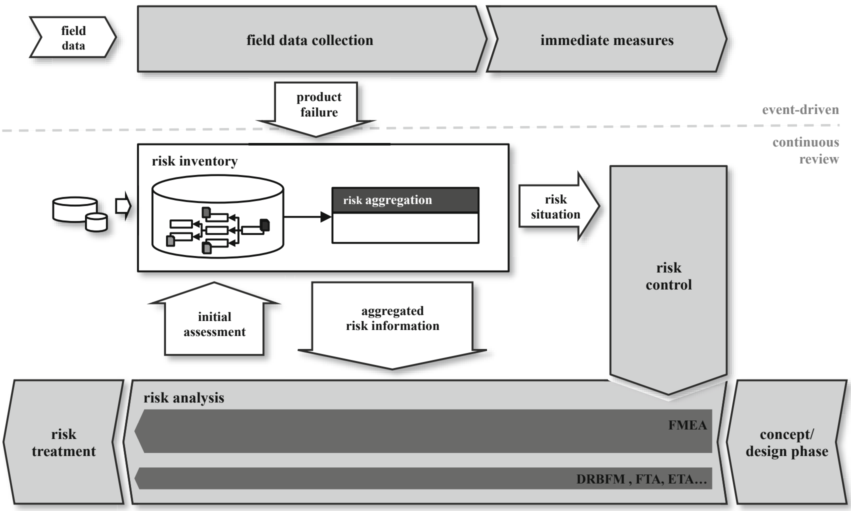

Fig. 4. Concept of the process model for risk management

The sequence of the event-driven part of the process model is based on the first steps of the 8D-method that serves for systematic analysis and correction of problems and is e. g. frequently used within the execution of reclamations by manufacturers in the automotive sector [5]. Besides identifying the problem, immediate measures are executed, to ensure that the customer is not further affected by the problem. Furthermore failure causes are determined and measures are initiated to fix the problem. In the process model all incoming product risks are not treated in this complex way. In fact a decision based on the assessment of possible consequences of the single risks to the customer is made, whether immediate measures are necessary.

In the second part of the process model the identified single risks are aggregated for continuous review of the organization risk situation. The aggregated risks picture the risk situation of a product in field, to initiate risk treatment measures, whenever the situation deviate from the goals defined in risk strategy. With the initiation of measures the loop is closed, as gained knowledge from the field data is fed back into the product development process. Central instrument of risk control is the risk inventory in which all risks occurred in the field and each result of the activities along the risk management process is entered. The data structure enables the aggregation of single risks and the address-related supply of information relevant to risk management. Innerhalb des Modelles kann die zuvor präsentierte Methode der RSM innerhalb der Risikoanalyse verortet werden. Hier kommen ebenso Methoden wie die FMEA oder die FTA zum Einsatz.

Module Risk Control. In the module of risk control the actual risk situation pictured in the risk inventory is compared to the defined targets in risk strategy. The module serves as an actuator that initiates more detailed risk analysis when deviations occur.

The cause analysis for risks occurred in field is executed in the following module of risk analysis and takes place using existing methods from product development (e. g. FMEA, DRBFM, FTA or ETA). On the one hand impulses for the execution of risk analysis come from the module of risk control. On the other hand risk analysis are initiated after the development of a new product concept. In the following the module risk inventory is introduced more detailed.

Module Risk Inventory. Task of the risk inventory is the structured collection of all risks occurred regarding a product. In addition to every product risk in the field, the risk inventory must allow the registration of additional information, like initial assessments of the risk in the product development, taken measures or responsibilities. As the initial point of information relevant to risk management is the product itself, the representation of single risks is done in accordance to the product structure – as it is usual in methods of technical risk management like e. g. FMEA. Every product can be divided into assemblies, which can further be divided into single parts. The smallest unit of a product is a part that cannot be further deconstructed respectively is not further deconstructed by reason of defined criteria.

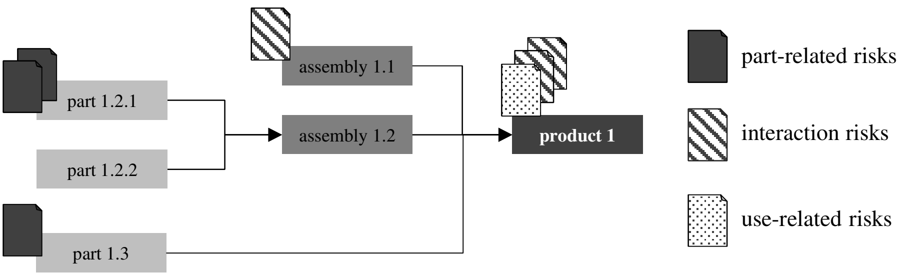

Fig. 5. General structure of risk inventory

Three risk categories can be distinguished. On the one hand risks that can be assigned to a part, as for example the mechanical breakdown of the part due to construction failures or failures in manufacturing. Furthermore risks can origin from the interaction of different components (parts or assemblies), for example by the incompatibility of several components. The third risk category describes risks that occur within the use of the product, for example in human-machine-interaction or through environmental effects.

The collection of product risks in accordance to the product structure has several advantages. On the one hand the gathering is done in accordance to the existing and supporting methods of risk management. On the other hand this structure allows the aggregation of risks.

Practical Application in Medical Industry. The validation of the module risk inventory was done based on interviews with the goal to collect the existing approaches in practice of medical engineering more detailed. By this the designed structure of the model can be compared to practical approaches and improvement potentials can be identified and implemented.

In the interviews the imprecise definition of parts was criticized, as it is not clear, how to handle purchased assemblies and how the term is associated with the term component. The application of a level-model consisting of several sub-components or systems was seen as potential for improvement. In reference to bought-in parts it was observed that often the correctness of the manufactures data regarding the failure probability is not further questioned or analyzed. Knowledge of part-related risks is hence hardly possible. Only in rare cases the analysis of interaction between assemblies or parts can be used to gain data regarding risks of single parts.

Another note was that the sequential procedure within risk assessment and with it the structure of the inventory for a new product should be amended with an iterative process. Within a practice example it was shown that first part- and assembly-related risks along the production process are analyzed, before in the next steps also risks of the human-machine-interface are considered. The results of the use-oriented FMEA are finally implemented in the development process. This process is executed until the remaining risk is on an acceptable level. The existing model has to be amended with a back loop depending on the scenario of application.

Overall, the method and model have been seen as facilitative tools within the control and assessment of technical risks. The reasonable extent of use of the method is still to be tested.

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A Simultaneous Engineering Approach for Free Form Bifurcated Sheet Metal Products

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Abstract. In this paper a simultaneous engineering approach is introduced to cope with the complex and elaborative engineering design process for bifurcated sheet metal products. The design process comprises product design, sheet blank design, and tool design. Free form surfaces derived from mathematical optimization processes are the starting point for product, tool, and sheet blank design. Part design is strongly connected and references to the underlying free form surface. For the 3D-CAD models a modeling concept is introduced where free form surfaces are referenced from an external source. A workflow to manage the design process and to deal with possible changes and iterations during product development is also developed and presented.

Keywords: CRC 666, simultaneous engineering, free form modeling.

1 Introduction

The members of the collaborative research center 666 "Integral Sheet Metal Design with Higher Order Bifurcations - Development, Production, and Evaluation" research and develop tools and methods for the development, production and evaluation of sheet metal products with bifurcations. Linear flow splitting and its derivative linear bend splitting are the underlying manufacturing techniques that enable the production of sheet metal profiles with bifurcations made in integral style. Today, multi-chambered profiles can be made in an appealing quality. Subsequent deformation of sheet metal stringers produced by bend splitting further increases the product range of bifurcated sheet metal. The product development process for this kind of products is highly integrated and includes the domains of product development, mathematics and production. The collaborative research center 666 developed an algorithm-based product development process for sheet metal profiles that aims to generate optimized solutions from product requirements. To achieve this aim product requirements are transformed into optimized product topology and geometry by mathematical optimization processes. The generated geometry is subsequently transformed into 3D-CAD models that build the basis for detail design and manufacturing [1]. For free form sheet metal products the algorithm-based approach is reconsidered and adapted to the new requirements. The mathematical optimization now begins with a starting geometry that is optimized with regard to parameters and objective functions derived from

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product requirements. The target functions for optimization can be for example maximum stiffness, minimal weight, or maximized heat transport. The optimization process is described in section 3.1

In this paper a simultaneous engineering approach for development and production of this new kind of products is presented. First state of the art and the main ideas of simultaneous engineering are presented in section 2. It is also explained why simultaneous engineering is necessary and valuable for free form sheet metal products with bifurcations especially when a mathematical optimization process is executed. Then a brief introduction to linear bend splitting and the forming process is given to identify the special requirements to product development processes from bifurcated sheet metal products. Section 3 describes the developed concept to enable simultaneous engineering for bifurcated sheet metal and the associated development processes. The different product models are described and a method to link external geometry to CAD models to enable simultaneous engineering is explained.

2 Fundamentals of Simultaneous Engineering

Simultaneous engineering (SE) is a powerful approach to improve the product creation process. SE describes methods for integrated product and manufacturing process development. The major goal of SE is an optimization of product creation with regard to the “magic triangle”, i.e. shorter time-to-market, reduction of costs, or an increase in quality [18, 19]. The decrease in product development time allows a quick reaction to trends and demands on the market which is the most promising and effective way for company’s success [18].

Although many definitions for SE exist the main characteristics can be identified as integration and parallelization of processes. Process parallelization implies that processes are started with uncertain or incomplete information. To achieve parallelization of processes a detailed process analysis is required to identify sub-processes with their minimal required information. In a composition phase the sub-processes can then be rearranged and reordered to a simultaneous engineering workflow.

Reconsidering the primary aim of simultaneous engineering, the parallelization of processes and a decrease in time-to-market an additional advantage of simultaneous engineering becomes obvious: the early accumulation of knowledge by interdisciplinary teams and the high amount of communication between formerly sequential processes leads to a broad understanding of the product and the manufacturing constraints. Errors and disadvantages can be identified and corrected in an early stage of product development. This effect is called “front-loading”. It increases the product development process and leads to a decrease in the total product development costs but shifts those towards the early phases [19].

Applicability of Simultaneous Engineering

The mentioned advantages and characteristics of simultaneous engineering implies that simultaneous engineering is an obvious and generally suitable method for every product and company. In fact simultaneous engineering requires complete restructuring of the company's processes, workflows and working culture. It is also required to be well prepared if the desired product shall be suitable for simultaneous engineering. Products with a high volatility in requirements, products that are based on new technologies, and products with uncertain success are better designed by sequential product development process.

3 Product Creation of Bifurcated Sheet Metal

3.1 Mathematical Shape Optimization

The product development approach within the collaborative research center 666 applies mathematical optimization to generate the product geometry. The shape optimization uses product requirements and manufacturing constraints from product planning to derive optimized product geometry. The process starts in a conceptual phase by collection of product requirements and the creation of a preliminary product shape. The shape is a free form surface with defined parameterization for example a NxM control point matrix with a defined B-Spline degree. For the mathematical optimization process input data from requirements is transformed into objective functions, constraints and optimization parameters. A finite element calculation is executed as described in [1]. The outputs of this process are new control point coordinates for the starting free form surface and the relative position and parameters of the stiffeners, i.e. the bend-splitted flanges. The output is used in CAD modeling to automatically generate 3D-CAD models from the preliminary product shape. For details on the mathematical optimization please refer to Ulbrich et al. [21].

3.2 CAD Modeling

Most 3D-CAD systems apply solid modeling techniques to generate 3D-CAD models [7]. For simplification and standardization of the modeling process feature technology is used. A feature is set of geometry and/or information with a certain purpose for example manufacturing features, quality features, or assembly features. The most commonly used features are form features (e.g. block, cylinder, and cone) and manufacturing features (e.g. holes, chamfers, and threads) [8]. To generate product models for bifurcated sheet metal products modeling features for linear bend splitting and linear flow splitting were developed [9] and [10]. To create flanges on non-linear profiles and on free form surfaces a new feature approach had to be developed that processes B-Spline based reverences. This feature approach was presented in [11]. Within the collaborative research center 666 the created 3D-CAD models are used for manufacturing and finite element analysis of the deep-drawing process (see section 1.1).

3.3 Manufacturing Processes

Flow Splitting and Bend Splitting

Linear flow splitting and its derivative linear bend splitting (fig. 1) are cold massive forming techniques that enable the creation of bifurcated sheet metal products without material doubling or joining [2]. Linear flow splitting is an incremental forming process. Sheet metal is "split" at the sheet edge by a set of a forming roll and two support rollers and formed to a Y-shaped profile. For linear bend splitting the sheet metal strip is initially bent by roll forming in a 90 degree angle. Thus a new edge is created and the forming is conducted by a splitting roll and a set of support rollers to back the sheet metal from buckling. Bend splitting increases the product range of bifurcated sheet metal by enabling the creation of flanges at almost any position on the sheet surface [3]. Sheet metal stringers made in integral style are profiles with two or more flanges. The forming process induces an increased strength in the deformation zone and in the created flanges [4, 5].

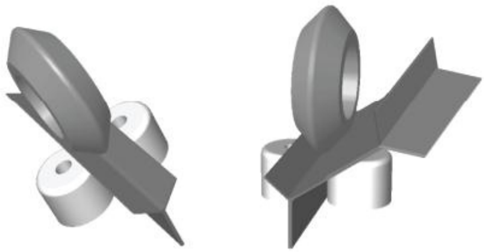

Fig. 1. Linear Flow Splitting (left) and Linear Bend Splitting (right) [20]

The term "linear" with flow and bend splitting describes the geometry of the edge where deformation takes place. New approaches enable the creation of non-linear flow-splitted parts, i.e. profiles with variable cross sections. In this case the sheet edge is preliminary curved by high speed milling or laser cutting and then formed by a moving tool set [16]. For non-linear bend splitting the edge is curved by flexible roll forming. This technique becomes relevant in particular when deep drawn stinger profiles ought to have flanges with specific distance and orientation on the product. During the forming process the relative position of the flanges differ slightly on the sheet surface because of the unequal material movement into the mold. Thus the orientation on the sheet blank must be calculated and manufactured so that it will fit the positioning requirements after the deformation process.

Hydroforming of Bifurcated Sheet Metal

Bifurcated sheet metal stringers made from bend splitting are well suited as semi-finished products for hydro-forming. With this forming process the created flanges can be formed within certain limits. The working fluid supports the flanges and prevents their deformation. To create sheet blanks from bend-splitted stringer profiles a sealing zone is milled. The blank is then inserted into the tool. A hydraulic press provides the pressure for closing the bottom and top mold and a pump builds up the forming pressure from which the sheet blank is deformed and pressed into the tool [5]. A schematic picture of the process is shown in fig. 2. The process is very restricted concerning the degree of deformation and possible flange heights i.e. flange to sheet thickness ratio. As in any forming process the product underlies a back-spring effect, caused by the elastic behavior of the material. It is significantly increased by the bend-splitted flanges. The back-spring effect depends on various parameters such as geometry, material, the retaining force, the applied tool, and friction. For bifurcated sheet metal products a computer aided simulation of back-spring effects is required as common assumptions and simplifications are no longer valid [6]. Besides product shape the back-spring effect is the most important factor for tool design. To derive process parameters and to ensure manufacturability, the process is simulated using finite element analysis. Detailed information about the forming process and the parameter identification can be found in [4] and [17].

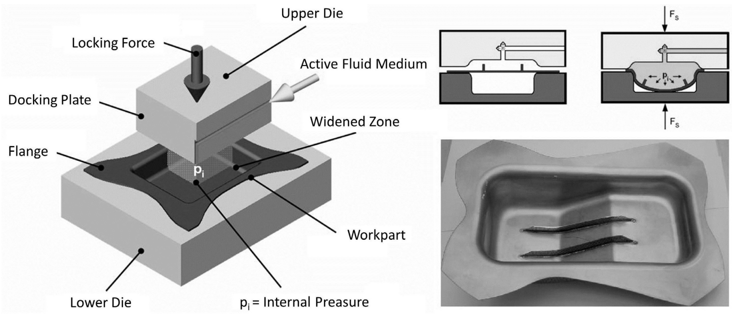

Fig. 2. Hydroforming of Bifurcated Sheet Metal and Example Product [5]

4 Simultaneous Engineering for Bifurcated Sheet Metal

The introduced advantages and properties of simultaneous engineering do fit well for the product creation processes in the collaborative research center 666 where different domains collaborate with respect to a single product. In fig. 3 the development process for bifurcated sheet metal products is shown. As described in section 1, the engineering design process for bifurcated sheet metal is very complex and requires different domains to collaborate and to process information. Anyhow, the products created within the product range of bifurcated sheet metal are similar in their general structure and manner. A general concept can be developed that is valid for the whole product range. The differences from one design project to another are the product shape, the free form surface, the number and orientation of flanges. But in general the structure of each product is quite similar. Product development and manufacturing planning are the domains involved in the engineering design process. The main idea of this paper is to enable a simultaneous engineering design by external geometry linked to CAD models from product design and manufacturing planning. The external geometry is easily accessible by the different domains and serves as input for the mathematical optimization process. A XML file is used to store the geometry data. It is independent from CAD models and other proprietary file formats. The aim of the approach is to have different domains working simultaneously with yet uncertain geometry information. By linking this external geometry to 3D-CAD models the geometry can be optimized while the CAD models are in detail design or used for simulation processes. The external geometry then works as placeholder within the models.

Product creation of bifurcated sheet metal requires three different 3D-CAD models: The product model, the tool model (i.e. lower die), and the sheet blank model. Each CAD model has its own characteristics and modeling structure. The product

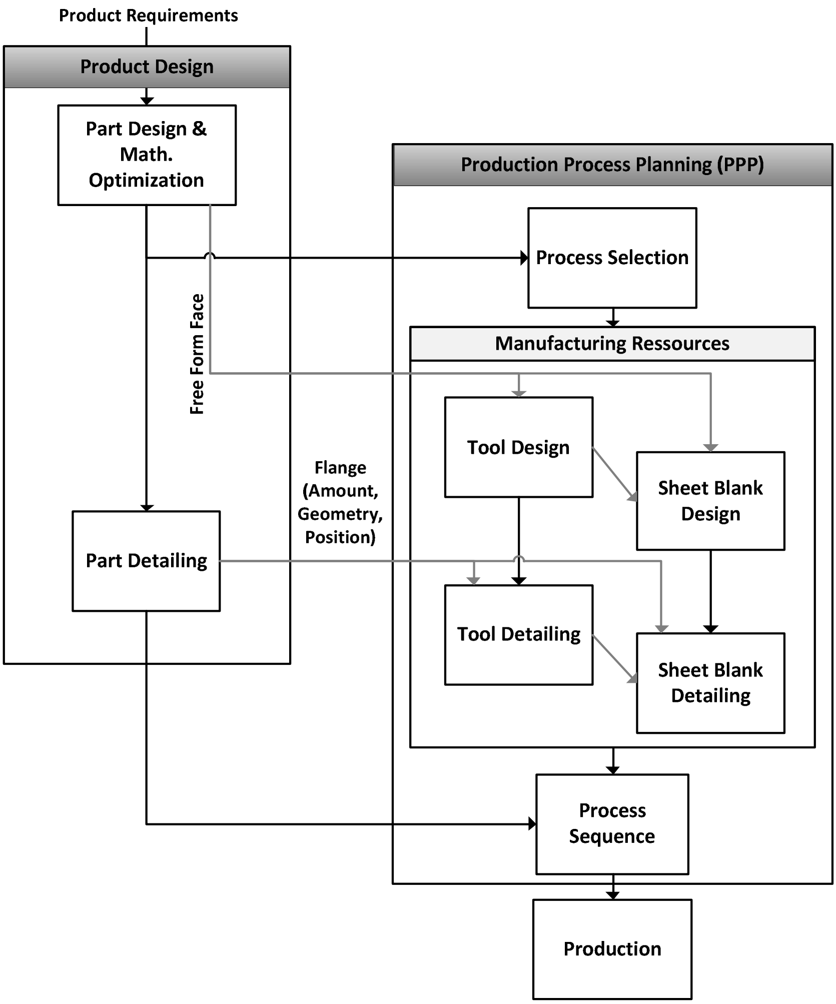

Fig. 3. Simultaneous Engineering Process for Bifurcated Sheet Metal

model describes the product itself in its deep drawn and cut out state. The tool describes the tool geometry with all required process specific components. Back-spring effects are considered in the tool to ensure, that the demanded product geometry is achieved successfully. The sheet blank describes flat geometry before the forming process. It is of special interest how flanges need to be oriented so that they will be placed in the desired position on the product after the forming process.

All parts have similarities and shared geometry. This concept uses these similarities to generate a base structure of geometry that is referenced from an external source. All CAD-models adapt automatically to changes in this external source.

4.1 Model Dependencies

It is required to identify dependencies between the CAD models and the external geometry to further detail the development processes and to ensure a consistent information flow.

- Product model:
  The product free form is the basic geometry for the whole product development process and the driving input in development. Nevertheless changes in the free form can be necessary if problems occur in tool design or sheet blank design.
- Tool model:
  The free form surface of the tool is derived from the product free form and the compensation of back-spring effects (derived from a finite element analysis). The flanges on the product significantly influence the back-spring effect.
- Sheet blank model:
  The flange positions and orientation on the sheet blank depend on the tool and product design. The flange positions are derived from manufacturing simulations.

Considering these dependencies it is obvious that a general sequence of product design, tool design and sheet blank design is required to ensure a consistent information flow but it is also obvious, that iterations are required and that models need to be changed during development. The identified dependencies and the conclusions drawn from that analysis are important to create a simultaneous engineering concept and build the foundation for process detailing.

4.2 Referencing External Geometry

To enable the introduced simultaneous engineering processes the external geometry needs to be linked to the 3D-CAD models of tool, product and sheet blank. In this section a method is described that references an external source file, e. g. a XML document that contains the free form data. As mentioned above, the free form surface is described by NxM control points and a B-Spline degree. To use this geometry in the respective CAD files an import filter is defined for each part. This filter uses the control point coordinates from the XML file and processes those for each element. The tool for example has a slightly different free form surface than the product. To the product's control point coordinates the back-spring compensation is added. For the sheet blank the product's free form and the relative position of the flanges are used to calculate the position and orientation on the blank.

The 3D-CAD models of tool, sheet blank, deep drawn product and the final product are shown of an example product. The design process was started with a simple tray. An example load case was defined and the mathematical optimization created a free form surface. The surface is then used in the different models by a reference to a XML file. Thus the parts could be predesigned while mathematical optimization was still in progress. The created product models were used for finite element analysis and the solutions from this analysis were in turn used for the final shape design. Each product model will automatically adapt to changes in the referenced free form surface basic geometry.

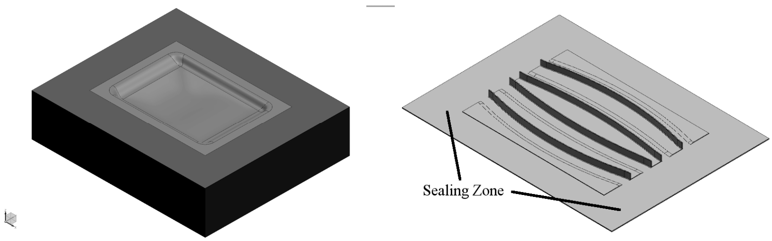

Fig. 4. Tool Design (simplified, right) and Sheet Blank Design (right)

In figure 4 a simplified 3D-CAD model of the tool is shown. The light grey area illustrates the geometry that is referenced to an external source. It will adapt to the changes in the XML file.

In figure 4 the sheet blank with flanges is shown. The sealing zone is also visible. The flange position (darkened) is referenced to the external source.

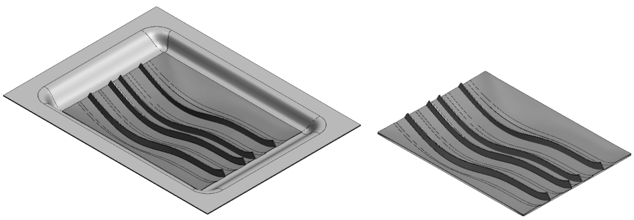

Fig. 5. Deep-Drawn Part before (left) and after (right) cut-out

The product model is shown in figure 5. The free form geometry is linked to the external source. It is the driving input for the product development process yet it also underlies changes that might impact manufacturing planning.

4.3 Data Management and Change Management

Within the CRC 666 an information model was developed that describes a data structure for bifurcated sheet metal and the information flows as well as workflows involved in the development process [1]. The structure is used to define the XML structure and to identify relevant processes and actors in the design of bifurcated sheet metal. To support an effective simultaneous engineering process it is crucial to deliver the required data in time to wherever it is needed in the workflow. For bifurcated sheet metal characteristic information is the free form surface and the position and orientation of the bend-splitted flanges. Both are stored in a XML file. The file itself can be stored in a PDM system or any data base.

For effective simultaneous engineering, change management processes are required. Thus everyone concerned by a performed change in the base geometry is notified automatically by the implemented workflows. These notifications provide information about changes that affect the work of the recipient. He can then use the changes for further detailing or to check if the work done is still valid.

Two different cases of changes can be distinguished in the scenario of bifurcated sheet metal products: One represents changes that affect the free form face and/or the flanges (change type 1), the other represents all other changes that have no effect on the free form surface like changes in holes or other detail design features on the product (change type 2). Each change in the flanges or the free form surface requires changes in tool design and sheet blank design. Thus it is not necessary to categorize changes any further.

The start of the process chain begins always with the generation of the product geometry: In case of a change in product geometry because of new features, the change affects the free form surface and thus the flanges (change type 1). As soon as the change process is started the subsequent processes, in this case tool design and sheet blank design are notified and supplied with the new geometry data.

5 Conclusions and Future Work

In this paper a simultaneous engineering approach for sheet metal products with bifurcations is introduced. To specify the required information flows the geometrical connections between the 3D-CAD parts were identified and described. Thus it was possible to develop a process for data exchange between product design and production planning in a time-dependent workflow model. In addition a method for change notification and support was introduced considering change types, information flow and relevant actors. The interaction and links between the 3D-CAD part files for tool, sheet blank, and product were demonstrated by an example product.

The referenced geometry is a single patch free form surface. In complex products free form surfaces are often built form multiple patches. The concept needs to be extended to such geometry. Until now only product development and manufacturing are considered in the concept. It could be extended to other domains and steps of the product creation process.

Acknowledgments. The results presented in this paper were determined within the framework of the subprojects A4 and A5 of the Collaborative Research Center CRC 666 fund by the German Research Foundation[1].

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Complexity Management in Product/Process Simultaneous Design for Implementing a Fresnel Thermodynamic Solar Plant

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Abstract. Fresnel mirror in thermodynamic solar power plant technology is an efficient power resource in many potential countries. The key challenge is cost effectiveness of the product and its settling. The importance of using this technology redounded in writing this paper to propose a methodology in order to design this system considering its complexities. Because of the dependency of the product with process of production and installation of this solar plant, a simultaneous design methodology is required. Moreover, a concept of movable factory, from one solar farm site to another one, is also discussed which is identified as a proper solution for such project with reusability.

Keywords: product-process interaction, design methodology, mobile factory design, complexity management, solar power plant, Fresnel.

1 Introduction

As Tsao stated, "In any given hour, more energy from the sun reaches earth than is used by the entire human population in a given year" [1]. In addition to this fact, solar power, with free and available source of energy in many countries, has the minimum environmental damages among different types of renewable energies [2]. Considering these advantages, although, recently there was a fast growth in solar generation but still according to US Energy information administration; only 13% of energy is supplied from renewable energies which less than 1% of that is from solar energy [3], [4]. Therefore, solar energy and specifically the technology of Fresnel mirror has chosen as target market for this paper.

Fresnel Thermodynamic Solar (FTS) technology is a new generation of concentrated solar plants to use the thermal energy of the sun. A FTS system uses the heat of sunray as solar energy and reflects and concentrates this energy by a Fresnel mirrors over a flow of fluid to create steam. This paper focuses on this technology of concentrated solar power plant but the method and discussions can be applied to any other type of project with similar nature.

The target project is to produce and install a 500,000 m² solar farm (i.e. 50,000 reflectors of 10m² and 136 receptors of 240m long each) in 6 months. This plant is supposed to supply energy for at least 40 years [5]. Logistics aspects suggest a movable

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factory as a relevant solution instead of manufacturing in one place and shipping all the material. In addition, the temporary factory needs to be movable to produce for at least in five different locations.

One of the main issues is the interaction of product with production. Therefore, in the product development aspects, the ease of production and installation method in the process of product design needs to be considered. So, it would be a concurrent designing. To sum up, lack of a systematic methodology for this concurrent designing, together with time limit and the concept of movable factory, makes the design process relatively complex.

Thus, the hypothesis of this paper is to introduce a methodology to design a product and process for planting a FTS system taking into account the complexity of the design process.

2 Complexity and Variability Management in Design

According to Seth Lloyd, there are several ways to use the word "complexity" [6]. It can be the amount of computation, scale of measure, or amount of effort which is needed to manufacture a product [7]. The design method of this solar plant is considered as a complex system because;

1. The scale of project considering the required effort is relatively large,
2. The target time limit compared with the size of the project is short,
3. The concept of movable factory is needed to be applied,
4. The product and process is closely dependent on each other.

So, with a methodological design, by means of movable factory, a large part of this complexity would be solved. In addition, different levels of variability as presented by ElMaraghy, have to be faced in this project which leads to a high level of complexity that should be managed [8]. Al-Hakima promotes graph representation to map this complexity [9]. At the information level, the interactions and the exchanged knowledge also have to be mapped [10].

First, the product is designed in a parameterized way (1st level of complexity). Indeed this design has to be adapted to the process of production and installation. Taking into account this potential product variability, the mobile factory has to be designed and optimized, (2nd level of complexity). Moreover, the manufacturing system has its geographical dependencies in terms of logistic aspects, power and water supply as well as potential local supply (3rd level of complexity). All these design solutions should minimize the cost of solar field considering the concentration factor and on the other side the cost of mobile factory should have return on investment after five times solar plant installation [11].

Dealing with solar field design requires defining the objective. This objective mainly could be to have maximum energy from a field, to have minimum field area to achieve a desired amount of energy, or to maximize the energy obtained from collector unit area of a field [12].

There are other related complexities in the process as well. For instance the difficulty of protect the installation process from environmental effects because of large project area and environment condition of locations such as deserts.

3 Methodology

In the past, many designs have been made empirically, iteratively and intuitively, based on years of experience and creativity with involvement of much trial and error. Therefore, the methodological design has been created to establish a theoretical foundation for engineers in order to increase the creativity and reduce the iterative trial-and-error processes [7].

The design process in this project starts from early stage of product/ process definitions. Thus, a good orientation could be a top-down approach from macro model of extracting energy from sun to micro model of components and characteristics. This model is shown in figure 1.

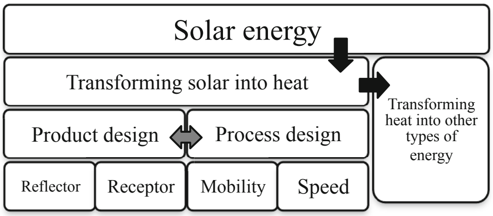

Fig. 1. Top-down approach for design of FTS [5]

As Nam Suh stated in the book of “Axiomatic design”, design is the process of mapping between “what we want to achieve” and “how we want to achieve” [7]. In one interpretation, this definition can be interpreted as mapping between product/implantation itself and the process of designing the product/implantation. But, this definition can be adapted to our goal which is the design of product, and design of the process of achieving the product. Since the process must be based on the product and on the other side, in the process of designing the product, the production and installation method also must be considered. Product/Process and Behavioral modeling approaches give possible representation of these interactions [13], [14].

According to axiomatic design, first the aim of the project should be identified and then the functional domain which includes the functional requirements. These functional requirements map the physical domain which includes design parameters and finally the process domain (see figure 2) [15].

The process needs to be divided into sections to be evaluated. For each section, in the process domain, after literature review and examining the basic available methods based on the stages of the process, there are three simple steps; first, choosing the best related methods among the traditional methods; second, combining the traditional methods to create a new method; and third, the innovative ideas which are obtained by brainstorming and taking ideas from similar methods.

This approach has led to create some possible conceptual solutions with keeping an eye on the limitations of the project. These limitations are time, budget, resource availability, and required specifications for the product with high quality and long-term reliability. Then the best method according to the criteria should be chosen.

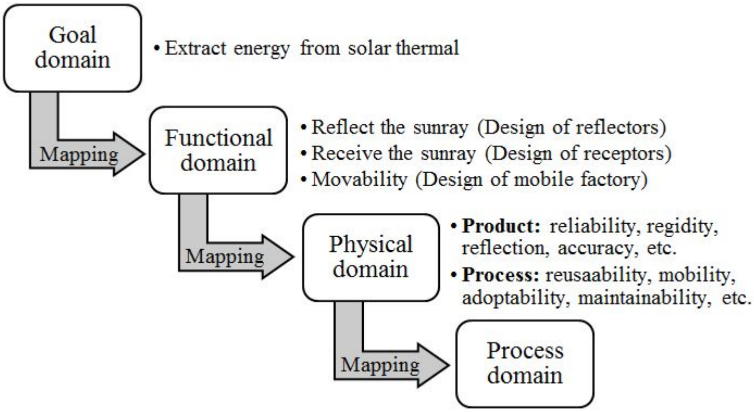

Fig. 2. Four domains for design of FTS

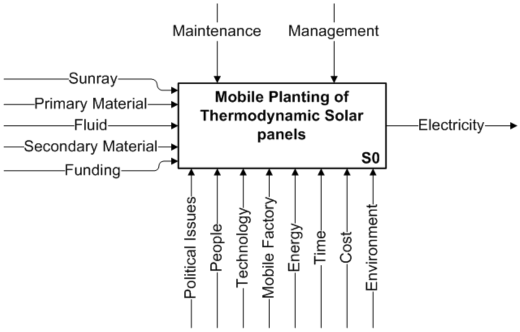

Fig. 3. Key parameters for FTS system analysis [5]

In every stage of design, all the effective factors need to be considered. Figure 3 shows the main factors for a thermodynamic solar plant as IDEF0 (The complete IDEF3 diagram for this project is available in [5]). As it is illustrated in this chart, in the design process, all the material flow, processes, controls and resources should be taken into account. The economical solution will depend on the manufacturing processes and mainly on organizational issues such as material purchase, implementation time, energy and fluid access for the factory.

3.1 Product Design

In brief, the product in this project consists of two main parts, “reflectors” and “receptors”. These two parts are supposed to be installed and work together. So, the process of designing depends on each other. According to the proposed process in Figure 2, first, the characteristics of the product need to be examined. Since the product doesn’t exist to be examined, the aim of the product is scrutinized. For instance, the reflectors are expected to reflect the sunray in the most efficient way to the receptors. Moreover, it needs to be rotatable to follow the sunray during the day. Based on these primary objectives, one can characterise the product and shall proceed to the next steps for designing the rotators, connectors, mirrors and the main challenge which is the support. After, these characteristics become more in detail such as size and geometry, structure of support and so on to satisfy the required accuracy and rigidity.

For designing the receptor, with the same procedure, the objective is to receive the concentrated sunray. To obtain this goal, the receptor must contain pipes for the flux and also should have an insulator to prevent heat release. This system must implement in the height. Therefore, the receptor must contain several tubes with special material to resist from heat while it conducts the heat to the flux. These pipes need to be hanged using holders. Moreover, the cover of receptor, needs to have flexibility to keep straighten in case of thermal expansion which might be different in top and the bottom side. Also, this cover must carry the insulator too.

3.2 Process Design

Beside the product characteristics, the method of production and installation of the plant also needs to be specified. This method is considered as "process" in this paper. As process, managing resources such as material, machines, labor as well as facilities and working conditions are also included. Since our product has two parts of reflector and receptor, one production process has to be designed for each product. Because of dependency of production method with product, the number of process to design would be the combination of these two. It means that, if there are x number of solutions for designing of reflectors and y number of solutions for designing of receptors, there needs to be z number of solutions for processes which $z \geq x{\times}y$ considering x and y are dependent. In spite of manufacturing, we also have to design a method(s) to install these elements. Note that, because of the interaction of these two parts, the installation of them must be adopted to each other and also to the criteria. The main criteria for process are: i) ability to produce the whole solar farm elements within 6 months, ii) reusability for at least 5 times, iii) install and uninstall of the factory in two months, iv) ability to move, v) adoptability with different locations.

So, factors such as **time, reusability, reliability, adoptability** and **mobility** need to be considered during the process of design (figure 2). In this case also the similar methodology of design should be followed. Different stages of the production and assembly line as well as installation stage need to be examined. In most of the production and installation stages, the process is known and could be applied. By considering the criteria, the most suitable method should be chosen and any method needs to be adjusted along with the goal domain.

The production environment has an important role in this project. For instance access to energy, working temperature, dust and etc. will affect the plant and working facilities design. The installation equipment should be portable to cover large area. Levels of portability which will be discussed in next section also need to be chosen. In several design solutions, dividing the processes of production and installation is not appropriate. Modular design of the factory can be applied using shipping containers as structure module.

4 Product/Process Evaluation Tool

As it is mentioned earlier, one of the most complex issues in this project is the interaction of design factors in this project. Interaction between the different levels and product-process is mapped using graph representation as illustrated in figure 4.

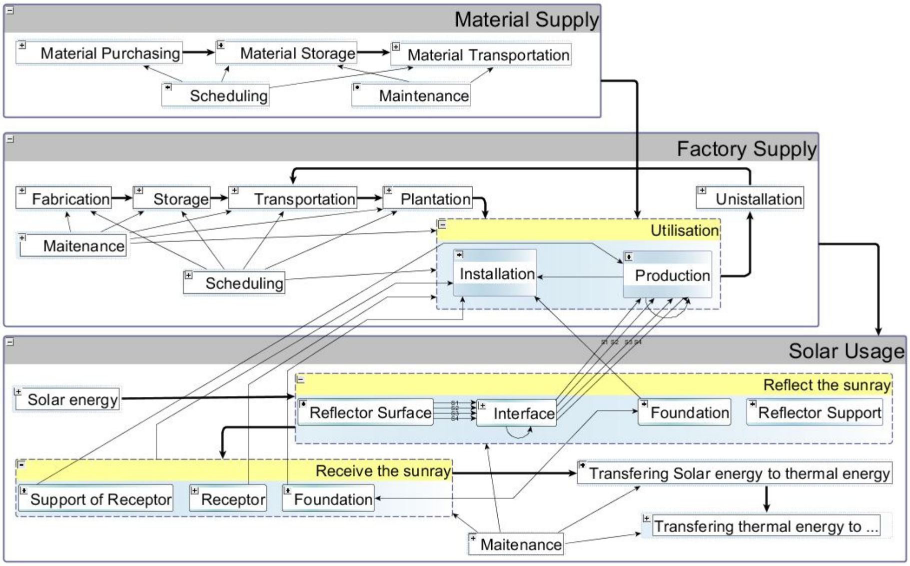

Fig. 4. Product/process elements interactions [5]

After designing stage, regarding these links, each design solution need to be evaluated based on: 1) Process steps and sub-steps, 2) Cycle times, 3) Throughput time, 4) Human resource (number and skills), 5) Types and cost of material, 6) Type and cost of machines, 7) Number of container needed to move the factory, 8) Number of container needed to supply the materials, 9) Bottle necks, 10) Machines' efficiency, 11) Product mass and weight, as presented in Appendix A.

For cost evaluation, reusability of the mobile factory needs to be considered. Assuming five times for reusability, the total cost will be calculated as;

$$\text{Total cost of } \mathbf{1} \text{ solar plant} = \left[\mathbf{5} \times \text{Cost of material} + \mathbf{5} \times \text{Cost of}(\text{Transportation, Labor} \ldots) + \mathbf{1} \times \text{Cost of factory}\right]\big/_{\mathbf{5}} \quad (1)$$

5 Movable Factory Design

As an initial idea for this project, the project supposed to be implemented in North Africa but the special resources are available in source country which is considered as France. By special resource, it is meant materials and machines which are not found in many places (especially North Africa) as well as experts, robots and customized equipment. In addition, the process supposed to be used for more than one project. In this case, the first idea could be to build the product in origin and transport to the destination.

As table 1 illustrates, the cost of transportation for only reflectors panel will be about 775 k€ which makes the project non economical. While, if the material is transported instead of ready panels, the cost would be around 32 k€ which is significantly cheaper. This difference, even without considering the reduction in possible damages during the transportation can justify transporting labor, equipment and etc. and producing in the destination point in case of receptors, the 200m length requirement, rationalizes the proposed transportation method even more. Hence, the concept of mobile factory is used in this project.

Table 1. Cost of transportation for ready panels vs. materials from France to North Africa

40ft Container	Size: 12m×2.35m×2.4m , Volume limit: 37 m^3 , Weight limit: 36500 kg transportation cost of each container: 340 € Fixed transportation cost: 2,300 €	
	Required container	Estimated cost of transportation
Prepared panels	2273	**775 k€**
Materials (Glass & Aluminum)	88	**32 k€**

As DesJardin presents, there are three major level of mobility for a factory; Fixed, transportable and portable. Various factors should be considered to make a factory in high level of portability such as size reduction, weight reduction and power source [16]. In this project, there are two aspects of mobility. First, because of the size and complexity of the product, it's not possible to move the finished goods. So, the idea is to move the material, equipment, labor, and energy source to the destination and then produce and install at site.

The concept of movable factory is not limited to solar plant. Offshore workshop, used in Navy, is a good example of movable production system which enables carrying the missions' maintenance system anywhere in the world. Movable assembly line is another example of using this concept in aerospace industry to have a leaner and more efficient production system.

Second aspect is to use portable factory. A portable factory which is also dubbed as "factory in a box" is a pre-assembled group of equipment which is transportable and can be used as plug-and-play in site. These kinds of buildings are just placed in the site and can be easily removed and transported to another place afterwards. In such buildings, features such as HVAC system, energy generators, etc. could be housed in a 20ft shipping container which can be shipped, trucked or airlifted to any location.

Thus, in the process of production and installation design for such project, movable factory based on the level of mobility, factory life cycle, interdependency of process and product, and other issues needs to be designed.

Before starting to design, the life cycle of the process to build the solar plant needs to be examined. This cycle includes preparation, storage, transportation, installation, use, and uninstallation. The transportation stage means either to move from the source to the project site or from one project to another. In this stage, three categories of human resource, machines and robots, and material need to be transported. In each category some elements could be used by local resources while others need to be transported. Table 2 is the summery of these elements and the way to utilize. The cycle starts from the preparation of equipment, materials, labors, etc.

The installation stage means to install the temporary factory (e.g. in 6 months) in order to build the solar plant and in "use" stage the factory is used to produce the components and install it.

Table 2. Using local resources vs. transporting resources

Category	Transport	Local resource	Category	Transport	Local resource
Human Resource			Material		
Experts	✓		Reflector (glass)	✓	✓
Simple workers		✓	Metal (aluminium)		✓
Trained personnel	✓	✓	Foundation (concrete)		✓
Machines / Robots			Pipe	✓	
Special robots	✓		Prepared components	✓	
Customized machines	✓		Water		✓
Normal equipment		✓			

Because of the difficulty of components like receptor, and time shortage, these two stages need to be done in parallel with a proper scheduling. For fast establishment of large area foundation, machines such as concert slip forming machine, asphalt finisher, track renewal train and etc. could be occupied. These machines create a flat surface which makes it easy for equipment and labor to move in the project area especially for portable factories and also it can be used to install the solar plant components. After installation and use, with considering the concept of green factory, all the equipment of plant production must be collected from the site except those which are necessary for the utilizing the solar plant.

6 Conclusion and Discussions

This paper proposed an example and the starting elements of a methodology in order to deal with complexity in design of product and production/installation process with bearing in mind the cost, quality and time. The main complexity which is faced first in this project is the interaction of product with process which made it necessary for a concurrent designing. The next level that must be integrated is the adaptability and reliability requirements due to mobility.

To evaluate a design as a "good design", at first the goal has to be identified. So, this methodology is started from goal domain. This goal maps the functional requirement which maps the physical domain for product and process. Finally, in the process domain, the procedure needs to be divided properly and the three steps apply for each section.

After designing the product and processes, the solution needs to be evaluated by the "evaluation tool" which was proposed. By means of this tool, different solutions of product design would be examined and subsequently, the design of process is evaluated. Regarding the goal domain, the design decision is made based on the result which includes cost, scheduling, number of containers, etc.

After the conceptual design phases, other aspects such as movable factory are also integrated which according to the project, the level of movability needs to be chosen. This movability makes the process less expensive in transportation, more efficient for covering large area, and possible to be reused for at least five times. The reason of choosing "five" as reusability is that considering transportation time, inventory waiting time and production time, five times of implanting a solar power plant takes about 5 to 7 years. After this time most probably the product is no longer on top of technology and should be replaced by a competing product which gives a better performance.

Since the time is so limited in this project in comparison with size of the project, milestones are substantial to be scheduled and therefore each process needs to be illustrated as simogram. This Gaunt chart is fundamental as far as so many processes may happen in parallel in this project and it's crucial to have them all on time.

This methodology, using the evaluation tool, works as a dynamic tool for "what-if" scenario. At any stage, one factor can be modified and the result is being observed. However, the discussion is for the early stage of design and the next developments will give more precise rules for evaluation (costs or time). These sharper equations can be easily integrated in the evaluation tool and use its final results (input/output data). After evaluation of the solutions, if the result is not satisfactory, the characteristics of domains change and then the method applies again until the desired result is achieved.

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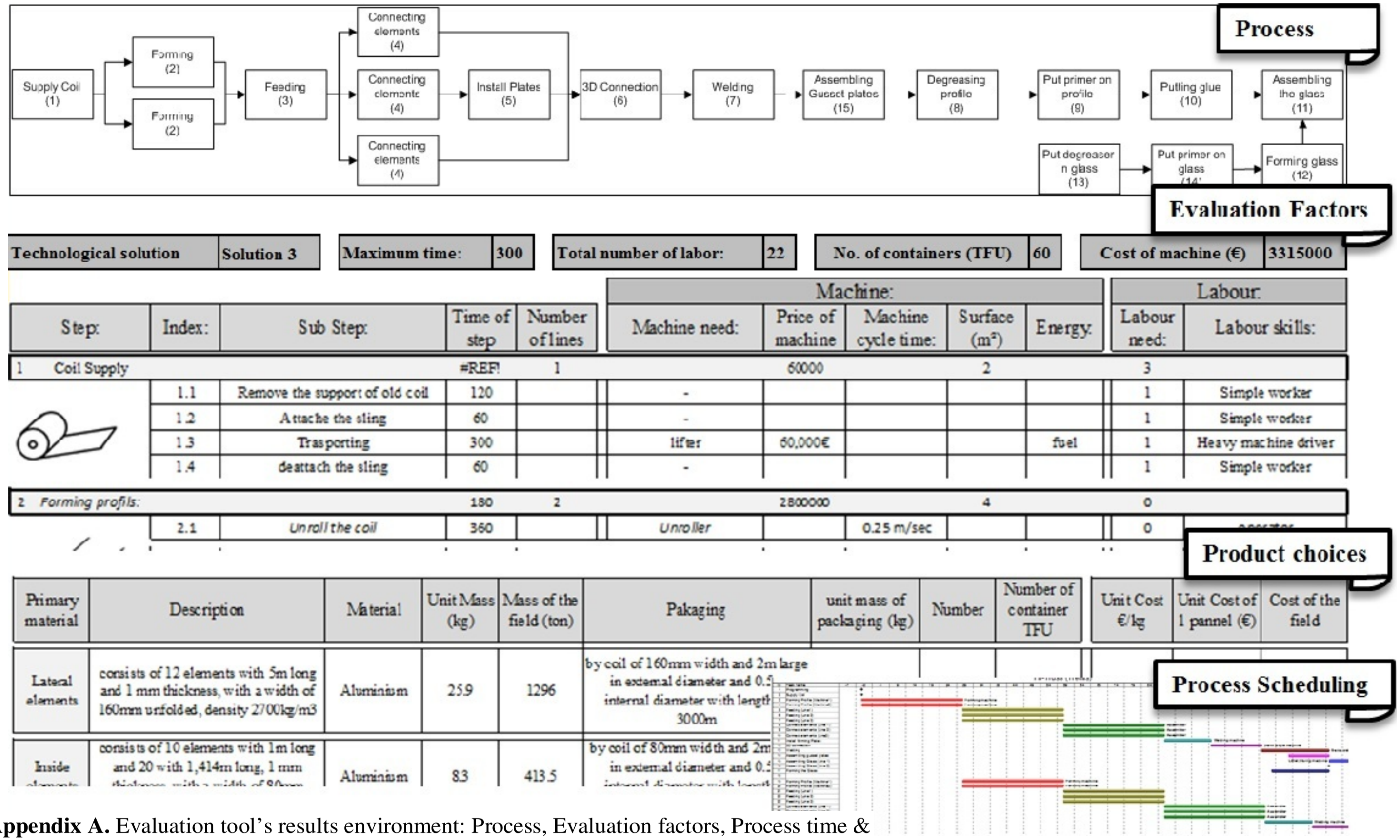

Appendix A. Evaluation tool's results environment: Process, Evaluation factors, Process time & Product choices [5]

Embodiment Discrete Processing

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Abstract. The phases of the embodiment stage are sequentially conceived and in some domains even cyclic conceived. Nevertheless, there is no seamless integration between these, causing longer development processes, increment of time lags, loss of inertia, greater misunderstandings, and conflicts. *Embodiment Discrete Processing* enables the seamless integration of three building blocks. 1) *Dynamic Discrete Representation*: it is capable to concurrently handle the design and the analysis phases. 2) *Dynamic Discrete Design*: it deals with the needed modeling operations while keeping the consistency of the discrete shape. 3) *Dynamic Discrete Analysis*: it efficiently maps the dynamic changes of the shape within the design phase, while streamlining the interpretation processes. These integrated building blocks support the multidisciplinary work between designers and analysts, which was previously unusual. It creates a new understanding of what an integral processing is, whose phases were regarded as independent. Finally, it renders new opportunities toward a general purpose processing.

Keywords: Embodiment, Design, Analysis, Dynamic Meshes, Mesh Modifications.

1 Introduction

The use of a digital representation of an (either existing or conceptual) object or shape in different domains, such as in engineering, entertainment, cultural heritage or medicine, is essential for representing the 3D physical reality. This is true for several shape representation schemes such as point clouds, isosurfaces, subdivision surfaces, meshes, parametric surfaces, and B-reps, among others. These representation schemes have a tight inherited relationship with their corresponding production technique. On the one hand, in the case of physically born objects, for example a laser scanner can typically generate a point cloud suitable for triangulation, while a computed tomography - CT scanner - can usually generate volume data suitable for isosurfacing. On the other hand and referring to digitally born objects, CAD systems ([1]) classically model with B-reps or Constructive Solid Geometry - CSG - schemes and freeform surface modeling systems normally work with parametric, polygonal or subdivision surfaces.

Although the representation schemes for digitally born objects can easily be transformed into the representation schemes of the physically born objects, the opposite case is not a straightforward process. Furthermore, the domain application also influences the utilization of specific representation schemes. For instance, in engineering

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B-reps, parametric surfaces and meshes are commonly used; polygonal, subdivision or parametric surfaces are frequently employed in the entertainment industry; in the cultural heritage field subdivision or polygonal surfaces and meshes are widely established; while B-reps, parametric surfaces and meshes are extensively exploited in the medicine sector.

Nevertheless, regardless of the domain application and the corresponding representation scheme, producing and using a shape demand dedicated processes. In the mechanical engineering domain, a workflow in the context of the Systematic Approach to Engineering Design, proposed by Pahl and Beitz [2], presents this more clearly. This workflow has four stages: a) task clarification, b) conceptual design, c) embodiment, and d) detail design. Task clarification mainly deals with collecting the requirements for the given problem; conceptual design aims to propose a feasible solution(s) based on the identified requirements; embodiment builds a digital representation of the solution and verifies its performance against the expected functionality; and detail design generates the specification of the evaluated solution toward manufacturing.

The embodiment stage illustrates the dedicated processes for producing and using a shape and it is subdivided into two main phases: i) design, and ii) analysis. The design phase entails the different processes, which are needed to produce a shape for the analysis phase, e.g.: digitization, processing, modeling, or synthesis. The result of the design phase is a shape, whose geometric characteristics are described in a specific representation scheme. The analysis phase involves the different processes for interpreting the shape, in other words, for correlating the shape with other properties, such as semantics, materials, physics, and functions, among others.

2 Related Work

Although the phases of the embodiment stage are sequentially conceived and in some domains even cyclic conceived, there is no seamless integration between these, causing longer development processes, increment of time lags, loss of inertia, greater misunderstandings, and conflicts, etc. The lack of integration is motivated by several aspects: i) representational - designers require a geometric representation and analysts require an analytic representation, ii) functional - designers constantly change the geometry of the shape and analysts normally take a snapshot of the geometry, iii) deterministic - designers want to describe a shape, while the analysts want to infer properties from the shape, and iv) cultural - designers and analysts do not communicate with the same terminology. This situation is found in several domains and industries.

This is the case for producing a mechanical part in the engineering domain, where on the one hand, the embodiment design is carried out using a CAD system with an internal representation schema based on B-reps, which supports several modeling operations for specifying and constructing the geometric characteristics of the part. And on the other hand, the embodiment analysis is performed using a CAE system with a discrete representation (e.g. a tetrahedral mesh) for simulating the dimensions of the part with its material, in order to satisfy a functionality described by physical laws. Thus, there is a need for an extra representation, in order to correlate the geometric characteristic of the part with its functionality. These cases become even more demanding, if the analysis produces new requirements toward the design and these need to be communicated by the analysts to the designers, since there is no established transition between analysis and design, as its counterpart between design and analysis.

This situation of multiple representation schemes for two highly interdependent phases poses a major challenge: how to efficiently handle the different representations for streamlining the process and for achieving multidisciplinary environments? Different strategies can be followed in order to address this challenge: 1) improving the transition techniques between the different representations, 2) complementing existing representations with some of the missing capabilities of the other phase, and 3) developing an existing or new representation, which is able to efficiently handle the design and the analysis phases.

In the context of transition techniques, the research community has pursued the development of efficient and robust meshing techniques ([3] and [4]), nonetheless this transition process is not interactive for volume meshes and it is not always automatic. In terms of enhancing representations, they also proposed the isogeometric analysis for 3D NURBS ([5] and [6]), in order to perform mechanical simulation on parametric representations, however it still requires a transition from the 2D NURBS of the B-rep to the 3D NURBS for the analysis and so far it is only possible to simulate simple shapes. Additionally, there are also some approaches dealing with mesh deformation, either only the geometry (morphing [7]) or the geometry with the topology (smoothing and re-meshing [8]), but for the first case there are issues with the quality of the elements during the deformation and it could also insert inconsistencies in the mesh, for the second case the performance is a drawback and the range of operations is limited.

3 Building Blocks

There is so far no effort devoted to developing an existing or new representation able to concurrently handle the design and the analysis phases. In order to develop such an integral solution, which can consistently and robustly deal with the embodiment stage, the following research questions need to be resolved: 1) What is a suitable representation scheme to dynamically deal with the changes of the shape in the design phase and to capture the needed properties for the interpretation process of the analysis phase in a concurrent manner? 2) What is the set of operations that such a dynamic representation needs to support, in order to efficiently and robustly enable the required geometric changes of the shape, while keeping its quality? 3) How can the interpretation process be streamlined given the multiple changes in the characteristics represented by the shape?

These research questions are addressed and integrated in this work ([9], [10], [11], [12], [13]). This work is based on a deep analysis of the related work and the research opportunities, which strengthen the selection of a discrete representation (i.e. mesh). Thus, the *Dynamic Discrete Representation* is capable to concurrently handle the design and the analysis phases. The *Dynamic Discrete Design* deals with the needed modeling operations while keeping the consistency of the discrete shape. The *Dynamic Discrete Analysis* system efficiently manages the dynamic changes of the shape within the design phase, while streamlining the interpretation processes. The seamless integration of these three building blocks is called *Embodiment Discrete Processing*.

This environment allows for the multidisciplinary work between designers and analysts, which was previously unusual. It creates a new understanding of what an integral processing is, whose phases were regarded as independent. And it renders new opportunities toward a general purpose processing.

3.1 Dynamic Discrete Representation

Compact representations are only feasible for static meshes; changes in the topology of the mesh demand a re-encoding of the connectivity. Dynamic representations are mostly dealing with multiresolution problems; hence the computation of the multiresolution model is usually performed offline. Regardless of the characteristic of the existing representations, the current solutions are limited to the type (e.g. surface or volume) or the quality (completeness, orientation or manifoldness) of the input mesh. Thus, representing meshes with dynamic changes require generic and robust methods, in order to reliably compute the neighboring information and consistently updating the topology of the changing mesh.

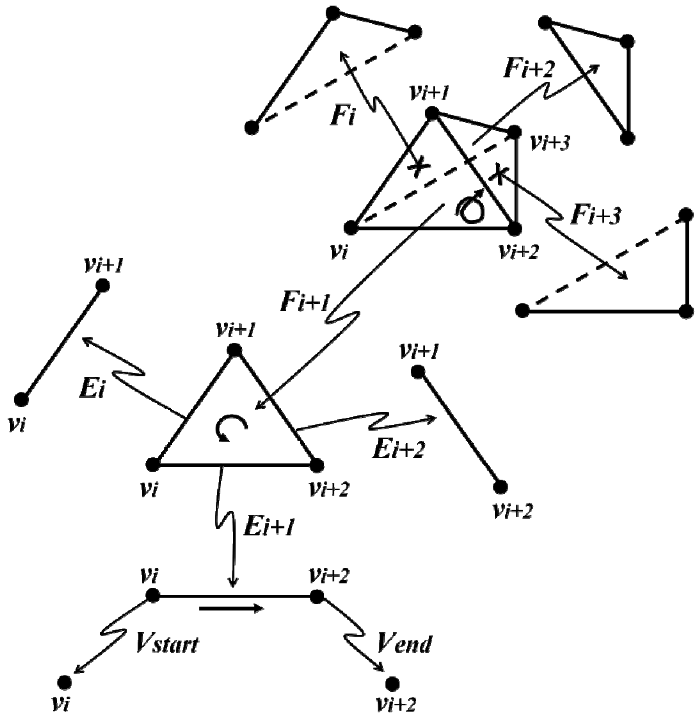

Fig. 1. Dynamic Discrete Representation

The Dynamic Discrete Representation is the building block responsible for keeping a consistent representation of the shape. It is a dynamic mesh data structure, which enables a generic and robust description of the topological entities and their corresponding interrelationships, while efficiently allowing the dynamic modification of the geometry and the topology of the mesh. The main characteristics of the data structure (see Fig. 1) are: a) balanced trade-off between memory and performance, b) robust hierarchical construction, iii) efficient query support, and iv) dynamic changes on the mesh.

3.2 Dynamic Discrete Design

The design of a discrete shape requires the interactive modification of the elements of the shape, while preserving the quality for the following interpretation process. However, many of the proposed assessment methods only consider the individual elements, which could bias the assessment process and the few methods considering the global shape, do not perform at interactive rates. On the other hand, many modification techniques only deal with the geometry of the shape, keeping the topology constant and generating artifacts for large deformation. Additionally, the techniques dealing with the topology (e.g. meshing, remeshing, multiresolution) are not suitable for interactive performance.

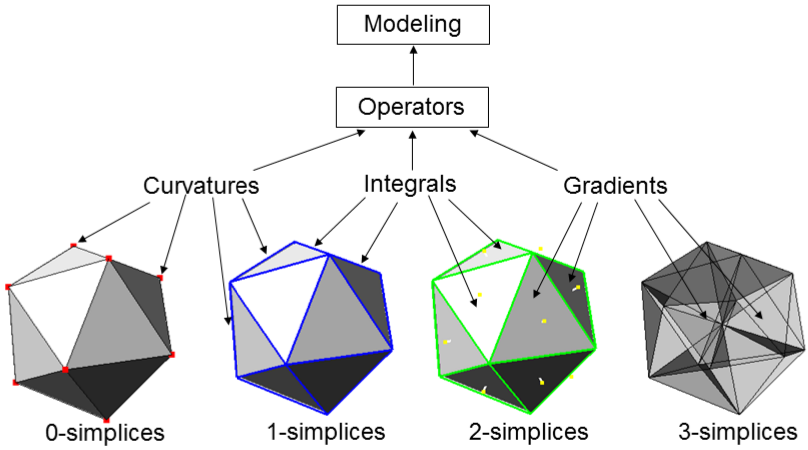

Fig. 2. Dynamic Discrete Design

The Dynamic Discrete Design profits from a novel neighboring based quality measure, which computes the quality of 1-ring vertices, capturing a better understanding of the local mesh configuration. This quality measure evaluates the condition of the 1-ring vertex neighborhood, by means of computing for every involved simplex the deviation between the direction of the gradient vector and the direction of the mean vector (see Fig. 2). These deviations are averaged, providing a value in the range [0, 1], which quantifies the quality of the 1-ring vertex. In addition of capturing a better understanding of the local mesh configuration, the 1-ring quality measure also provides clues on the ill-conditioning of the 1-ring neighborhood, which is tackled by improving its interpolating condition and therefore the gradient of the vertex regarding the 1-ring neighborhood, leading to a low condition number of the linear system and therefore accuracy in the solution. In order to improve the interpolating condition of the 1-ring vertex, regarding the neighboring vertices, the algorithm applies an optimization procedure, which combines complex topological operations and smoothing techniques, aiming to generate optimal local configurations. The optimal configurations are found by averaging the height direction of the affected simplices, regarding the 1-ring vertex. The resulting direction suggests an infinite line, where an optimal configuration can be found for the ill-conditioned area, such that the 1-ring-vertex can improve its gradient. The possible configurations are found by either: i) modifying the neighborhood (by displacing the 1-ring vertex over the line), ii) creating a new neighborhood (by adding a new vertex over the line) or iii) eliminating a neighborhood (by collapsing the 1-ring vertex to a vertex in the neighborhood). The evaluation of the possible configurations is based on an objective function, which maximizes the 1-ring quality for the set of predefined configurations.

3.3 Dynamic Discrete Analysis

The suitability of a shape of being able to be interpreted is what makes a shape versatile. However, only a limited set of representation schemes are suitable to be interpreted. Discrete shapes are a versatile representation, since these can deal with design and analysis processes. One of the interpretation processes supported by a discrete representation is the understanding of its intrinsic semantic properties. The semantic properties cannot only be derived from the geometry, the context in which the shape is conceived, need to be considered as well. Additionally, the resolution of the shape should not affect its semantics and changes in the form of the shape should also be handled by the interpretation process at interactive rates. On the other hand, discrete shapes also support the evaluation of functionality. However current approaches only handle static shapes or shapes, whose connectivity remains constant, while the geometry is deformed. This is motivated by the performance cost, associated with the changes on the geometry and the topology of the shape, which need to be replicated to the linear system, responsible of capturing the correlation of the different properties (e.g. dimensions, materials, physical laws).

The digital representation of a shape, either a conceptual or an existing one, is essential for the digital processing of products (in a general extent). However, the shape with its geometric description does not integrally support this process, since the functionality of the shape needs to be interpreted as well. In the context of the Embodiment Discrete Processing pipeline, the shape is represented with the Dynamic Discrete Representation and the shape is modified (and possibly created) with the Dynamic Discrete Design processes. Now, the shape is interpreted with the Dynamic Discrete Analysis system, which is able to flexibly handle the dynamic changes of the shape, in order to streamline the integral embodiment pipeline. This flexibility is achieved, by means of creating an equivalent system (see Fig. 3), which is able to efficiently correlate the properties related to the shape. The equivalent system exploits the updated neighboring information, which is kept by the Dynamic Discrete Representation, enabling the dynamic changes without performing a rebuild of the system for every change. The main characteristic of the system resides on the flexible and efficient correlation of the properties of the system without the need of a static encoding, achieving an alternative representation for linear systems of equations.

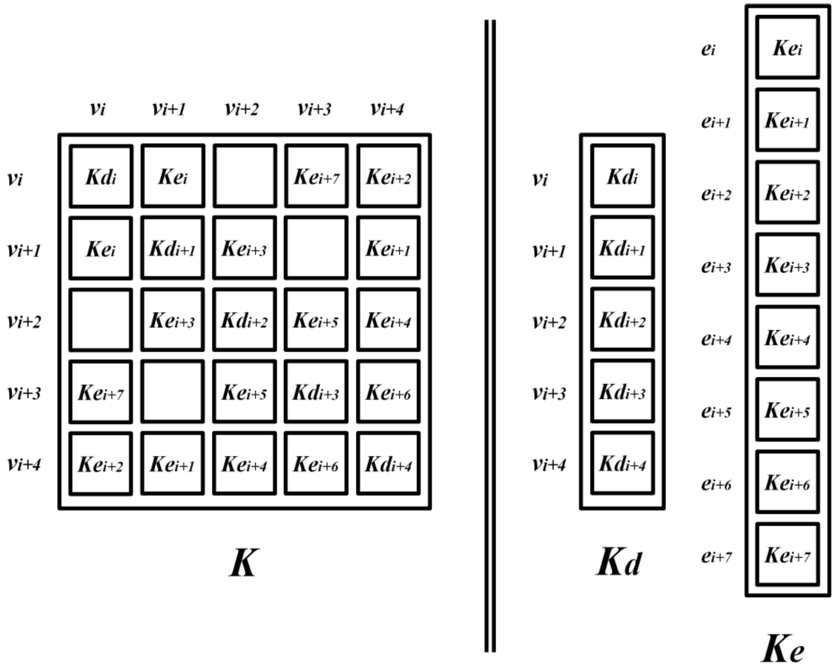

Fig. 3. Dynamic Discrete Analysis

4 Conclusions

The interplay of these three building blocks will enable a multidisciplinary work between designers and analysts, a new understanding of what an integral processing is, and new notion of general purpose processing (see Fig. 4). One of the possible new scenarios would be: in a single environment (without the need for external interfaces), designers and analysts work together in the solution of a problem, the designer builds the shape, while explaining the analyst the reason of specific styling characteristics. The analyst understands the situation and invites the designer to evaluate the current design against the expected functionality. Hence, the analyst takes over the control of the environment and sets a couple of constraints and conditions, in order to perform the evaluation. The result is shown to both experts and the analyst explains the designer, where critical conditions for the current design could affect the functionality of the solution. Thus, the designer operates the environment, in order to modify the shape, in view of the mitigation of the critical conditions, while maintaining the styling characteristics. Finally, the analyst repeats the evaluation and verifies the improvements achieved with the changes on the shape within a single and dynamic environment for multidisciplinary collaboration.

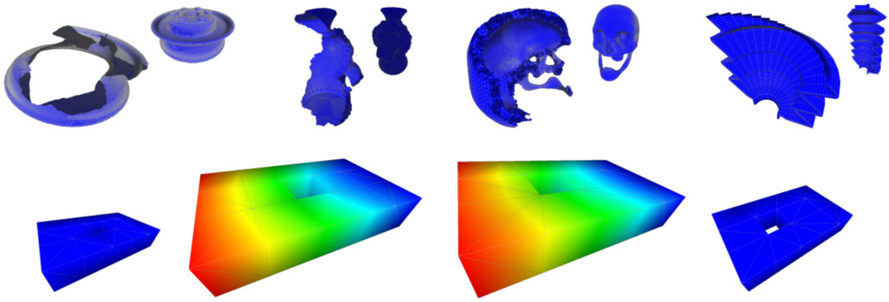

Fig. 4. Embodiment Discrete Processing

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A Virtual Prototyping Approach Based on DOE Analysis to Support the Design of a Centrifugal Impeller

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Abstract. The development of appliances focuses on more efficient and high functionality products. The recent European legislation limits energy consumption for several domestic devices, including kitchen hoods which encloses an impeller moved by an electrical motor. A correct impeller design is important to guarantee fluid dynamic performance and the reduction of resistance torque in a cooker hood system. The traditional design approach is based on pilot manufacturing and related experimental tests. This paper aims to present a methodology design for centrifugal impellers integrating a multi-level approach based on a Virtual Prototyping tool, Design of Experiments (DOE) method and Rapid Prototyping system in order to support the project design. The proposed research has been validated during the design of a fan wheel for domestic cooker hoods. A DOE approach, based on main impeller parameters, has been applied to the virtual experiment with CFD tool to reduce cost and time-to-market.

Keywords: impeller, kitchen hood, Virtual Prototyping, Design of Experiments, Rapid Prototyping.

1 Introduction

European directives govern household appliance manufacturers in the research of more efficient products with less environmental impact [1], while the market also demands higher performance [2] and extended functionalities [3]. The context of cooker hoods regards specifications related to air-ventilation, air-quality, noise control and electricity consumption. This appliance is often installed in wide living rooms, where ventilation and air-quality is necessity [4]. An adequate fan removes smoke, volatile organic compounds, grease particles and vapour from the kitchen area [5]. These issues require a flexible design methodology which would be able to support the engineer in a virtual physical analysis and also in rapid decision making, in order to increase product quality.

Nowadays, Virtual Prototyping technologies are often used in design processes to guarantee flexibility and reliability during the first project phase [6]. These solutions reduce the project development lead-time and the physical prototyping, according to the needs of kitchen hood development. The cooker hood design concerns different project levels such as aesthetical design, structural analysis, fluid dynamics performance and electricity consumption. The ventilator, which groups the electric motor and

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fan wheel, is the main component in the cooker hood architecture. The integration of virtual and rapid prototyping tools allows the blower's geometrical configuration to be optimized and reduces many experimental loops. From a medium-large sized production point of view, this means an efficient redistribution of the available resources.

2 Background Research

The design of kitchen hood impellers concerns repetitive phases: parametric modelling, pilot mould manufacturing and experimental tests to investigate the performance of several prototypes. This procedure increases cost and development time in finding an optimal product configuration, which means spending company resources. In literature, some design procedures are available to improve the design and engineering of products like kitchen hood blowers. Therefore these tools and methods are often used alone. The main subdivision is between the real testing procedure and virtual prototyping.

The first step in improving impeller design is to introduce a rapid prototyping (RP) approach in order to reduce the more expensive pilot manufacturing and development time. This allows a quick response to business opportunities thus ensuring company competitiveness. The RP is a 3D printing process which forms items by adding plastic material layers [7]. The RP systems are relatively faster and cheaper than traditional machine tools. The main objective is the realization of early physical prototypes, in order to validate the model performance with a low manufacturing cost of pilots. The advantage of using the RP technique regards the product development in order to reduce the time-to-market. While the use of RP tools reduces the pilot cost and the related manufacturing time, the number of the experimental tests and the necessary pilots is uncertain. The design of kitchen hoods concerns many geometrical parameters which are correlated with each other, so an RP approach has to provide several 3D printed models to achieve the required characteristics.

A design of experiments (DOE) approach is the solution to plan the physical tests according to the paradigm of Robust Design. This second design approach allows the pilot manufacturing and related experiments to be reduced. In particular, through the formulation of orthogonal matrices provided by Taguchi's method, it is possible to investigate a large number of parameters and to obtain important results with a minimum number of experiments [8][9]. This approach is suitable for the kitchen hoods application in order to support the engineer in the main parameter definition and to plan a little quantity of tests and prototypes. After the experiment analysis, the consequent result is the optimum parameter configuration which satisfies the specifications. Therefore, this approach requires a certain number of physical experiments, depending on the number of parameters. Therefore, an investigation of many parameters (n) requires a similar number of experiments (n+1).

The third available solution to increase impeller design is the introduction of simulation tools for a computational fluid dynamics (CFD) analysis [10]. Even if the fan geometry is simple, a fluid dynamic study provides important information to improve hood performance and the airflow distribution in the kitchen [11]. In order to evaluate the airflow distribution and the local temperature gradient, these tools also support the designer in the study of innovative solutions for improving the air quality in domestic kitchens. The main difficulty concerns studying the turbulent air flow elaborated by a rotating wheel [12].

In literature it is possible to find many examples of virtual prototyping methods, rapid prototyping approach and DOE analysis, but the difficulty lies in integrating these methods into a design process for product development.

This paper aims to validate a design methodology to support the designing phases for centrifugal impellers. This research work proposes a DOE (Design of Experiments) approach based on virtual simulations, which are planned with an L4 orthogonal array in following Taguchi's theory. The proposed analysis allows the designer to define an optimum parameter configuration in order to maximize the inlet flow rate and efficiency. Then, the rapid prototyping tools enable a quick pilot in order to compare the simulation with real-world physical tests. The main objective is the reduction of time and cost due to trial and error experiments.

3 Methodology

This section presents the methodology studied to support the fan wheel design for a kitchen hood. The achieved methodology integrates three different levels of analysis: virtual prototyping, Design of Experiment (DOE) and rapid prototyping. The virtual analysis allows the geometrical parameterization of a simplified model to be defined and simulates the performance of each configuration at working conditions (Figure 1).

The proposed DOE approach is based on virtual experiments according to the necessity of reducing time and costs during the first design phase. The optimum parameters configuration, defined by the previous step, is useful to define the geometry of a reliable virtual model. The final level is the realization of a 3D ventilator with a rapid prototyping printer. The obtained component is now evaluable at the test bench to investigate the air flow rate and the electric power consumption.

The virtual prototyping level concerns the phases of model simplification, geometrical parameterization and virtual simulation. The simplification of the virtual model is the first step where early analysis identifies the less important geometrical entities. At this level the engineer interacts with CAD tools to reduce the geometrical complexity of the real model. The resulting geometry is a closed volume which excludes through holes, threads, small fillets and chambers, electrical components, etc. The simplified model does not consider the geometrical details which not influence the fluid dynamics analysis. The next step includes the parameterization of the main geometrical dimensions. Therefore, the parameter choice is related to the DOE analysis which requires an orthogonal array to plan the virtual experiments.

The DOE approach guides the analysis of virtual simulation by identifying a certain number of parameters which influence the performance. The simulation basically regards CFD analysis which reproduces system behaviour without physical manufacturing. The DOE level provides the experiment plan definition related to the parameters chosen in virtual modelling. The engineer can use his know-how to set the parameter range and to evaluate the most suitable configuration. According to Taguchi' methods, a reduced number of experiments is required to elaborate the final optimum condition. Each test includes a combination of the set values in order to investigate the influence of each parameter. The objective function includes two levels of specifications: the maximization of air flow rate and the reduction of the necessary motor torque, which means the efficiency increasing with low energy consumption. Analysing the CFD results, it is possible to evaluate the optimum condition and to simulate the elaborated configuration.

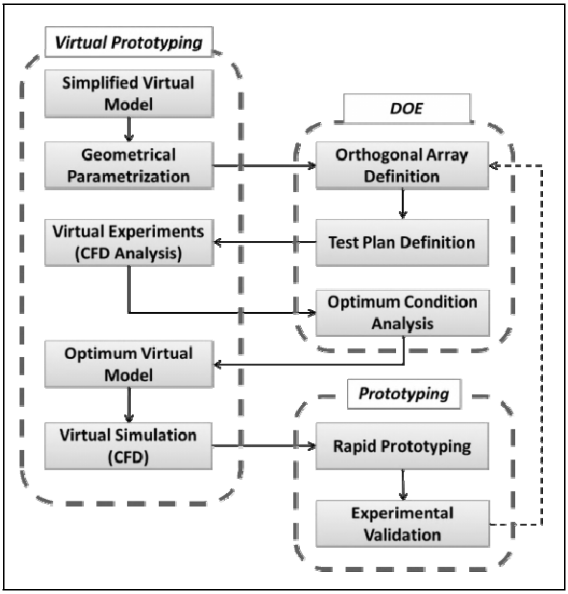


Fig. 1. The research methodology

The result of the DOE approach, including the virtual experiments, provides a better parameter configuration. The elaborated settings could be simulated to evaluate the performance with virtual tools. The next step is the rapid prototyping of the better candidate parameter configuration, using a 3D printer tool. At the test bench, the real world experiments can confirm the final analyzed configuration of the printed model.

4 Test Case

The proposed approach has been validated during the design of a fan wheel for domestic hoods in collaboration with a large company working on kitchen hoods. The applicative target concerns the fluid dynamic optimization of an existing blower in order to increase ventilator efficiency, air flow rate and to reduce energy consumption. The optimization process, described below, concerns the investigation of the wheel blades, while the fan volute and wheel dimensions are fixed for this application.

The model simplification is the first step in the CFD analysis. This activity concerns the reproduction of a less detailed model including the essential parts useful for the fluid dynamic analysis. Figure 2 shows the difference between a detailed model and a related simplified body for the proposed test case. However, the virtual simplified model includes the original geometry of blade shape and internal volute, and the parametric relations to support the configuration changes. The geometry characterization is important to reduce the compute time due to the model complexity.

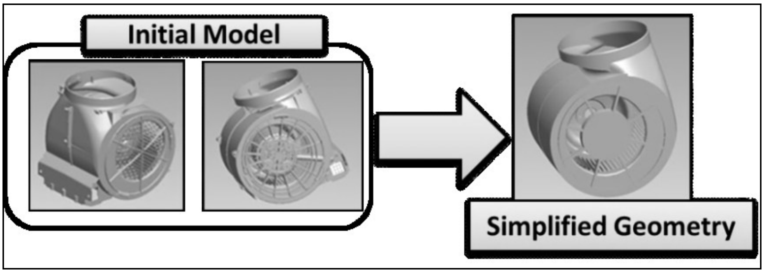


Fig. 2. A comparison between the initial and the simplified model

During this phase, it is fundamental to analyze the characteristic curves in order to evaluate the motor operating point at the free-delivery condition. This supports the engineer in the early design phase of the impeller-volute system. The operating point of the blower system is the intersection between two characteristic curves: the torque of the electric motor and the fan prevalence. Defining a motor behavior, a blade geometry has been investigated to increase air-flow rate and reduce the resistance torque.

4.1 Geometrical Parameterization and DOE Approach

Following the proposed methodology, a DOE plan is defined to organize the required virtual experiments. Table 2 reports the L4 orthogonal array analysed in this test case. The three chosen parameters (Figure 3) are: the blade number (P1), the blade outlet angle (P2) and the blade chord angle (P3). Each parameter can hold two possible configurations (level -1 and level +1), and the total number of experiments is 2n (4 in this case), where n is the number of investigated parameters.

The objective function takes into account the mass flow rate and the necessary torque, assigning the same weight (0,5) to each criterion.

$$Y=0{,}5\cdot Cr_1+0{,}5\cdot Cr_2 \tag{1}$$

The term $Cr1$ identifies the criterion related to the mass flow rate, calculated with the method Big Is Better (BiB), while the term $Cr2$ concerns the necessary torque and is evaluated with the Small Is Better (SiB) methods. This is because the increasing mass flow-rate is a desired effect, whilst the resistance torque is a value which has to be reduced to optimize electricity consumption.

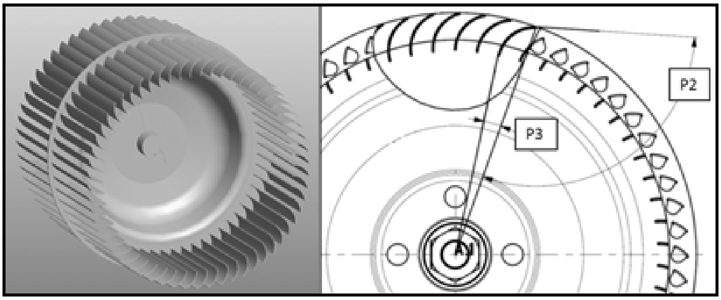


Fig. 3. The geometrical parameters investigated in the proposed test case: the blade number (P1), the blade outlet angle (P2) and the blade chord angle (P3)

Table 1. DOE parameters defined for the proposed test case

Parameters	Initial value	Level -1	Level +1
Blade number	55	50	60
Blade outlet angle	125°	120°	130°
Blade chord angle	7°	5°	9°

4.2 Virtual Experiments

The need to reduce the design cost and the time-to-market leads designers to reduce the number of experimental tests and promotes the use of virtual simulations in order to predict the behaviour of a real system without building the physical prototype. After the model simplification, shown in previous sections, the mathematical geometry has been meshed in many elementary elements. Figure 4 shows the discretized model with different levels of thickening. A thick mesh provides a simulation close to real world behaviour, but which increases computational resources.

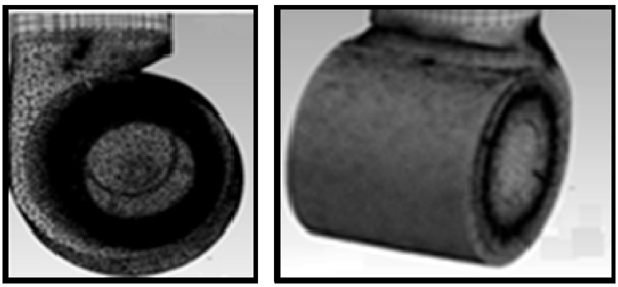


Fig. 4. The mesh related to the test case model

The last column of Table 2 reports the DOE results calculated using Equation 1 with the related criteria. Figure 5, 6 and 7 show the variation of the objective function values depending on analyzed parameters (P1, P2, P3), and the major inclination indicates a more important impact on the system. The maximum is obtained by positioning parameter P1 on level -1, P2 to level +1 and P3 to level -1. Thus, the optimal configuration provides 55 blades, a blade outlet angle of 130 °, and a blade chord angle of 5 °. This condition has to maximize the air-flow rate and the efficiency.

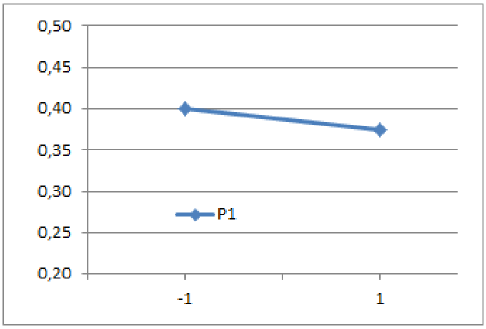


Fig. 5. The incidence of P1 parameter on the objective function

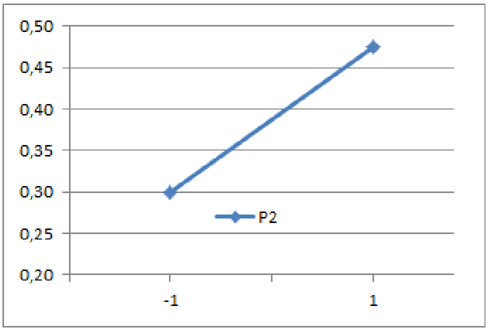


Fig. 6. The incidence of P2 parameter on the objective function

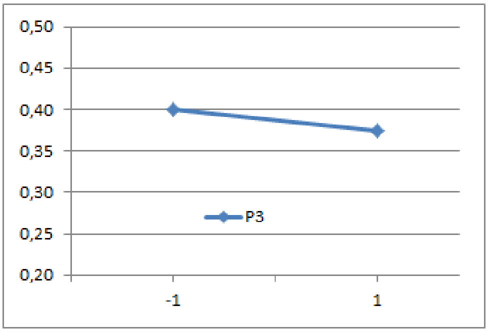


Fig. 7. The incidence of P3 parameter on the objective function

Table 2. The orthogonal L4 array

Experiment	P1	P2	P3	Y
1	-1	-1	-1	0,33
2	-1	+1	+1	0,48
3	+1	-1	+1	0,28
4	+1	+1	-1	0,48

4.3 The Optimum Configuration

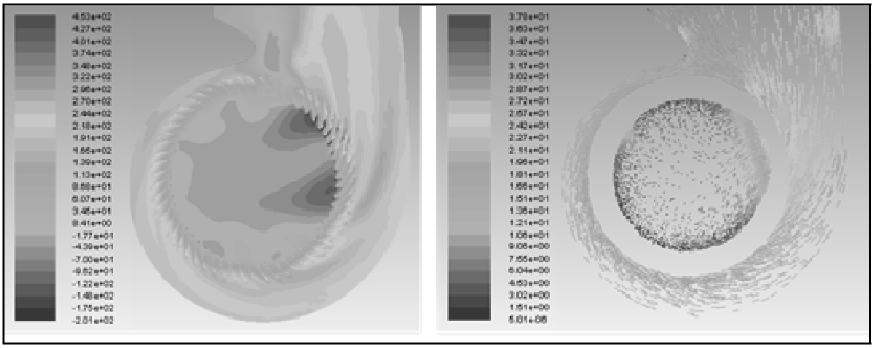
For each experiment reported in Table 2, the air-flow rate and the resistance torque values have been calculated through using the previously described Equation 1. Bearing in mind the previous consideration, Table 3 shows the optimal condition calculated for the proposed test case. The best configuration candidate has been first verified through a virtual simulation and then tested at the test benches with a 3D printed model (Figure 8). Figure 9 shows the trend of pressure (a) and the velocity vectors (b), which are obtained through the virtual simulation with a CFD tool. This report is also useful to investigate the velocity field in the more critical zones in order to maximize the efficiency of the system. The test bench used for air-flow rate detection is comply with the standard ISO 5167-1 “Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full”.

Fig. 8. The test case prototype printed with a RP machine

The chosen configuration concerns 50 forward blades optimized to maximize the air flow rate and the efficiency. As reported in Table 3, the angle of blade outlet is 130° in forward direction, while the chord angle is 5° related to the center of the wheel. The virtual model achieves an air flow rate of 875 m3/h and a torque of 4.95 N·cm. This result is better than the previous configurations. After the virtual validation, a rapid prototype (Figure 8) has been printed to confirm the simulated result. The real air flow tester provides a maximum value of 840 m3/h, with a related torque of 5.25 N·cm. Thus, the CFD analysis includes an average error of 5% and can be used as alternative to physical prototyping.

Table 3. The best parameter configuration and performance result after CFD analysis and real testing on rapid prototype printed.

Blade number	Blade outlet angle	Blade chord angle	CFD results		Prototype Test Results	
			Airflow [m^3/h]	Torque [N·cm]	Airflow [m^3/h]	Torque [N·cm]
50	130°	5°	875	4,95	840	5,25



(a) (b)

Fig. 9. Some CFD reports: a) total pressure; b) velocity vectors

5 Conclusions

The proposed approach has been validated during the design of a fan wheel for domestic cooker hoods. The main geometrical parameters have been analysed and has been defined a L4 orthogonal array in order to plan the necessary virtual experiments. Using a CFD tool has been simulated the fluid dynamic performance for each planned experiments. The geometrical model, which includes the impeller and its volute, has been previously simplified using a parametrical approach. An objective function has been formulated in order to give a value to each virtual experiments. The valuating criteria are based on air flow rate and resistance torque. After the simulation computing, an optimum configuration has been found. The new configuration has been first validated by a CFD analysis and then printed with a rapid prototyping machine. The physical prototype has confirmed the CFD results with a variation of almost 5%.

The use of the DOE method allows a decreases in the number of experiments, while the introduction of virtual prototyping reduces pilot manufacturing. The use of rapid prototyping for the final impeller configuration results the best solution to verify quickly the effective result.

As a future development, the proposed methodology will be extended to the design of a new fan for domestic kitchen hood. In particular a different type of volute and impeller will be analysed in order to validate the design approach. This future test case would include a L8 orthogonal matrix with more parameters.

Acknowledgments. The authors wish to thank Faber SPA for their precious contribution in the development of this research program.

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Towards a Context-Driven Front End in New Product Development

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Abstract. The fuzzy front end (FFE) of new product development (NPD) has been an important area of research during the last decade. The FFE is recognized by several researchers as the part of the innovation process where most substantial improvements can be achieved with minimum cost. This paper investigates former research to determine if there is a common perception of the FFE. Referring to state of the art and the nature of the FFE, it is argued that an 'ideal' FFE model brings limited value to a firm. A number of contextual factors that influence the characteristics of the FFE are presented to further argue this finding. That is, the context is far too important to be overlooked in the search for a FFE strategy.

Keywords: fuzzy front end, innovation, concept development.

1 Introduction

Innovation is vital for survival of any organization in the 21st century. Globalization has forced companies to bring products to market faster than ever before. With the emergence of low-cost countries, such as India and China, advanced manufacturing has become a commodity, forcing companies that operate in high-cost countries to create products with higher customer value than its competitors operating in low cost countries. In order to achieve increased customer value, it is necessary to innovate, and develop new and better solutions than its competitors. To quote the CEO of SRI International, Curtis Carlson: "*The goal of every innovation is to create and deliver customer value that is greater than the competitors*" [1].

According to Koen and Ajamian [2], the innovation process can be divided into three stages: the fuzzy front end (FFE), the new product development (NPD) (process) and the commercialization stages. The NPD process has been under extensive research for several decades. The focus has in large parts been on creating an ideal *process* for developing and managing the development of new products. Well-known approaches such as Robert G. Cooper's Stage-Gate® process [3] and the PACE® approach have been used for managing the product development process with great results [4]. For the FFE, however, a well-established, commonly accepted process does not seem to exist.

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This paper considers different FFE models proposed by several authors and compares them to see where there is agreement and where there is not. Answers to the following research questions are sought out:

RQ1. Is there a common understanding of what the FFE is, where it starts, where it ends and what activities it should include to create products of superior value to customers?
*RQ2***.** Can the FFE be generalized to the degree that it is covered by one single model? What are the dimensions that make this possible or impossible, and how are they related to each other?

2 Former FFE Research

The FFE is a term popularized by Smith and Reinertsen [5] and is most commonly defined as the portion of the new product development cycle between when work on a new idea could start and when it actually starts [6]. The phase is described as rather chaotic and unstructured [7].

Several authors have identified the FFE as the part of the innovation process where the most substantial product improvements and cost reductions can be made [8-11]. Extensive research has been conducted in the FFE field in the recent years. Case studies have brought into light how the phase is actually conducted in certain (type of) industries, for example the automotive industry [8], aerospace [12] and process firms [13]. Numerous attempts for developing a common language and a framework have been made [14-16]. It is argued that it would make it easier for researchers to build upon one another's work if there is a common understanding of the definition and a framework for the FFE. To be able to compare different models it is necessary to distinguish between two different approaches for investigating the FFE. Most of the research deals with the FFE within the company – best practices, tools, activities and so on, while Reid and de Brentani [15] propose a theoretical model that explains how information flows in radical innovations. They thus explain *how* radical innovation occurs by examining the initiation of the innovation. They suggest that information flows in the opposite direction of incremental innovations; that is, from the outside environment into the firm. This paper will for the most part focus on FFE research within the company sphere, comparing the different models proposed by various authors.

There appears to be at least two common ways of viewing the FFE within a firm. One way to interpret and model the phase is as a structured process where there exists an 'ideal process'. The other is as a more contextual, situational-driven view where there does not exist one ideal FFE model. Several authors argue for the process view of the FFE. Khurana and Rosenthal [17] divide the front end for incremental innovations into three phases: pre-phase zero, phase zero and phase one without implying that there might occur feedback or iterations between and within the phases. Even though they state that the front end process needs to be adapted to the product, market, etc., the model presented is still a process view of the front end.

One example from the other end of the spectrum is the framework presented by Koen and Ajamian [14]. Their model takes into account that the FFE is indeed fuzzy and unstructured. Suggesting that there are five elements driving the front end: opportunity identification, opportunity analysis, idea genesis, idea selection and concept &

technology development. In addition to the five elements there are influencing factors from the outside environment and the support from senior and executive-level management. This model does not present the FFE as a straight-forward process; the elements proceed in a random and iterative fashion. The framework proposed by Hüsig and Kohn [16] is perhaps the most comprehensive one in terms of building on former research. It is based on over sixty empirical NPD studies that identify relevant factors for front end activities and thirty specific conceptual and explorative FFE papers. The result of the work is a FFE framework for future research; see Figure 1 for a simplified illustration. The learning organization is placed in the center of the framework, surrounded by factors that can (to some extent) be controlled by the corporation, such as senior management, corporate creativity, horizontal co-operation, cross functional FFE team, etc. Further away from the center, the contextual factors get gradually less controllable by the management. These factors include the firm context: its age, size and organizational macro structure, industry context: structure, competitors, customers, age, market dynamic, etc., and finally the macro environment: natural resources, research institutions and universities, regulation and so on.

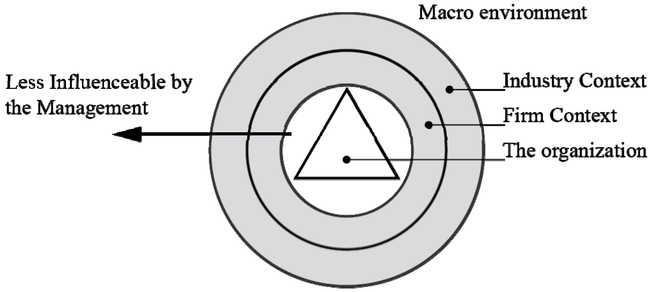

Fig. 1. Simplified illustration of FFE framework by [18]

Table 1. Activities in different FFE models

<table>
<tr><th>Author</th><th>Cooper (1983)
[19]</th><th>Nobelius and Trygg (2002)
[20]</th><th>Khurana and Rosenthal (1998)
[17]</th><th>Koen et al. (2001)
[14]</th><th>Ulrich and Eppinger (2012)
[21]</th><th>Hüsig and Kohn (2003)
[16]</th></tr>
<tr><td>Activities</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Opportunity identification</td><td></td><td></td><td>x</td><td>x</td><td></td><td>x</td></tr>
<tr><td>Idea generation</td><td>x</td><td></td><td>x</td><td>x</td><td></td><td>x</td></tr>
<tr><td>Concept generation</td><td></td><td>x</td><td rowspan="3">x
“Product Concept”</td><td rowspan="3">x
“Concept and Technology Development”</td><td>x</td><td></td></tr>
<tr><td>Concept screening</td><td></td><td>x</td><td>x</td><td></td></tr>
<tr><td>Concept definition</td><td>x</td><td>x</td><td></td><td>x</td></tr>
<tr><td>Business analysis</td><td>x</td><td>x</td><td></td><td></td><td>x</td><td>x</td></tr>
<tr><td>Project planning</td><td></td><td>x</td><td>x</td><td></td><td>x</td><td>x</td></tr>
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When different FFE models are compared, it has to be taken into account that the authors use different terms and provide various degree of details, thereby making it difficult to compare them directly; in other words, a common language does not exist. An example of this can be seen in Table 1. All concept activities have been merged into one cell for [17]. The reason for this is that they vaguely describe one of their phases as “Product Concept”, indirectly implying that all of the concept development activities have to be conducted in order to end up with a product concept. As the table indicates, there is no consensus on the activities included in the FFE. [21] provide a schematic overview of the different phases in the entire product development cycle, starting with planning and ending with production ramp-up. Phase 1 – Concept Development is described as ‘The Front End Process’ and is clearly separated from opportunity identification. The same goes for the synthesized model by [20], i.e., the opportunity identification is treated as an *input* instead of a part of the front end itself. The *concept* seems to be the most important and agreed upon part of the FFE. Even though it is not consistent what part of the concept development each of the authors includes, it is recognized as an important activity in all of the models.

3 Discussion

3.1 The Importance of Context

Taking the Context into Consideration

Despite the attempts of creating a unified model, there is no consensus of exactly how the FFE looks like, and what elements it consists of. However there does, to some degree, seem to be an agreement of the definition of when the FFE starts and ends. The FFE starts with an idea or opportunity, and ends with a go/no-go decision. Some of the authors have, however, treated the opportunity identification as a part of the front end, see Table 1.

Whether the phase should be treated as a structured process, or if a less structured guiding framework is more suitable, is an ongoing discussion. Nobelius and Trygg [20] argue that there is no point in chasing *the* front end process. Through a case study they show that each individual project is too different to be adapted to one single model. Hüsig and Kohn [16] recommend a stronger focus on the context to see how changes to various parameters affect the FFE. They also indicate that the future research challenges could be found on a more micro level. For instance, the influence of factors like type of technology, size of project and interrelations between projects in a historical perspective needs further investigation. Based on the statements and the former research discussed above, it is argued that a common FFE model will be of limited value to a firm. The context (type of industry, level of innovation etc.) is of such great importance that if the FFE were to be generalized across several types of industries and products, this would have to be on such a basic level that it would result in a superficial model, unable to satisfy any firm or industry. The nature of the FFE is vastly different than the more structured NPD-process [2], and most likely less suitable for standardization. This does not, however, imply that there cannot be a somewhat common perception of *what* the FFE is; i.e. where it starts, where it ends, and to a certain degree what the activities and outcome should be. A common language for the researchers will be favorable in terms of bringing the research forward but will most likely not give a firm within a specific industry the level of details needed to improve its front end phase.

There are most likely numerous of important contextual factors that will affect the FFE, but it is impossible to take all factors into consideration here. Therefore, the purpose of the following discussion is to emphasize some of the key factors that will play a major role in the front end. The elements presented in the next section are meant to highlight some of the product and innovation specific contextual factors. The scale presented for each of the elements is by no means to be considered absolute or definite. The purpose is to illustrate the span and the variation of each element by presenting its extremes. Their interdependence and actual influence on the front end need further investigation and validation.

3.2 Contextual Factors

Degree of Innovation

Different levels of innovation require different approaches to the FFE. Before the importance of degree of innovation can be discussed, however, it is necessary to define the various degrees of innovation.

Following the definitions used by [15] there are three different degrees of innovation, incremental, "really new" and "radically new". Incremental innovations typically involve product improvements using existing technologies targeted toward existing markets. To be classified as a "really new" innovation, changes to existing technological *or* marketing infrastructure are required, while "radically new" implies changes to both. Discontinuous innovation is a term that covers "really new" and "radically new" innovations [22], the definitions are summarized in Figure 2.

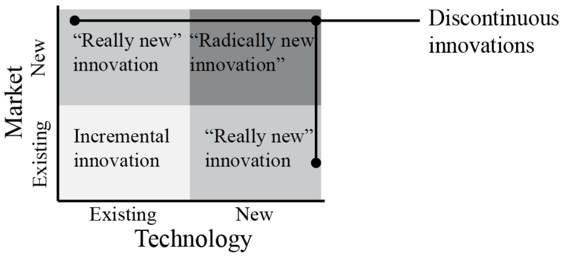

Fig. 2. Visual presentation, the various degrees of innovation

According to de Brentani and Reid [23] "*discontinuous innovations typically are not the result of explicit and structured organizational processes, as is the case for incremental innovations*." Their research shows that discontinuous innovations are more dependent on contact with the environment through individuals called 'Boundary Spanners' at the Boundary Interface, the interface between the firm and the outside environment. Firms that operate in the incremental innovation area acquire most of the knowledge needed from within the firm, thus they need to focus more on optimizing internal parts and processes to be successful at innovating. For firms operating in the discontinuous innovation area, on the other hand, the interface with the outside environment is the most critical part to focus on. Most former research uses the degree of innovation to separate different firms. Khurana and Rosenthal [17], for example, investigate companies that range from consumer packaged goods to electronics and industrial products in the same case study. This might be useful for creating a generalized model that explains what the FFE is and to a certain degree what activities it consists of. However, it might not be specific enough to explain how to conduct the FFE.

Concept Driving-Force

The concept driving-force may affect the entire innovation process and is closely tied to the customer characteristics and the degree of innovation. Backman and Borjesson [8] report that customer and market concepts (ones that are less technology-driven) need a contextualization to be more easily understood and granted funding for further development. Contextualization in this case, according to Backman and Borjesson [8], means that "*the concept is dressed in a way to fit an NPD context, facilitating both understanding and evaluation.*" In their case-study, one example of contextualization is the development of a concept car. By placing the less technology-driven concept in a larger context, there is a greater chance that its value will be recognized by the management and continue into the NPD process. This finding suggests that there might be different optimal approaches based on whether the concept is technology-driven or based on customer or market knowledge. They report that pure technology-driven products found their way into the development cycle considerably easier. This has several possible explanations, one of them being that the NPD process and management in the organization studied are used to evaluating technological concepts. However, if a generalization is to be made, it might also be due to the fact that it is easier to convey and argue for a new, tangible technology where you can clearly see the benefit.

Customer Characteristics

The customer is always crucial part in new product development, whether this is through direct or indirect involvement. Without a customer there is no need for a product. The translation of customer needs into product requirements may require deep customer understanding. The method for acquiring the needed knowledge depends on several factors; degree of innovation is one of them. It is obvious that an incremental improvement of an existing product, driven by a single factor such as price, weight, new material etc. requires a vastly different approach and user-insight than creating a radically innovative product with new technology for new market segments. In the former case, the firm already has a lot of knowledge and experience from managing similar products and a structured approach might be satisfactory. For radical innovation, on the other hand, more uncertainty and a great deal of risk is usually involved, and the validity of a concept is related to uniqueness and variation [24]. Flint [25] discusses the importance (and lack of) building the voice of the customer into the FFE. He claims that one of the standard brainstorming rules 'quantity breeds quality' leads firms into believing that they have too many ideas, hence assuming that the ideation stage is not the problem. He states that it is not only about coming up with creative ideas but incorporating deep customer understanding into the ideation stage. The nature of customer's needs and wants can be placed within the scale ranging from overt to latent [26]. The more latent the needs are, the harder it is to uncover what the customer actually wants. These kinds of needs can be tied to more radical innovations, where the market segment is either new or the existing one is transformed [27].

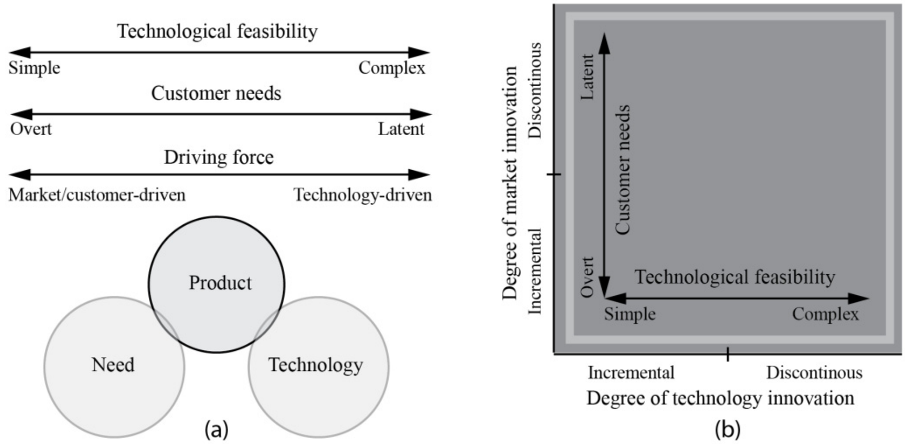

Fig. 3. (a) Contextual factors, product, need and technology. (b) Innovation, customer needs and technological feasibility.

Summary of Contextual Factors

To improve the FFE, a deeper understanding of the factors influencing the phase is needed. Some of the factors that will influence the characteristics of the FFE have been discussed in this paper. To summarize, the findings have been placed together in Figure 3. The need and the technology enable a product to be created. In order to generate the product requirements, customer needs have to be identified, understood and translated. The customer needs can range from being overt to latent, meaning that a range of various tools and methods may be required in the front end in order to uncover the needs, depending where on the scale one is located. The driving-force for creating a product can range from market/customer-driven to pure technology-driven. As discussed earlier, the level of contextualization needed varies with the driving-force of the concept. Technological feasibility reflects something about how technologically demanding the product is. This is a factor that is strongly correlated with the degree of technology innovation, and consequently affects the FFE.

According to several researchers it seems like the degree of innovation to a large extent dictates the characteristics of the FFE. [15, 17, 28] are some of the authors who use the degree of innovation to differentiate between companies. The degree of innovation is determined by numerous of factors. The customer's needs and the technological feasibility can be linked to each axis of the degree of innovation, as illustrated in Figure 3 (b). For discontinuous innovations in terms of technology, it can be directly connected to complex technology feasibility for the product. For discontinuous innovations in terms of generating a new or transforming the market, it is most likely that the customer needs are well hidden, requiring a substantial effort to be uncovered. Hence, they are latent needs, according to [27].

3.3 A Framework and a Definition

Two Different Stakeholders

Throughout this paper it has been discussed that there are inconsistent perceptions of the FFE among various researchers and a lack of details in the models when it comes to providing firms with information on how to conduct and improve the FFE. Based on these findings it seems appropriate to differentiate between two different stakeholders: the research community and the industry. These two stakeholders have different needs and goals, making it difficult to satisfy both with one single approach.

To bring the research forward it is at first important to define, understand and describe the FFE on a less detailed, basic level. This will not be of any direct value to the end users (the industry), but it will ensure that researchers speak the same language and stop confusion about terms and contents within the FFE. This is a topic discussed by both [14] and [16]. It would be more convenient and effective conducting research within the FFE field if there was a common language and an agreed upon definition of the FFE and its activities. The point being that there is *one* agreed upon *definition*, today most researchers use their own definition. This is imprecise, confusing and problematic when it comes to comparing different models and discussing the FFE in a general context. Furthermore, the boundary and the activities of the FFE should be defined. The purpose is not to go into detail of each of the activities; it is to define what is considered a part of the FFE and what is not. The outcome of the FFE should be 'something' that allows the firm to make a thorough decision whether to launch or kill the project. That is, after all, the main purpose of the FFE; to evaluate whether an opportunity is worth pursuing or not.

To provide the industry with valuable applied research, the contextual factors have to be taken into account to create a more detailed, (custom-)tailored approach. It is necessary to dig deeper into the details to understand how to improve the front end; that is, it is not sufficient to describe what it is and what the inputs and outputs are.

4 Summary, Conclusion and Future Research

Former research has been investigated by comparing the work of various researchers. It is evident that there is no agreement on what activities the FFE consists of, or whether the phase should be regarded as a process or a less structured framework.

Several arguments support the assumption that an 'ideal' FFE model is not optimal and that a less structured framework is more suitable. Some of the contextual factors that seemingly cause the FFE to be less suitable for standardization are presented. Furthermore, due to different needs, it has been suggested to differentiate the research between two different groups of interests. For the *research community* a simplified model defining what the FFE *is* to create a common language among the researchers is suggested. For the *industry*, on the other hand, a more contextual approach is proposed; to satisfy the specific firms in terms of improving the FFE by investigating *how* to best conduct the phase.

Based on the identified inconsistencies associated with definition of the FFE, the following future research is suggested:

- Develop a definition of the FFE and a common language for the researchers; a definition of *what* the FFE is, where it starts and where it ends. This will prevent each researcher from making his or her own definition of the FFE. This again will make it more manageable to compare research and bring research forward. This definition has to be on such a basic level that it is general and not affected by contextual factors.
- Identify the industry, company and project-specific factors, and how they relate to one another. Some factors are proposed in this paper, but far more research is necessary to examine, test and validate the factors with regard to their individual or collective influence on the FFE.

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Multistate Feature Modelling of a Very Complex Design Feature

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Abstract. This paper presents a Knowledge Based Engineering (KBE) application developed for the aeronautical sector. Specifically, this paper describes a KBE application that aids on the definition of the contact interface between turbine discs and blades of low pressure turbines, namely the firtree. Designing firtrees requires more than 60 different entry parameters, a check for static stresses, de-featuring for fatigue finite element analysis and as cast design for manufacturing and weight management purposes. The application delivered at first the typical benefits of KBE applications: significant time savings, error reduction and standardization. However, the challenges posed by the aeronautical industry, quickly pushed designers out of the standard agreed topology for the firtree. This raised the typical issue on development time and maintainability of KBE applications. The challenge was partially solved through designer knowledge capture and reuse in the form of a User Defined Feature library integrated in to the original KBE application.

Keywords: Knowledge Management, Design Automation, NX, Unigraphics, Knowledge Fusion, Firtree, User Defined Feature, Feature Based Design.

1 Introduction

In order to be able to respond to the ever increasing demands of the aeronautical sector and society in general, of reduced development costs and time, fuel consumption and emissions, and at the same time, increased safety and more strict regulations in aero engines, a Low Pressure Turbine (LPT) supplier started an initiative to capture LPT Systems Life Cycle Knowledge into a Knowledge Based Engineering (KBE) application.

After an Added-Value analysis of the different components, turbine discs and blades were chosen for the development of the first applications. Specifically, this paper describes a Knowledge Fusion application that aids on the definition of the contact interface between turbine discs and blades, i.e., the firtree.

Firtrees used to be defined on a different in-house application based on a legacy KBE language, the Adaptive Modeling Language (AML®) by Technosoft, as regarded by the LPT supplier. This legacy application, helped designers in defining this

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complex interface's profile with more than 60 different entry parameters, check for static stresses and output an IGES file.

Later on, the IGES file had to be imported into NX for detailed mechanical design. As IGES only supports plain geometry, the non-parametric firtree profile was integrated into a parametric disc through non-parametric operations, losing the advantage of the parametric nature of the disc. Thus, any change to the input parameters, used to lead to a return to the AML® based application and lots of manual rework.

Besides, parametric standards for downstream states of the feature do actually exist on the company's standard engineering processes that were manually generated in NX6. Two additional parametric states lacking software support were identified:

- de-featured for fatigue Finite Element Analysis (FEA),
- as cast for manufacturing and weight management purposes,

Thus, a requirement to develop the new firtree application in NX ®'s KBE language Knowledge Fusion® was set out from the very beginning to achieve full integration into NX® and had to cover:

- helping the profile definition phase with its more than 60 input parameters,
- checking static stresses,
- developing the solid features for the disc in detailed and de-featured for FEA states,
- developing the solid features for the blade in detailed, de-featured for FEA and casting states,
- text-file output for archiving purposes,

Therefore, according to the following literature review the expected benefits of the application were:

- time saving due to the integration of the Firtree Design tool into NX,
- time saving in the development of solid models in the different states,
- error reduction due to elimination of manual data re-input,
- standardisation of feature solid modelling,
- reduced training time for new disc & blade design engineers.

2 Definition of Knowledge Based Engineering

From an academic perspective the definition of what KBE is, is an open-ended question as recently pointed out in a KBE review [1].

Technically, nearly all KBE systems share that they are a declarative, demand-driven, value-caching, Knowledge Based Systems (KBS) linked to a Computer Aided (CAx) system, written on an Object Oriented Programming language. The rationale behind such architecture is, to use the KBS to capture, reuse and make integrated multi-disciplinary decisions in order to automate the repetitive, non-creative tasks an engineer should perform over the CAx system. A very detailed technology-oriented description can be found in [2].

Originally, the focus of KBE was on integrating multi-disciplinary knowledge on the early design stages and it used to automate only the geometrical engineering tasks performed on Computer Aided Design (CAD) systems. For instance, in [3] Bermell-García et al, reported a reduction in development time of a wind tunnel from 2 weeks to 2 hours, due to the generation of an specific application that linked a KBS to a CAD. In [4] Rios et al, developed another specific application that linked a KBS to CAD system to design and manufacture fixtures for High Speed Machining.

In order to alleviate the engineers from searching the optimum response solution, a desired design response that could be determined by an analytical equation based on the design, and an optimization system that could drive the designs to an optimum, were added to a KBS linked to a CAD system, creating a Multi-disciplinary Design Optimization (MDO) system for composite panels of aero-structures in [5].

In order to be able to find responses in designs where no analytical equations were available, the analytical equation was replaced by a Computer Aided Engineering (CAE) model pre-processing, solving and post-processing. Thus, another CAx tool was integrated into the KBE system in [6].

Approaching a more different engineering discipline, in [7–9] a KBS was built around a Computer Aided Manufacturing (CAM) system, in order to automate 5-axis machining process planning.

Therefore, KBE practitioners must be thorough in defining what the scope of their KBE application is. In particular, the work presented in this paper addresses the knowledge capture and reuse, and reduction of repetitive engineering tasks by the generation of Higher Level Primitives as named in [5], design features as named in [10] or standard features as named in [11]. In all cases, they refer to wrapping several commercial off the shelf CAD commands into a semantically richer one in the context of application. Thus, a design feature contains by definition the knowledge about the construction procedure in the CAD system and any further constraints its parameters might be bound to, as stated about basic features in classical textbooks on parametric and feature based modelling systems [12] and [13].

Specifically, the KBE application will define a single design feature which has two different linked representations on two different parts: the wheel and the blade. The constraints of the parameters are linked to a historical database due to the complexity of modifying the manufacturing process in terms of cost. Besides, the representation on the wheel must support two different states: detailed and truncated for CAE purposes. Finally, the blade representation must also support three different states: detailed, as-cast and truncated for CAE purposes.

3 Methodologies for Knowledge Based Engineering

In order to properly elicitate, capture, store and maintain the expert's knowledge into the KBE application several methodologies have been defined. The most remarkable is MOKA (Methodologies and software tools Oriented to Knowledge-Based Engineering Applications) [14], [15]. MOKA defines a KBE application lifecycle in six steps: Identify, Justify, Capture, Formalize, Package and Activate. It focuses on adapting existing KBS development methodologies by providing adapting the Capture and Formalize steps to the specificities derived from the linkage of a KBS to a CAD system, in KBE applications. More precisely, in the Capture step it defines the ICARE forms (Illustration, Constraint, Activity, Rule and Entity forms) where the knowledge that is going to be integrated into the KBE application is registered in the format of a knowledge book, or informal model. Regarding the Formalize step, the formal MOKA model is composed of the Product Model and the Design Process Model. In the latter, it defines a UML variant, namely the MOKA Modeling Language (MML), in order to adapt the modelling language for OOP to KBE development by linking it to the ICARE forms previously defined.

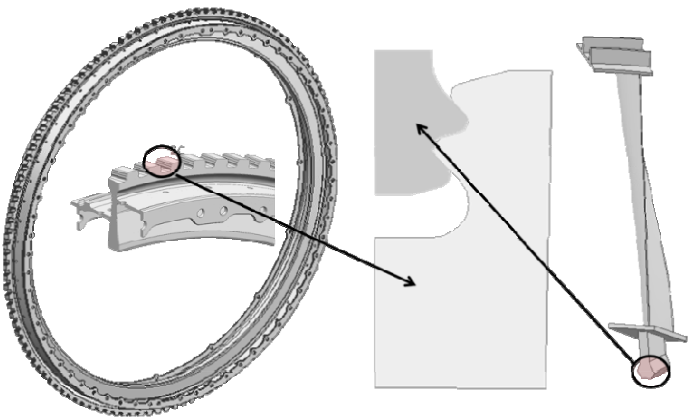
Similarly, in [7], [8], [16] the MOKA methodology was adapted to increase its capability to handle the knowledge related to 5-axis machining process-planning for KBS systems linked to CAM systems.

However, if the scope of application is multidisciplinary design optimization (MDO), the KNOMAD methodology adapted for so can be found in [17].

In this work, as the design feature was already modelled across several internal standard practices, no particular KBE methodology has been used, as diagnosed by [1]. Nevertheless, the MOKA methodology could have been adequate for this purpose.

4 Definition of Firtree

As shown in Figure 1, a firtree is a design feature (b) that links the wheel (a) and blade (c) in a LPT. It has two different representations on the wheel and the blade. Both of them are composed by an extruded complex profile, which are: a slot in the wheel and solid in the blade. The profiles share some parameters and depend on the others representation parameters to be geometrically fully defined, thus, the profiles are tightly linked.



(a) (b) (c)

Fig. 1. Wheel and blade assembly through the firtree

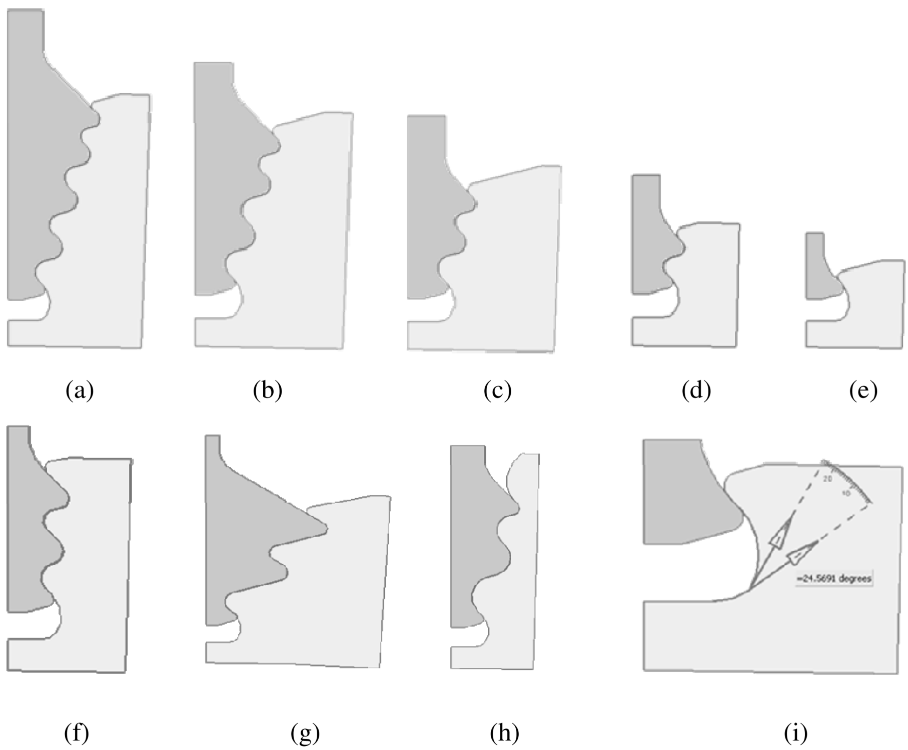


Fig. 2. Supported firtree configurations

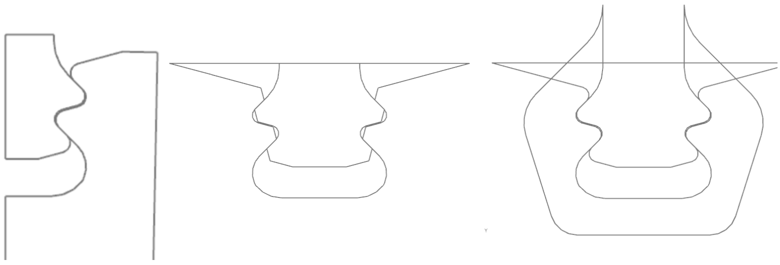
The profile topology contains many configurable elements. As shown Figure 2 firtrees with lobe number ranging from 5 (a) to 1 (e) are supported. The overall pressure angle can be modified (f) and (g), and the parameters of the two arcs present in each lobe can be specified individually (h). Finally, the bottom of firtree profile in wheels is composed of several arcs that may not be tangent on every design (i). In total, more than 60 parameters have to be specified to fully define the profiles of the firtrees.

5 Firtree Development Process and States

The firtrees as the whole wheels and blades, have to be modeled in different development states throughout their development processes.

The development process of this linking design feature starts by reviewing the validity of existing ones, due to the high cost of their tailor-made manufacturing tools for the wheels, i.e., broaches.

Following, if the designer finds out that none of the existing firtree designs is valid for the new project. It starts to generate new firtree profiles. During preliminary design iterations, static stress checks are performed to ensure certain validity of the proposed designs. Thus, the detailed firtree design is proposed, see Figure 3 (a).



(a) (b) (c)

Fig. 3. Different states of the same firtree during the development process of wheels and blades

When the preliminary design gets accepted, it is thoroughly checked for fatigue life though CAE analysis, and the lobes need to truncated and slightly modified according to internal CAE standard practices, see Figure 3 (b).

Following, when the blade design is approved, an as-cast model of the blade has to be generated and the firtree is covered up with stock material and changes its topology completely, see Figure 3 (c).

Finally, the approved wheel and blade designs' raw material models and detailed models are submitted to the Process Planning department to set out their manufacturing processes.

6 KBE Application Development

As aforementioned, the amount of parameters to be gathered from the users and the amount of calculations to be performed are quite big. Therefore, the KBE application was architected as shown in Figure 4.

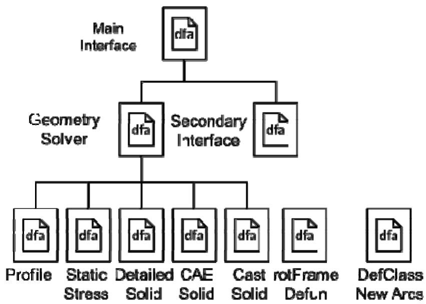


Fig. 4. KBE application class hierarchy

A class linked to the main dialog is used to mainly gather the desired state of the firtree and the profile positioning parameters in its attributes. All these attributes are directly accessible in any other object generated by itself or any descendant, due to the automatic inheritance of attributes in Knowledge Fusion. As the parameters to define the profiles are too many, they were moved to a sub-dialog. These parameters are passed into the Geometry Solver by reference chain to the main class.

Thus, all parameters are available at the Geometry Solver class that analytically solves the detailed profile points. As all the classes that generate geometry are created by this class, the solution is inherited and ready to be drawn in the different states. The Profile class supports the engineer during the preliminary geometrical design checks and simply draws the solutions with curves on the XY plane. The Static Stress class generates the profiles as sheet bodies to get the area of the profiles and performs the static stress calculations to aid the engineer during the preliminary checks. The Detailed Solid class positions the profile on the blade or wheel and extrudes the corresponding profile to generate the corresponding solid for the Boolean operation. The CAE Solid class derives the truncations out of the inherited solution and again generates the solid by extruding the corresponding profile. Finally, the Cast Solid is only applicable to the blade and calculates the outmost lobe to add stock at a distance from it recalculating a brand new cast profile.

Regarding the user interface a decision to integrate everything within a single dialog was made to simplify the interaction for the user. The tabs present in the dialog, represent the different steps along the development process to make it flow naturally. Figure 5 (a), shows the initial dialog with several options to load different designs and main profile position parameters. Pushing the Parameters Dialog button, the dialog n Figure 5 (b) is displayed to allow the user modify profile parameters. Figure 5 (c) corresponds to the preliminary static stress check step. Finally, the dialog in Figure 5 (d) allows the user to integrate the designed firtree profile in the corresponding wheel or blade solid in the desired state: detailed, truncated for CAE or (in blades) as-cast.

A remarkable effort was made to increase the productivity of users in defining the big amount of input parameters. Therefore, a close look to Figure 5 (a) show a displayed pop-up menu showing many different ways of loading existing definitions.

The “New” option allows the engineer to start from scratch.

Options starting with “Existing …” load parameters from a library of text files, where the parameters of manufactured broaches are stored. “Existing Standard” constrains the user and does not allow editing the parameters related to the broach, at all. “Existing Standard” corresponds to broaches that have been manufactures but assessed as non-valid. Whilst, “Existing and Edit” is a way to start a new design, taking as starting point an existing one.

Those options containing “HD” refer to design iterations that have been saved to the hard drive for future re-use. In this case, the engineer can decide whether he is allowed to change the parameters or not.

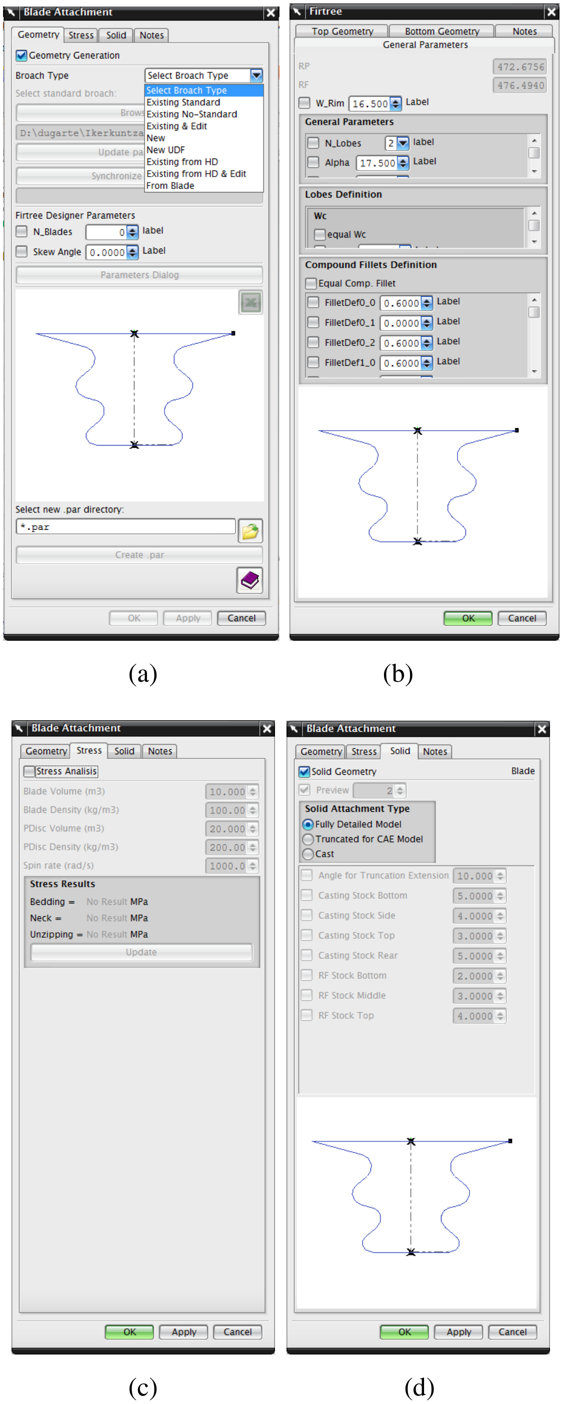


Fig. 5. KBE application dialog and tab content

Finally, the "From Blade" is designed to be used by the engineers that design wheels. This option allows reading the definition of the firtree profile from the NX part file where the KBE application has been used to define the firtree of the blade. This is possible because typically the development time of discs is longer than for blades.

7 KBE Application Validation

The KBE application went through two validation processes: 1) against the existing AML KBE application, and 2) against the NX experts within the LPT supplier.

On the first validation, all pre-existing firtree designs where fed into the Knowledge Fusion based firtree application and compared the outputs between the IGES file that the AML based application output with the curves generated in NX by Knowledge Fusion. A 100% of matching results were achieved.

On the validation against internal NX experts, the check was performed regarding usability of the application. The usability of the KBE application was assessed as good.

Thus, the KBE application was approved and activated.

8 KBE Application Maintenance

Despite the initial approval, after some successful firtree designs a new project came in. First iterations were performed based on the existing KBE application and, on the opinion of design engineers, no satisfactory solution was found based on the approved topology (type and amount of curves present in the profile). Design engineers required the bottom of wheel groove to be curved and not flat (cylindrical in 3D) in the firtree profile for the wheel.

As can be spotted in Figure 2, all supported configurations relied on a bottom flat groove profile, and no curved bottom was supported by the KBE application.

Therefore, a knowledge management challenge was confronted. What should be done in such a case? Should the application include the new firtree configuration? Should engineering management force design engineers to constrain themselves to the standard configuration?

In this case, modifying the Geometric Solver class to support the new configuration would have been costly, as it would have required the class to be rewritten from scratch.

The latter, forcing engineers to follow the standard topology, is a two folded decision. Any standard should provide the benefit of reducing costs. However, at the same time, they may also hinder innovation. So it is definitely a complex management decision.

Therefore, an intermediate solution was taken in this work.

NX, as a fully-fledged feature based design CAD application, supports User Defined Features (UDF) definition, management and instantiation. UDFs are customization elements. During UDF definition, the way a design feature is geometrically constructed is captured. During the UDFs definition some constraints on parameter values can be set, but their semantics are very limited. Most importantly for the KBE field, UDF definition happens over an NX part any design engineer may have constructed. Therefore, capturing the geometrical construction knowledge can be done very quickly through UDFs. Thus, only UDF's geometrical construction capabilities were exploited in the solution.

As an intermediate solution, the user was also enabled to choose between a set of firtree UDFs during the definition phase. This was achieved by including the "New UDF" option on the displayed popup-menu on Figure 5 (a) The benefit of such an approach is the ability to quickly partially maintain the KBE application. The counterside of such a solution is that there is no support for the following states of the firtree.

9 Conclusions

The firtree KBE application did meet its expectations and significant time reductions were achieved, as expected. However, as described in [1], one of the critical aspects of KBE applications is knowledge management. Within this context, to manage knowledge means to take the decision when a new knowledge item (a new firtree configuration, in this case) deserves to be integrated into the knowledge repositories or KBE applications of the company and when it has to be regarded as a single exception solution.

Whenever the KBE application requires any maintenance it is convenient to consider the observation made in [18], where the authors state that typically customization/UDFs have a much better return on investment, than automation/re-coding KBE application.

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Virtual Validation of the Manual Assembly of a Power Electronic Unit via Motion Capturing Connected with a Simulation Tool Using a Human Model

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Abstract. A key challenge for gaining important time and cost potentials in production engineering projects is an early virtual validation during the pre-series. Under the premise to replace physical by digital mock-ups, we will present requirements and solutions of a virtual validation focused on manual assembly of power electronics in automotive industry. Using a digital human model for dynamic analysis is not very prevalent, because of the high modeling complexity in the digital environment. The resulting motions of the human model are furthermore unrealistic. Hence the need for research is a time saving and, regardless, a realistic movement design for virtual validation by a human model. To achieve this goal, we use an experimental setup including a variable eight camera motion capture system, a data glove and an interface for the connection to the digital validation software.

Keywords: virtual validation, manual assembly, motion capture.

1 Introduction

The future competitive situation in the automotive industry and the increasing market demands will inevitably lead to higher complexity in product development, production planning and pre-series. Longer lifecycles of assembly systems based on highly flexible production cells with a rising number of integrated processes call for new solutions, especially in production engineering. An early virtual validation is helpful for simultaneous engineering and leads to production-oriented product design and development. [1] In this early stage only digital mock-ups are available. Human models are used for the virtual validation of manual assembly tasks. The movement of the worker is either unrealistic, or time expensive to realize. Hence the need for research is an optimization of virtual validation using a human model.

A motion capture (mocap) system, a data glove and an interface for the connection to the validation software is used for improvement. This setup allows an object and human tracking at the same time. The human tracking is connected with virtual affixing of the assembly. With this experimental setup the correlation of the real and

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virtual situation is tested. The collision calculation and a dynamic Rapid Upper Limb Assessment (RULA) analysis are possible in real time as well as a later processing with stored data after the tracking. Additional a transient ergonomic analysis with the Ergonomic Assesment Work Sheet (EAWS) is realized with the ALASKA software from the Institute of Mechatronics (IfM) in Chemnitz, because EAWS is not yet implemented in DELMIA from Dassault Systemes. The flexible system setup concept with eight cameras is also presented. This concept is developed for a highly flexible camera positioning for different assembly tasks to avoid occlusion. The visualization of the digital environment is realized in 3D.

2 State of the Art

It is difficult to create postures or movements of human models in simulation software like DELMIA. Software upgrades for the analysis workbenches are necessary. For different postures and especially for movements and time depending analyses, scientific models are missing. The manual assembly of limp components is not possible to validate in conventional software for example. Besides the time consuming teaching of the human model, the resulting movement of the worker in the virtual environment is unrealistic and hence not a good base for ergonomic analysis. Regarding the appraisal possibilities of the analysis there is also need for action in order to be able to filter critical situations, postures, tasks etc. clearer and faster and additionally to define the elements for an optimization of the situation. Important functions are view and reachability analysis. More complex analyses like posture analysis are used less often. [1–5]

A lot of manual teaching of the human model is necessary to simulate and accordingly validate a manual assembly task. Generally there are two different conventional ways of setting the manikin to the desired position or orientation. The most time expensive option is to move every single body part manually with a function that is usually called forward kinematics. The second possibility is using some kind of inverse kinematics. The operator has to set the final position and orientation of a certain body part, e.g. the hand, and the posture prediction system generates the corresponding movements of the other involved body parts, e.g. the arm and shoulder. Although the option of using a posture prediction system is much faster in comparison with the forward kinematics function, one crucial disadvantage persists: The generated movements are often unnatural and an appropriate examination is difficult [6].

The different ergonomic analyses depend on the joint angles of the human model, so a realistic movement is fundamental for acceptable results. Filming the real assembly movement is a good way to create comprehensible movements of the human models. That's because the postures and positions of the relevant body parts such as hands, arms, torso and legs, can be taken directly from the video documentation. Despite good analysis results, this method is very time consuming. To create rapidly and more detailed ergonomic simulations the possibilities of motion capture are the most promising.

To avoid problems in the production process, because of the high number of variants, virtual validation is a useful tool. The subsequent integration of high voltage components in existing car concepts is an actual example for the increasing variety in automotive production. Therefore different requirements arise from the assembly situation to produce different engine concepts in one production line. [7]

Especially for automotive industry, an increasing interest in an effective way for virtual validation is observable. Insufficient experience and expert know-how in the field of e-mobility concerning the assembly and the mounting of electric components are trademarks of today's production environments. Anticipatory planning of the entire production process in an early stage of product development – including a collision-free feasibility and accessibility, validation of assembly sequences and posture analysis of the mechanic for ergonomic reasons – is the future for automotive industry. [8, 9] Research in this field is also interesting because of the medical aspect [4].

3 Generating Realistic Movements of the Human Model

The underlying idea is to use an experimental setup including a variable eight camera motion capture system, a data glove and an interface for the connection to the validation software, in order to solve the different problems. To record the movement in a digital environment the motion capture system is used. To simplify the teaching of the human model the captured data is transferred from the tracking program directly to the analysis program via a data interface. In this course the problem of unrealistic movement is solved too. With the system setup shown in figure 1 the following experiments are carried out.

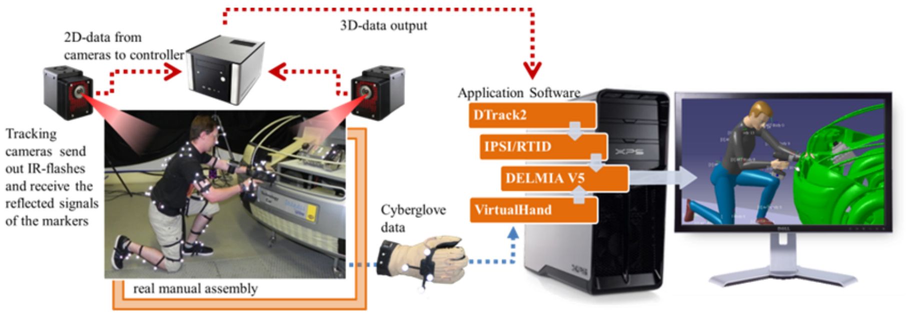

Fig. 1. System Setup for generating realistic human model motions [12, 13, 22]

The advantages of virtual in comparison to physical validation are defined by Flick and Riedl [10, 11].

3.1 Motion Tracking/Capture System

To capture the movement of a worker during a manual assembly task a motion tracking system is used. Since optical systems have the highest accuracy of the common motion capture technologies, we use an eight camera system from Advanced Realtime Tracking (A.R.T.) GmbH. Other technologies use e.g. mechanical or inertial sensors to measure the relative motions of the human joint angles. The cameras are placed around a 3.5*3.5 m² working area and they send out a synchronized infra-red-(IR)-flash. The actor wears a sensor set of 17 targets, consisting of retro-reflecting spherical markers. The targets reflect the IR-radiation into the direction of the incoming light. At least two cameras must receive the reflected signal, to calculate the six-degrees-of-freedom-(6DOF)-orientation of the targets. If more cameras cover a certain target, the tracking signal is redundant, but more accurate. Every tracking signal of an optical motion capture system (MCS) is calculated with its absolute position and refers to the defined origin and orientation of the room coordinate system. This gives optical MCS the opportunity to not only track human motion, but also capture the movement of any object and their interaction, when a target is fixed on it. The main problem is to avoid occlusion due to obstacles in the recording area or by the actor himself. We try to solve this problem by rearranging the cameras in order to create an application-specific setup by visualizing the cones of light (see figure 2).

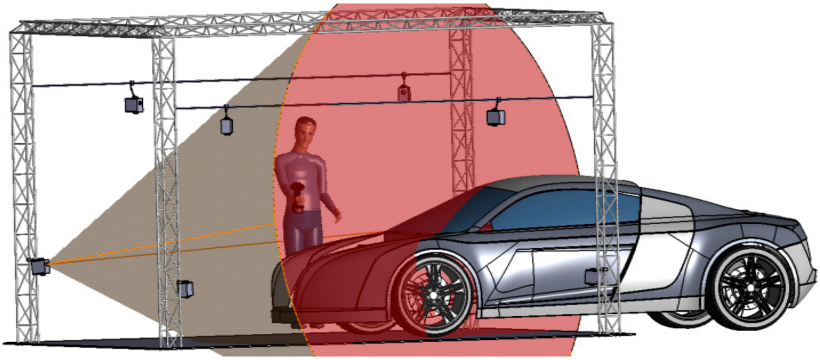

Fig. 2. CAD-tool for the flexible application-specific setup

The application software DTrack2 does all necessary calculations. It serves as a graphical user interface to the controller and offers the position and rotation tracking data for further use. [12]

3.2 Data Glove

Data gloves are used to measure the finger angles of hand and finger joints. For the realization of these measurements various measuring principles are used in different current data gloves. The data glove used in our experiments was the CyberGlove II in its wireless version. It contains 22 sensors based on the principle of strain gauges. Namely these are three bending sensors per finger, four abduction sensors and sensors for thumb crossover, palm arch, wrist flexion and wrist abduction. [13]

The thin gauges are made up of an electrically conductive material. When a gauge is bent in consequence of e. g. the flexion of a finger, its resistivity is increased. This effect makes it possible to determine the corresponding finger movement with the help of a calibration process. The use of strain gauges makes the CyberGlove more efficient than other data gloves. [14]

The CyberGlove offers no ability to calculate the position and orientation of the hand according to the room coordinate system. This is why an additional hand tracking is obligatory. As the CyberGlove itself has no ability to give the user any kind of force feedback, CyberGlove Systems distribute solutions for force feedback which can be also used in combination with the CyberGlove.

3.3 Interface Software

The Haption RTID software is an interface to connect the CyberGlove and the motion tracking software with the simulation tool DELMIA V5. RTID stands for Real Time Interaction for DELMIA and consists of the components RTID Core and Human. The application is based on the physics-engine Interactive Physics Simulation Interface (IPSI) and allows the processing of all prevalent V5-formats. Movements, captured with various mocap-applications, can be recorded as move to posture-activities or as .xml-data file. Because of the Client/Server-principle of the IPSI-engine, the main computing is done by the IPSI-software and can be sourced out on another processor. Therefore the client only has to do the visualization. Haption also offers possibilities for the integration of collision mechanisms. [15, 16]

3.4 Validation Software

In this study, the digital human model and work environment are designed in DELMIA V5. It’s the basis software to do the digital analysis for the manual assembly. The human model used for DELMIA is human builder. It includes all the functionalities that human models should have for the purpose of using them in ergonomic simulations [17] and also to study the interaction between the man-machine relation. The sophisticated manikin structure consists of 99 independent links and 148 degrees of freedom and has access to data from multiple populations. In addition, the manikin possesses fully articulated hand, spine, shoulder, and neck models to accurately reproduce natural movement, which includes default inverse kinematics for manikin motion [18]. Also the natural constraints of the joint angles are considered.

The Human Activity Analysis tool allows static posture analysis, lifting/carrying according to Niosh and push/pull according to Snook & Ciriello, hand-arm studies (RULA), motion, ergonomics, and handling investigations. The Human Posture Analysis provides a qualitative and quantitative real-time analysis of attitude with color marked single values for each joint. An automatic posture optimization completes the feature set. [3]

For an accurate visualization of the human model, the anthropometric data of the actor must be assumed for the virtual manikin.

4 Experimental Setup

To realize the above mentioned idea it is necessary to connect the different hard and software parts to a running system. For the accomplishment of the planned experiments, a separated room surrounded with black curtains was created. This conduced to the avoidance of reflections, what is important for the proper working of the optical tracking system. In the recording area, different objects building the assembly scene were placed. These were a demonstrator vehicle, an assembly table, a cordless screwdriver and a power electronic unit. Furthermore a silver screen was added to show the captured scene to the particular test person and to relieve the communication between the operator and the test person. Eight IR cameras were placed around the scene and the test person, who should provide the motion data for the manikin, was equipped with the optical targets and the CyberGlove II wireless. The digital virtualized experimental setup is shown in the following figure 3.

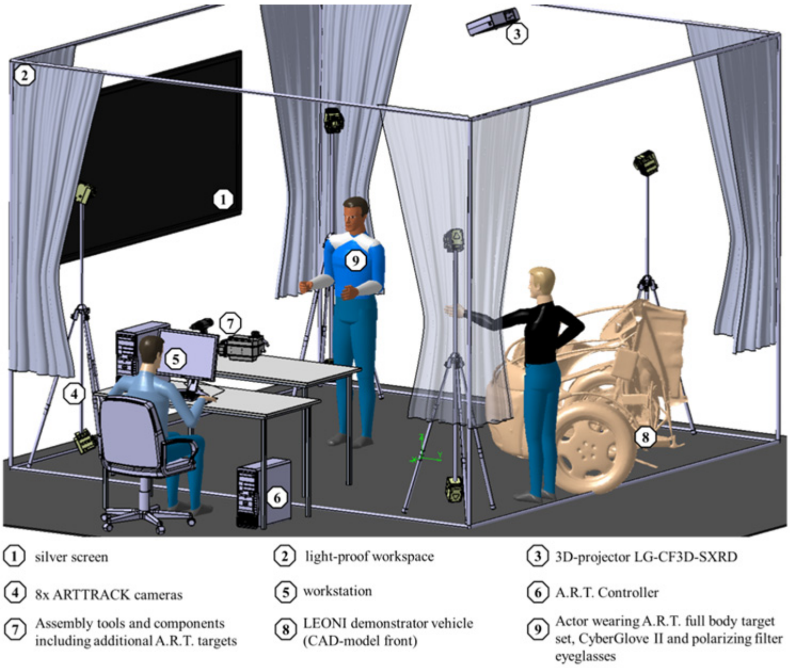

Fig. 3. Experimental setup in the digital environment of DELMIA V5

The IR cameras were connected with the DTrack Controller. The main computer, a CAD workstation, was connected witch the DTrack Controller, with the screens for the operator and for the test person and, via Bluetooth, to the CyberGlove II. In our experiments the software systems DELMIA, RTID, DYNAMICUS and VirtualHand were all installed on one PC, which carried out the main processing as well as the visualization. For future work an outsourcing of the main processing on a second computer is planned.

4.1 Experiments and First Experiences

The intention of the performed experiments was to gather information about the possibilities and limitations of the described hardware and software constellation.

The aim is the ability to capture the movements of humans and objects, to record them both together and to replay and analyze the generated movement sequences. Therefore an exemplary assembly situation was created, where a worker should fit a power electronic unit in the engine compartment of a demonstrator vehicle. The corresponding manikin movements should be analyzed in real time and also in recorded form. In Haption RTID the motion tracking of humans or objects is relatively simple once the required calibrations are made. The recording of the correspondent movement sequences is a little more challenging. Movement of the Manikin can be recorded as a DELMIA-internal "move to posture" or as well in the .xml format. Generally there are two ways of integrating movement of objects in the simulation process. On the one hand virtual objects can be attached to single body parts irrespective whether a physical counterpart is used or not. On the other hand optical targets can be fixed to real objects. When a linkage of the target and the corresponding virtual object is created in Haption RTID, moving the real object also determines a movement of the virtual pendant. For a realistic representation of the tracked movements, the matching of the real and the virtual subjects and objects is of great importance. This means, that the positions of the real and the virtual targets have to be brought in accurate accordance with each other in the course of the calibration process. If the calibration is not carried out properly, there might appear deviations between the real and the virtual position and orientation. During our studies we could for example observe gaps between the manikin's hand and a bored object. An easy possibility to add objects to recorded human movements is to insert a pick and place function into the sequence of the created move to postures. Unfortunately this method has nothing to do with the tracking of real objects. Another option is to add a target to a real object like described above. The problem lies in recording and replaying these sequences. Recording and replaying human and object movements apart from each other and replaying them all together is possible, but to perform this task, it is necessary to use IPSI scripting, a python-based SDK-application for the easy integration of changes within the software context. Once the appropriate scripts are created, it works very well. A further possibility to capture and analyze motion data is offered by IfM. The simulation tool ALASKA is a multi-body-simulation tool for the analysis of dynamic mechatronic systems. The software tool is modular, so that just the required plug-ins needs to be integrated. The DYNAMICUS/Recorder is a tool to record human tracking data as well as object movement. The motion data of any target is saved in a single .xml-file. For single ergonomic analysis the data can be transferred into DYNAMICUS/EAWS. For further interaction the motion data can be integrated into an ALASKA simulation environment. [19]

With the right calibration the capturing of finger movement with the CyberGlove II works quite well in DELMIA. This is again strongly depending on the corresponding calibration process. The current version of DYNAMICUS does not offer a CyberGlove interface.

4.2 Analysis

In order to visualize the captured motion data and interpreting it in relation to ergonomic matters, two different software systems were tested. These were on the one Hand DELMIA V5 with the corresponding plugin Haption RTID and on the other hand DYNAMICUS/EAWS. Both tools allow the ergonomic analysis of human movement but with two different approaches. While DELMIA offers ergonomic tests according to different international standards of which we chose the RULA analysis, DYNAMICUS/EAWS uses the European Assembly Worksheet EAWS. The basics of the two methods and the corresponding differences are illuminated below.

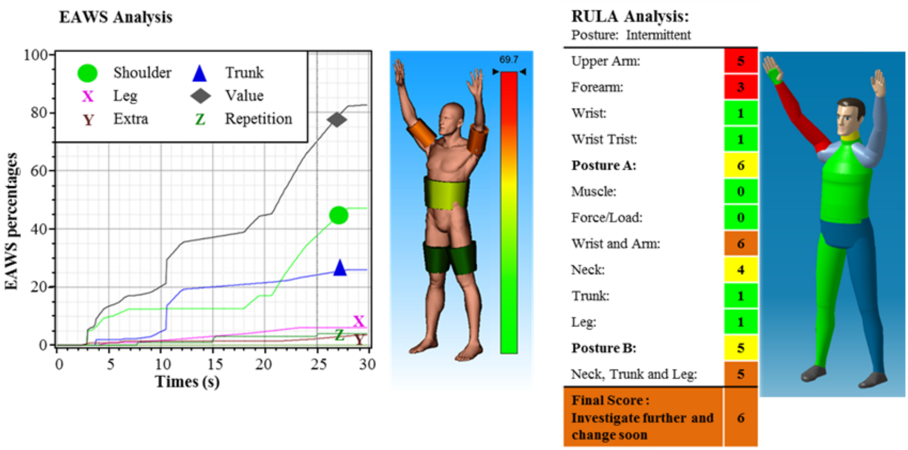

Fig. 4. The RULA and EAWS analysis with the corresponding human models

RULA. Is a survey method developed for use in ergonomics investigations of workplaces where work-related upper limb disorders are reported. This tool requires no special equipment in providing a quick assessment of the postures of the neck, trunk and upper limbs along with muscle function and the external loads experienced by the body. A coding system is used to generate an action list which indicates the level of intervention required to reduce the risks of injury due to physical loading on the operator. [20]

EAWS. In accordance to the German BAuA and the Toyota method, IAD tools grant load points for ergonomically unfavorable conditions. Dependent on the score a traffic light three zone rating system is associated with respect to the demands of the Machinery Directive. The EAWS consists of four sections for the evaluation of working postures and movements with low additional physical efforts (< 30-40 N or 3-4 kg respectively), action forces of the whole body or hand-finger system, manual materials handling and repetitive loads of the upper limbs.

Sections one to three base their evaluation on physiological and biomechanical criteria; section four is based on medical and epidemiological data. With respect to the different evaluation approaches the results of sections one to three are combined to a "whole body" exposure, whereas section four indicates the load situation of the "upper limbs". Both approaches are rated in a 3 zone rating system as shown in figure 3. The overall estimation is the worst case of "whole body" and "upper limbs". The dashed line in between the green, yellow and red zones indicate, that they are no concrete border lines, but transient areas. This means 47 and 53 points represent the same "orange" color, i.e. colors do not "switch from yellow to red", when crossing a score of 50. [21]

5 Conclusion

In this paper a virtual validation methodology for the manual assembly of a power electronic unit, using a virtual human model, has been presented. First, the problems of virtual validation and the state of the art are described. With the identified problems the need for research in this field is proved and leads to the idea of using mocap with a direct interface to the validation software. Second, the single systems connected with each other to a setup that allows the stipulated possibilities are presented. This concept enables us to detect possible sources of errors and hazards at an early stage, allowing installing preventive measures. Third, in addition to the product-related virtual validation, the modeling and simulation-based design of a manual workstation is performed with DELMIA to integrate the virtual human model to perform further ergonomic analysis within the virtual validation. Additional the EAWS analysis is performed with the ALASKA software. Summarized, this setup allows a time saving teaching of the human model, a realistic movement of the worker, so that digital becomes virtual, and an easy way to give an ergonomic feedback about the human-machine-system.

6 Future Work

This work has focused the application of the presented system regarding integration and testing the possibilities. Some remaining steps, i.e. force feedback and collision analysis, present future work. A particular problem therein is the virtual validation of flexible components, which is currently being researched. In order to evaluate the ergonomics of the necessary assembly steps, an extension to the virtual human model providing such information is a key research objective in the current eProduction research project and thus also presents future work.

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Simulation of Variation in Assembly Forces Due to Variation in Spot Weld Position

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Abstract. Resistance Spot Welding is frequently used for joining of sheet metal assemblies. Geometrical variation in parts to be joined, variation in fixtures and lack of repeatability in welding guns and robots, result in variation in spot weld position. Analysis of industrial scanning data showed deviations of spot weld positions of magnitudes up to 19 mm. This variation leads to variation in the initial gap between the parts to be joined and therefore, also to variation in the assembly force required to join the parts. In this paper, a simulation method for prediction of variation in assembly forces due to variation in spot weld position is presented.

Keywords: resistance spot welding, variation, welding gun, welding force, assembly force, joining, tolerances, variation simulation.

1 Introduction

Resistance spot welding (RSW) is the dominant joining method in automotive industry. Spot welds of good quality are important in order to fulfill key performance characteristics of the car, such as stiffness and crash behavior. Welding force, together with welding current and time, are the most important parameters which affect the functional performance of a spot weld. In RSW, a force must be applied to press the parts to be joined against each other in order to allow the current to pass through both parts. If the force is too low or too high the resulting joint will probably decrease in strength. Due to variation in individual manufacturing processes, the parts may not be nominal, and this, together with variation in the assembly process, may lead to gaps between the parts in the locations of the weld points. Those initial gaps need to be closed, and some of the predefined welding forces are then consumed in order to close the gaps. Therefore, it is important to take the variation in magnitude of the initial gaps into consideration when defining suitable welding forces. The initial gap is strongly affected by the position of the spot weld. In this paper the coupling between variation in spot weld position and variation in the force needed to close the initial gap is investigated and a simulation method for predicting variation in assembly forces is proposed. The term assembly force will be used to describe the force

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required to close the initial gap, while welding force refers to the total force applied by the welding gun.

In the following two sections, introductions to methods for variation simulation and spot welding in automotive industry are given. In those sections, also an overview of relevant literature is given.

2 Methods for Variation Simulation

Geometrical variation in parts is a result of previous manufacturing processes. The variation propagates from parts throughout the assembly systems and may lead to products not fulfilling requirements, with high costs and reduced competitiveness as a consequence. To foresee, and thereby also possibly reduce, these kinds of problems in a final assembly, methods to predict geometrical variation are crucial tools [1]. Activities of this kind, often referred to as variation simulation, are performed in early stages of the product development process in automotive industry. With increased demands on sustainability, virtual tools for variation simulation will be even more important in the future, since they can reduce the need of physical tests and pre-series.

Variation simulation is in many cases based on Direct Monte Carlo (DMC) simulation [2], where statistical distributions for the parameters affecting a critical dimension are defined. By sampling those distributions, the resulting value in the critical dimension can be computed. This procedure is repeated a number of times and thereby a distribution of the critical dimension can be approximated. By incorporating FEA techniques, non-rigid tolerance analysis may be performed. This analysis may be used to simulate how non-rigid parts or subassemblies of non-rigid parts, such as sheet metal and plastic components, behave after assembly.

Lee et al. [3] examine how welding sequences for continuous welding can be included in variation simulations by using a pre-generated database. Wärmefjord et al. [4] include the welding sequence in variation simulation and verify the result on an industrial case study. Hu et al. [5] investigate the effect of the welding sequence on a dash panel assembly.

3 RSW in Automotive Industry

During all welding, heat is generated. This may lead to deformations of the parts. For spot welding, this deformation is usually of minor importance [20] and is not included in this work.

The RSW process is mainly influenced by the welding time, welding current and welding force. The welding force, or electrode force, applied ensures the electrical contact and retains the weld nuggets from weld expulsion, which is ejection of molten material from the weld nugget during welding. Zhang et al. [6] conclude that the electrode force is the second most important parameter to control expulsion. Hamedi et al. [8] minimize the deformation of the final assembly by optimizing welding current, welding time and electrode force. The RSW process significantly affects crashworthiness of a vehicle [9].

Before welding, the parts are clamped in the assembly fixture. Due to springback after stamping, influence from previous assembly steps, positioning errors, weld point deviation from its nominal position etc., there will be gaps between the parts/flanges to be welded. This initial gap influences expulsion [10]. To avoid expulsion, the electrode force can be increased [11]. A too high electrode force will however increase the welding contact zone and thereby decrease the electric resistance, leading to a too small nugget size. Both expulsion and a too small nugget size lead to reduced weld strength. Therefore, it is important to take the initial gap into consideration in order to find a suitable electrode force for a sound spot weld. The force needed to close an initial gap is investigated by Murakawa and Ueda [12], who apply parametric curves and approximation curves to two simple structures. The force required to close the initial gap varies of course with the variation in the gap. Therefore, it is of great importance to be able to predict this gap/force variation in order to design good RSW. As shown later in the paper, the initial gap is dependent on the spot weld position and variation in spot weld position leads therefore to variation in assembly forces required to close the gap.

Most of the previous work investigating the correlation between initial gap and the necessary joining force tries a couple of different values of the initial gap. By running a Monte Carlo based variation simulation, aiming to predict the force needed to close the initial gap, an interval of probable values of this force can be simulated, as described later in this paper.

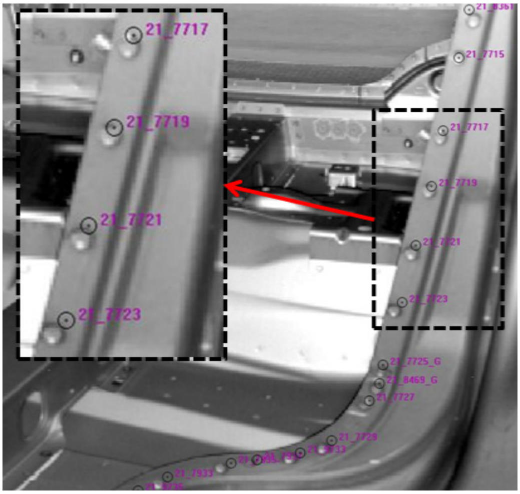

Fig. 1. The actual spot weld position compared to nominal spot weld position (indicated with black circles)

The positions of the spot welds affect many characteristics of the final product, such as stiffness and geometrical deviations. As shown later in the paper they also affect the required welding force. The variation in spot weld position is caused by:

- geometrical variation on the part level in areas where spot welds are located;
- variation in the positioning of the parts to be assembled;
- wearing of electrodes on the welding gun;
- lack of repeatability in the robot and the welding gun.

In [13], the effect of variation in spot weld position on geometrical variation in a number of critical measures was analyzed.

To investigate the magnitude of the variation in spot weld position in automotive industry, spot-welded assemblies were scanned and analyzed. The instrument used was a 3D scanner with phase-based distance sensor. In Fig. 1. a scanning of a spot-welded assembly from an automotive manufacturer is shown. The deviation between nominal and actual positions of the spot welds is in many cases quite large. For a number of more closely analyzed spot welds, the maximum deviation from nominal position amounted to 19 mm. The mean deviation was 9 mm.

4 Simulation Methodology

To be able to simulate the effect from variation in spot weld position on required welding forces and to build a distribution for the welding forces in all different weld points, Monte Carlo simulation is used. The Monte Carlo simulation is in this case enclosed in the software RD&T [14], where a total sensitivity matrix is implicitly defined in a FEA-based simulation model describing all mating conditions, kinematic relations and non-rigid behavior.

The inputs to a general variation simulation are, in the case of non-rigid simulation, part meshes, material properties, locating schemes, tolerances of the parts and fixtures, and information about the joining process – i.e. joining method, position of the joining points and joining sequence.

Direct Monte Carlo simulation combined with FEA is a standard technique for variation prediction of compliant parts. However, since a large number of replications are required for achieving satisfactory accuracy, the method is very time-consuming if a new FEA calculation is to be executed in each replication. Liu and Hu [15] presented a technique called Method of Influence Coefficients (MIC) to overcome this drawback, and this method is used in the work described in this paper. The idea of MIC is to find a linear relationship between part deviations and assembly springback deviations. The sensitivity matrix, constructed using FEA, describes that linear relationship. This sensitivity matrix is then used in the simulation, and a large number of FEA calculations can be saved.

Contact modeling is another important aspect to include in non-rigid variation simulations. It is a way to avoid that parts in the virtual model penetrate each other due to possible imperfections and variations in parts and tools. Instead, the resulting forces due to collisions are transferred to the parts via contact surfaces. Here, a point based contact algorithm is used [16].

The force needed to close an initial gap in welding point i (wp_i) is highly dependent on active contact conditions in the surrounding geometry. The distance to the closest contact points affects the simulated welding force. In order to minimize differences due to this effect, contact points are placed in all nodes adjacent to the welding point. This is illustrated in Fig. 2. Even though the position of the welding point is varied, the welding point is always surrounded by contact points.

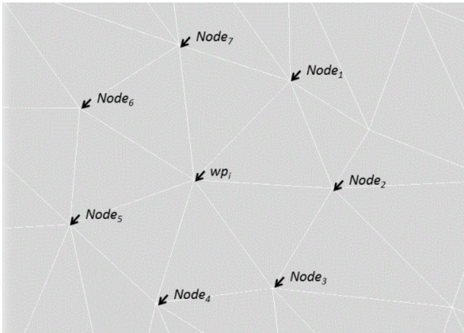

Fig. 2. A weld point and its surrounding nodes. Contact points are placed in all nodes adjacent to the weld point (i.e. in Node 1-7 in the figure).

The joining sequence is also taken into consideration in the simulation methodology. For a non-rigid assembly, the following steps are generally necessary to take into consideration when predicting variation and deviation in critical dimensions of the final assembly:

- Step 1: The parts are positioned/clamped in their fixtures, and over-constrained locating systems (i.e. clamps) are applied. Forces are applied to clamp non-nominal parts.
- Step 2: The parts are welded together in a pre-defined welding sequence. The gaps in the weld points are closed, one by one.
- Step 3: After the last joint is set, the assembly is unclamped and is allowed to springback.

The third step is not of interest in this work, since the focus is on determining the welding forces required in Step 2.

In the work by Wärmefjord et al. [17], Step 1-3 above is described in detail for RSW when a balanced gun is used. The assembly forces are calculated in each MC replication. The simulation method to do this is based on the following steps:

Modeling of step 1: Clamping the parts in the fixture

The parts a and b are positioned in their fixtures and over-constrained locating systems are applied. The gaps to be closed in the clamping points are gathered in the vectors $\{\mathbf{u}_\mathbf{p}^\mathbf{a}\}$ and $\{\mathbf{u}_\mathbf{p}^\mathbf{b}\}$ respectively. To close the gaps in the clamping points, forces $\{\mathbf{F}_\mathbf{p}^\mathbf{a}\}$ and $\{\mathbf{F}_\mathbf{p}^\mathbf{b}\}$ respectively are applied. The part stiffness matrices are denoted $[\boldsymbol{K}_\mathbf{p}^\mathbf{a}]$ and $[\boldsymbol{K}_\mathbf{p}^\mathbf{b}]$ respectively. The relations between forces and gaps can be described as:

$$\{\mathbf{F}_{\mathbf{p}}^{\mathbf{a}}\} = [\boldsymbol{K}_{\mathbf{p}}^{\mathbf{a}}]\{\mathbf{u}_{\mathbf{p}}^{\mathbf{a}}\} \tag{1}$$

$$\{\mathbf{F}_{\mathbf{p}}^{\mathbf{b}}\} = [\boldsymbol{K}_{\mathbf{p}}^{\mathbf{b}}]\{\mathbf{u}_{\mathbf{p}}^{\mathbf{b}}\} \tag{2}$$

<u>Modeling of step 2</u>: Welding the parts, weld point (wp) *i*=1,...,*N*

To set wp *i*, a force $\{\mathbf{F}_{\mathbf{A}}^{\mathbf{i}}\}$, where the index *A* stands for assembly, is applied and the relation becomes:

$$\{\mathbf{F}_{\mathbf{A}}^{\mathbf{i}}\} = [\boldsymbol{K}_{\mathbf{A}}^{\mathbf{i-1}}]\{\mathbf{u}_{\mathbf{A}}^{\mathbf{i-1}}\} \tag{3}$$

After wp *i* is set, the assembly is released from its fixture and will then springback (the release step is executed since it gives clearer and easier calculations compared to accumulating the resulting forces for each joint). The stiffness matrix $[\boldsymbol{K}_{\mathbf{A}}^{\mathbf{i}}]$, used to calculate the springback, describes the stiffness of the assembly after wp *i* is set and is determined in Equation (4).

After the springback, the assembly is brought back to its position by applying the clamps once more, and the required force $\{\mathbf{F}_{\mathbf{A}}^{\mathbf{i}}\}$ to do this, taking both clamping forces and forces due to contact modeling into consideration, is registered.

The stiffness matrix $[\boldsymbol{K}_{\mathbf{A}}^{\mathbf{i}}]$ is updated for every new wp by adding, to the stiffness matrix from the previous step, a new matrix $[\boldsymbol{K}_{\mathbf{wp(ia,ib)}}^{\mathbf{i}}]$ locking three translations and three rotations corresponding to the added joint. This means that

$$[\mathbf{K_A}^{\mathbf{i}}] = [\mathbf{K_A}^{\mathbf{i-1}}] + [\mathbf{K}_{\mathbf{wp(ia,ib)}}] \tag{4}$$

For the very first wp, the matrix $[\mathbf{K}_{\mathbf{A}}^{\mathbf{0}}]$ refers to the original part stiffness matrices, i.e. one for each part. The deviation used for the first welding point, $\{\mathbf{u}_{\mathbf{A}}^{\mathbf{0}}\}$, corresponds to the part deviations.

It should be noted that, with the terminology used in this paper, the assembly force $\{\mathbf{F}_{\mathbf{A}}^{\mathbf{i}}\}$ only refers to the force required to close the initial gap in wp *i*, and does not include the force needed to form a sound weld.

5 Case Study

In this section an industrial case study is presented. The case study is an A-pillar assembly, consisting of two parts: the A-pillar and its extension, shown in Fig. 3. The A-pillar and the extension are welded together with eight spot welds. The welding sequence is also illustrated in Fig. 4. For this case study, the position of the spot welds will be varied and the resulting variation in assembly forces will be investigated. The inputs in the simulation consist of:

- scan data, represented by FE meshes, of both of the geometries included in the assembly on part level;
- tolerances for spot weld position.

Variation simulation for this case study (without variation in spot weld positions, but based on the scanned geometries) aiming at predicting the deviation from nominal values in a number of inspection points has previously been conducted and the results have been validated against industrial scanning data of the complete assembly [18], [21]. The correlation between simulated results and scanning data of a complete assembly amounted to 0.94 for inspection points located on the A-pillar and 0.87 for inspection points on the extension.

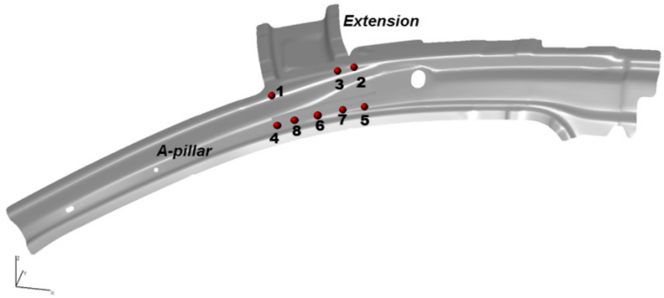

Fig. 3. The A-pillar assembly consists of two parts, the A-pillar and its extension, which are joined with eight spot welds. The figures show the welding sequence.

The outcome from the scanning shown in Fig. 2 is used to estimate a reasonable tolerance for the spot weld position. To each spot weld position, a circular tolerance consisting of an angle and a radius is allocated. The angle is uniformly distributed between 0 and 2π and the radius is uniformly distributed on [0, 7.5] mm. The element lengths in the mesh are approximately 3 mm, and since the node closest to the randomly generated spot weld position (according to the defined tolerance) is chosen as the weld point, the actual spot weld position may vary within a circle with radius up to 9 mm. A Monte Carlo simulation with 5000 replications is run. In each replication, a disturbance for every spot weld position is randomly generated and the node pair closest to the new position is chosen as the new position of the spot weld. For each new position of a spot weld, contact points are placed in nodes adjacent to the spot weld node. No other sources of variation, except the variation in spot weld position, are added. As already mentioned, the meshes for the individual parts are, however, based on non-nominal scanning data from industrial production.

In Fig. 4 the distribution of the assembly forces for each one of the eight spot welds are shown. As can be seen, there are quite large variation in the force required to close the gap between the two parts to be joined for each spot weld. For wp_7, the minimum value is 0.01 kN, while the maximum required assembly force amounts to 2.7 kN. For wp_8 there are actually three replications resulting in a value of approximately 6.2 kN, this is however just three values out of 5000. The fourth largest value for wp_8 is 2 kN.

It can be emphasized once more that this variation in assembly forces is due to variation in spot weld position, where the size of the variation is estimated from industrial scan data, and from part deviations from nominal, which in this case is based on scanned geometries from industrial production.

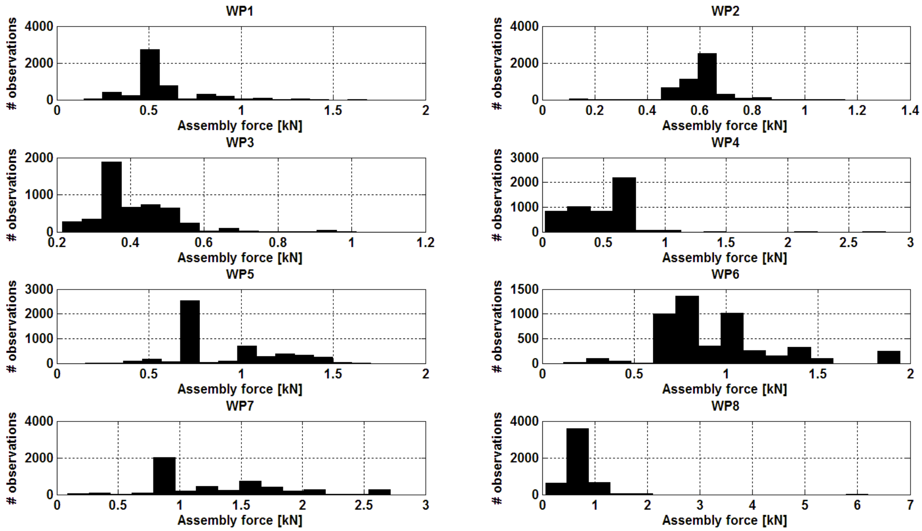

Fig. 4. Distribution of assembly forces in the eight spot welds

6 Discussion

The results presented in the previous section indicate that there can be large variation in the assembly force, i.e. the force required to close the initial gap. For the welding points showing the largest range in values, the assembly force goes from 0.01 kN to 2.7 kN. This can be compared to the values of typical welding forces between 1.5 kN and 3 kN given by Dennison et al. [18] or the values from a large spot welder manufacturer [19] where 3.9-5.2 kN is said to be a typical welding force for uncoated low carbon steel of thickness 1.6 mm if high force, short time conditions are used. If medium force and long time conditions are used, the corresponding value is 2.6-2.9 kN.

Assuming that a welding force of 3 kN is chosen, most of the force will in many cases be consumed in order to close the gaps, which may lead to welds of bad quality. If a higher welding force is chosen, in order to have some safety margins, the welding force will sometimes be too high, leading to too small welding nuggets.

The investigations of assembly forces for RSW included in this paper are applied to a case study consisting of low carbon steel, and as stated by Shen et al. [20], the critical value of the initial gap necessary to avoid expulsion is much smaller when using dual phase steel rather than low carbon steel. That means that dual phase steel is even more sensitive to variation in welding forces than the low carbon steel used in the case study shown here.

In order to avoid the problems with varying assembly forces due to variation in spot weld position, the variation must be reduced, the welding process must be robust to this kind of variation or an adaptive welding force with sensors identifying when the initial gap is closed must be used.

None of those points are very simple or economically viable to achieve. The main aim of this paper is to call attention to the problem and to demonstrate the effects of the variation in spot weld position. To reduce the variation in spot weld position, the contribution from the different sources listed in Section 3 should be investigated. Repeatability studies of the robot and welding gun are probably a good start.

7 Conclusions

In this paper the effect of variation in spot weld position with respect to assembly forces has been investigated. Assembly force is defined as the force required to close the initial gap between two parts to be joined. The assembly force is a subset of the total welding force, which is the total force applied from the welding gun. It is well known that the welding force is an important parameter in a welding scheme aiming at spot welds of good quality.

In order to get realistic values of the presumed values of the tolerance for spot weld position, scanning of industrial case studies were carried out. Those showed a deviation of the spot weld position from nominal value with up to 19 mm and a mean deviation of 9 mm. In the simulation in this paper, a tolerance with a radius of 9 mm was used.

To investigate the effect of the variation in spot weld position with respect to assembly forces, an industrial case study was used. The two parts of an A-pillar assembly, taken from industrial production, were scanned and this scanning was used as input to the simulations. On those scanned geometries, the weld point position was varied within given tolerances.

The results showed that the variation in weld point position leads to quite large variations in assembly forces. For the weld point showing the largest range in assembly forces, the required force varied between 0.01 kN and 2.7 kN. Since the welding force normally is fixed and in the magnitude of 2-5 kN for this kind of case, the variation in assembly forces due to variation in spot weld location can lead to spot welds of poor quality.

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Cutting Tool Data Representation and Implementation Based on STEP AP242

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Abstract. For cutting tool data exchange in manufacturing CAx (Computer-Aided technologies), standardized representation and classification of items and properties is important. ISO 13399 (Cutting tool data representation and exchange) provides a solution to represent cutting tool data classified with an ISO 13584 (Parts Library, PLib) based dictionary. However, ISO 13399 does not support classification of shape geometry directly, which limits its use. Another limitation is representing GD&T (Geometric Dimensioning and Tolerancing) as simplified general properties, which does not fulfill high semantic precision and validation rules. This research provides a unified solution to represent cutting tool parameters integrated with geometry and dedicated properties based on STEP AP242 (ISO 10303-242 Managed model-based 3D engineering). Standardized libraries such as the ISO 13399 dictionary can be reused with the modeling approach for AP242 cutting tool representation. Software is developed to validate and demonstrate how this solution facilitates the data integration process to support CAx applications.

Keywords: Modeling, STEP AP242, Cutting tool, Classification.

1 Introduction

Collaborations between enterprises put high requirements on seamless digital information exchange and sharing between software systems for industry. Standardized representation and classification of items and properties is fundamental for cutting tool data exchange between applications of PLM, CADCAM and CNC (Product Lifecycle Management, Computer-Aided Design, Computer-Aided Manufacturing, and Computer Numerical Control). With PLM applications, engineering information of cutting tools is integrated to support its development and deployment through the lifecycle. With CAD applications, cutting tool geometry, assembly structure, and relevant properties are defined in different viewpoints for production and utilization. With CAM applications, cutting tool requirements and usages are defined for operations with tool paths and cutting parameters. With CNC applications, operations are executed with input on cutting tool types, main dimensions, and tolerances on tool wear. For decades, information management has been regarded as the essence of

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cutting tool management for efficient computerized manufacturing control [1]. However, differences in terminology and data format between different computer-aided software are blocking cross-system interoperability.

An unambiguous way for the cutting tool data modeling and exchange is ontology based on industrial standards. A standardized hierarchy of classes and properties is the basic structure to describe taxonomies, as for cutting tool ontology. An important contribution in this area is the dictionary of cutting tool classes and property types within ISO 13399 (Cutting tool data representation and exchange). The dictionary is standardized underlying PLib (ISO 13584, Parts Library). A data set conforming to ISO 13399 is cutting tool data representation including its classification referencing the dictionary. On the other hand, shape representation is set outside the scope of ISO 13399. If needed, geometric models in other formats, e.g. STEP (ISO 10303, STandard for the Exchange of Product data), can be referenced from the data set. This separation approach is traditional for PLM systems.

A barrier for implementation based on ISO 13399 is the multiple data sets and associated data schemas that must be managed. For instance, an ISO 13399 cutting tool data set is transferred from a tool supplier to its customer with a corresponding geometry data set of STEP AP214 (ISO 10303-214, Application protocol: Core data for automotive mechanical design processes). System developers have to establish and maintain data integration based on the two standards and find a convenient way to convey both data sets without data loss. ISO 13399-1 is mainly a subset of AP214, which makes the practical situation even worse. As a result, there are two standards with mainly equivalent schemas to be synchronized for implementation and maintenance. Besides, the ISO 13399-150 usage guidelines describe implementation differently from how it is done for STEP AP214. It results in great efforts for implementers to develop and coordinate separate implementations.

The design of schemas also makes ISO 13399 differ from STEP in representation structure. It can be observed that both standards share the same functionality of GD&T (Geometric Dimensioning and Tolerancing) representation but with different modeling approaches. In STEP, the dedicated representation schema for GD&T is a basic functionality that is preferably reused for cutting tools, and the connection to geometry can be easily established. ISO 13399 instead uses general properties without a geometric context for shape dimensions. This does not meet high requirements for data consistency and interpretation precision in future CADCAM and CNC applications. A lack of a common schema for the geometry and GD&T results in a lack of a complete context and an unambiguous representation. With the representation of e.g. diameter classified as cutting diameter, the link to a specific geometry shape element is important information required in industry.

A standardized approach to represent cutting tool information is important for modern industry. The dictionary provided by ISO 13399 is promising for a system independent cutting tool library of CAM systems, which is able to establish interfaces between various tool makers and their customers [2]. Since it fulfills its defined scope for cutting tool data representation, ISO 13399 has contributed to several researches. Kaymakci et al. [3] adopt concepts from ISO 13399 for a general prediction model of inserted cutters, where the demands for “a unified geometric, kinematic, and mechanics model" are not what ISO 13399 is able to meet solely. Helgoson and Kalhori [4] use ISO 13399 for cutting tool data exchange in the context of machining process planning, where the solid model and cutting tool parameters are separately represented with STEP format and ISO 13399. Chungoora et al. [5] highlight the problems for joints usage of standard and present an ontology-based framework to consolidate various production information standards, e.g. ISO 10303, ISO 13399, ISO 13584, and ISO 15531. Generally speaking, integrated geometry models are commonly required regarding the adoption of ISO 13399. It becomes a must that multiple standards are integrated to achieve a complete modeling solution. Therefore, a modeling approach with a unified standard architecture such as STEP will be helpful for cutting tool data exchange.

Within the framework of STEP AP214, dimensions and tolerances are defined in a specific UoF (unit of functionality). Classification of items based on PLib is supported by AP214 in another UoF, which provides association with any dictionary conforming to PLib, e.g. the ISO 13399 cutting tool library. The draft standard AP242 (ISO 10303-242 Managed model-based 3D engineering) is going to replace AP214. Added capabilities in AP242 include supports for the Geometrical Product Specifications (GPS) standard. Dedicated schemas for GD&T and external references are integrated into this protocol and can be used to represent the needed information for CADCAM and CNC cutting tool data exchange as well as PLM applications.

In this research, STEP AP242 and ISO 13399 cutting tool library are combined for the comprehensive cutting tool modeling. Products, GD&T, features, general properties, and classes are basic elements in the model. The following section introduces the standardized modeling approach based on AP242, and the mapping strategy to a UML data model for implementation. The third section presents a prototype implementation which is able to classify AP242 cutting tool data sets with the ISO 13399 PLib-based dictionary.

2 Cutting Tool Modeling

Multiple types of information regarding cutting tool data are considered in this research, which requires data integration among schemas. The standardized product generic information modeling schema in STEP is able to support association of classes and properties defined in the ISO 13399 dictionary with products, shape elements, GD&T, features, and other elements. This capability also applies for different levels of details for different user requirements e.g. geometric level of details. For instance, tool suppliers use a complete model with a high level of detail for internal data exchange, but tool customers may only need the basic cutting tool parameters. Thus, exact geometry and other detailed design requirements, which in many cases also are confidential or unnecessary, should be trimmed from the complete model for external data exchange.

Figure 1 presents a STEP AP242 data excerpt of a diameter representation associated with a face on a solid body representation. In the model, a diameter of 22.0 mm with a tolerance of 0.05 mm and -0.1 mm is associated with a face. All geometric information is represented in the established way for STEP, which is omitted in the empty block. Using the standard modeling concept of shape aspect, dimension definition, measure representation and other properties are precisely integrated.

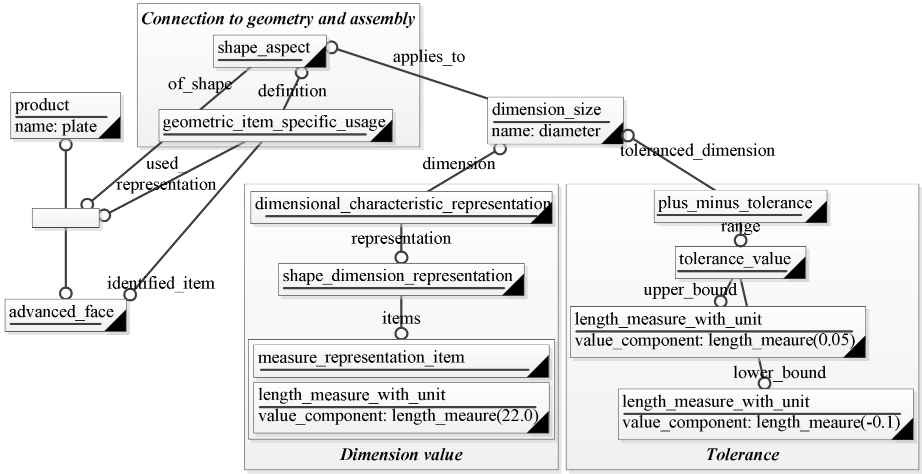

Fig. 1. Example of geometric dimension modeling in STEP AP242

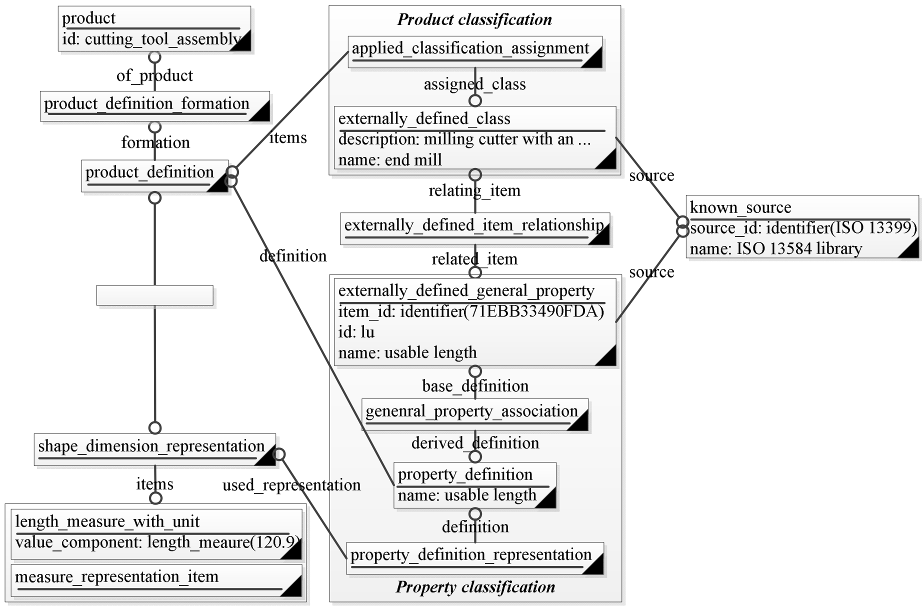

Fig. 2. Example of classification modeling in STEP AP242

Business cases may require hidden shape information, and then there will be no link between the dimension definition and the face. Nevertheless, the dimension itself is represented in a fixed way independent of existence of shape information. For a complete definition of GD&T, a geometric context is needed to establish coordinate system for the dimensions, e.g. supplemental geometry. Supplemental geometry is also known as help geometry or constructive geometry. Example data types are placements, points, curves and faces. These data types are not used to define shapes, but to support the definition of design requirements. It is a common CAD functionality also available in STEP. Recommended practices for implementing supplemental geometry are published by the CAx Implementers forum [6].

Figure 2 exemplifies the classification modeling approach within AP242. The ISO 13399 cutting tool dictionary is referenced in the model. The description of an end mill with a usable length is retrieved from the library and associated with the corresponding product and dimension.

3 Implementation

As an information modeling approach for computational applications, the result of this research should be validated with software implementation. The presented prototype software aims to evaluate the feasibility of the proposed solution and to provide a development strategy for industrial applications in the future.

The major function of the software is to classify products and other properties based on AP242 referencing the ISO 13399 cutting tool library based on PLib. The input is a p21 (ISO 10303-21, clear text encoding of the exchange structure) file of AP242 with its assembly structure, shape features, dimensions with tolerances, and other properties. Shape representation or supplementary geometry is optional. In a case study, the input STEP file is exported from a plug-in to Siemens NX 8.0 that is developed in this research project, of which the integration strategy is demonstrated in [7]. Assembly tree of cutting tool with the identification of each occurrence is displayed as a product part list breakdown. Thus, product parts, shape features, GD&Ts, and general properties can be classified according to PLib in an unambiguous way.

The development of this software reuses and contributes to a Java-based development project, STEP Toolbox. The scope of the STEP Toolbox project has a larger scope than product classification, e.g. kinematics and geometric errors [8]. In general, this project aims to significantly improve the usability of STEP standard for its major readers, CAx system developers. A complete solution to simplify STEP implementation is presented as a programming interface with high maintainability, reusability, and extensibility. The toolbox provides modularized functions to process different types of product information in engineering oriented perspective, i.e. to manage integrated geometry, kinematics, classification and other kinds of product data. Without requiring STEP knowledge, developers can produce their own standalone applications or plugins for CAD/CAM software based on the toolbox. The following data model design is a result of the research presented in this paper as well as a contribution of STEP Toolbox.

3.1 Data Model

STEP Toolbox aims to provide a friendly programming interface for CAx developers, rather than designers in a specific industrial domain. Therefore, concepts should be defined in a domain-independent way so that elements are reusable in multiple programming modules in the toolbox, e.g. the component is a widely used concept in geometry, kinematics, and GD&T. Thus, the toolbox solution adopts ontology model mapping from EXPRESS (ISO 10303-11) schemas in order to generate a proper design of computer interpretable UML model for programming. The ontology also helps advanced programmers to understand the conceptual relationship between EXPRESS models and UML models. Using the modeling principle outlined by Kjellberg et al. [9], an ontology model for cutting tool implementation has been used for mapping from AP242 in EXPRESS to a UML model (see Figure 3).

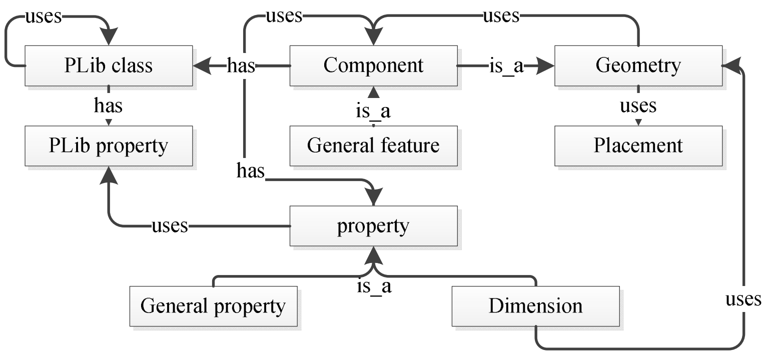

Fig. 3. Cutting tool implementation ontology

Note that the presented ontology model mainly serves the purpose of supporting computational implementation going from EXPRESS to UML. It does not necessarily express semantic relationship precisely. For example, a component actually does not own PLib class, but it can be multiply defined by several classes, which leads to such a composition relationship, e.g. a multi-functional cutting tool can be classified as an end mill and a drill. Another example is that semantically the general feature should not be defined as a sub-class of the component. However, it also can be classified and has classifiable properties, which indicates all the requirements of the general feature implementation can be met by the attributes and operations of the component. As a result, the general feature is set as the subclass of the component here. Geometry is a general concept, of which the subclasses include bodies, faces, edges, and points, besides the displayed components in the figure. Both the PLib class and the component have self-references to indicate the tree structure for presentation. Properties such as general properties and dimensions are associated with certain components or general features, which are defined semantically by PLib Property, e.g. a linear distance associated with a component is defined as usable length in a PLib dictionary (see Figure 2). PLib properties have strict ownership from certain PLib classes, which can only classify the properties of the components classified with corresponding owner PLib classes.

Programmers can use the ontology model to understand concepts easily, but a well-designed UML (Unified Modelling Language) model is fundamental for practical implementation. As a core part of UML, a class diagram is important of such a Java-based programming interface. In Figure 4, a simplified class diagram for cutting tool is illustrated. Methods of most classes are not displayed, but they are important for implementation, such as getters, setters, and constructors. As a part of STEP Toolbox, modules are divided and controlled by managers, such as the property manager and the classification manager. The STEP model manager provides basic operations for STEP data set, such as initialize, export, and close. Differences from ontology may occur for specific data model implementation. For example, both components and PLib classes have tree structures, but PLib classes also need to record a list of parents, rather than only the direct parent which is the case for component. This is caused by the inheritance of PLib properties from all relative parents.

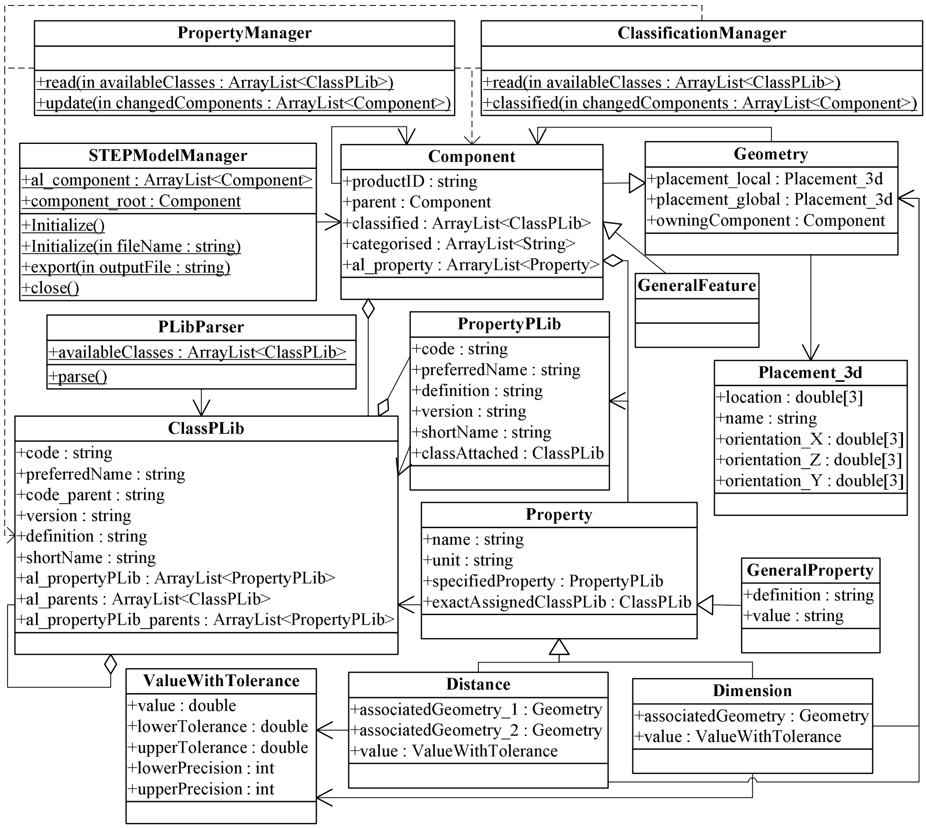

Fig. 4. Simplified class diagram for cutting tool development

3.2 System Development

An MVC (Model-View-Controller) structure design is illustrated in the Figure 5. The relative part of STEP Toolbox is integrated as the Model layer. The system starts with a file opening dialog. If the file exists and is acceptable, the Initializer triggers the STEP model manager to read the file and invokes the PLib parser to generate the standard definitions of classes and properties. The GD&T manager and the classification manager need to analyse the STEP model, read dimensions, general properties, and classification information. Then the assembly controller collects all the data and invokes the assembly viewer to display the assembly with GD&T in the graphical user interface (e.g. see Figure 6). The operation of classification is started by a selected component from assembly. A classification dialog is used to organise the PLib classes and properties in a displayable and selectable way (e.g. see Figure 7). The classifier in the controller classifies the products and properties only in the level of Java data model rather than the STEP model, and records the updated component whenever there is a user operation. Then, the exporter triggered by interface performs all the changes to the data set and exports it with specific configurations.

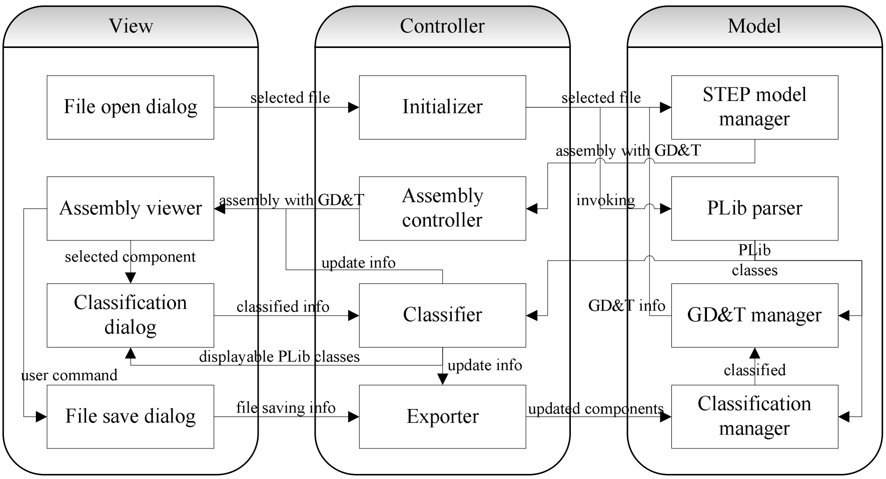

Fig. 5. MVC system design

3.3 Interface Design

The interface is designed to present and manage different elements in the data set with a clear structure. Figure 6 illustrates the basic design of the main user interface. Components are presented in a tree structure as commonly used in CAx systems. Features are displayed with a darker background color and a special category name. Both components and features can be selected to classify. The bottom table displays related properties of the selected item in the above tree table.

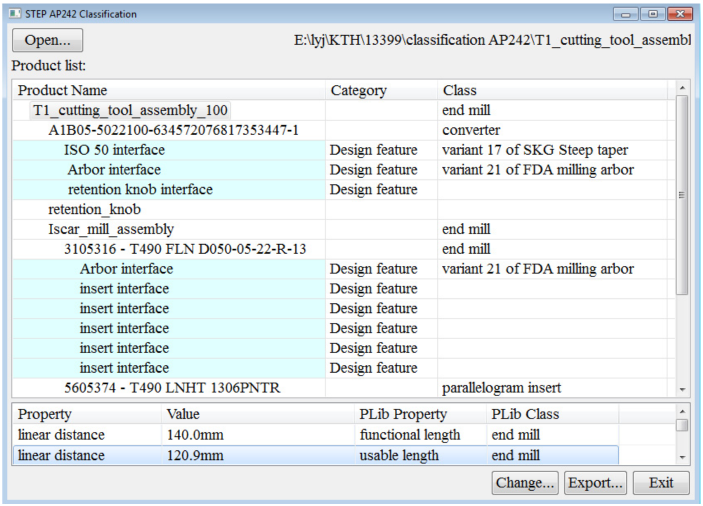

Fig. 6. Main user interface

The major function of this software is performed after the click of the "Change…" button. Then the classification dialog (see Figure 7) pops up with two lists of selection: a tree list of PLib classes that can be multiply selected, and a table list of PLib properties of the selected class. The combo list contains all available properties owned by the selected component/feature to be specified, e.g. the linear distance is specified as the function length of an end mill in Figure 7.

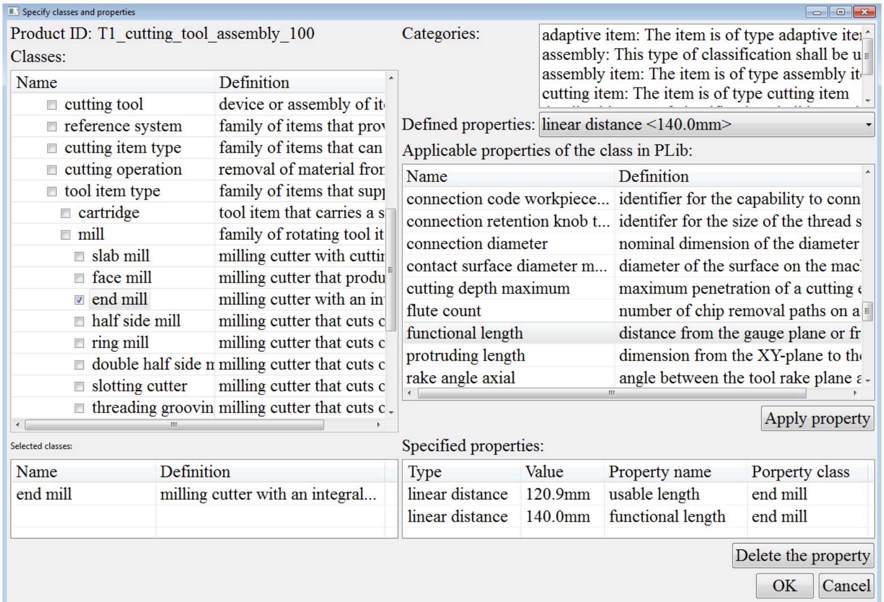

Fig. 7. Classification dialog

4 Conclusion

This research focuses on the description and evaluation of a standardized cutting tool data modeling approach. A unified computer interpretable model for data exchange and data integration is proposed and implemented. Benefits of the comprehensive representation structure of STEP AP242 are utilized and demonstrated in developed application. External standardized library, such as the ISO 13399 PLib-based dictionary, can be easily reused and associated with the shape representation. Practical data exchange is promising by integration developments with current commercial CAx systems. With the unified model, industrial practitioners can skip the barrier to coordinate multiple standards and achieve integration development smoothly.

Acknowledgments. We are grateful for the support from VINNOVA and XPRES (Initiative for excellence in production research), and for fruitful discussions with members of ISO TC184 SC4 WG3 T24 and industrial practitioners from Sandvik Coromant.

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Assessment of Sensitivity of Numerical Simulation in Sheet Metal Forming Process Applied for Robust Design

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Abstract. Considering variation of influent factors is a critical issue to enhance the robustness of sheet metal forming process in the product design process. The stochastic variability of uncontrollable factors results in the variations on the formed part which can lead to rejected parts. Since the inherent sources of variation in the sheet metal forming process comes from part-to-part, within batch and batch-to-batch variation. Therefore, the prediction and control of the variability influencing on the performance of the product is an essential demand of automotive and aeronautic manufacturers. Moreover, it is very necessary to have a numerically dedicated tool which predicts the process variability with a good confidence. In this paper, prediction of the variations of the formed part due to the variabilities of the sheet stamping process and the workpiece by numerical simulation will be carried out.

Keywords: robust design, variability, sheet metal forming, sensitivity analysis.

1 Introduction

Stamping process is an effective process applied for fabricating body panels in automotive manufacturers. The fact that there are around 100 to 150 stamped metal panels on vehicles produced nowadays. The process is mainly used in production of large batch because designing and manufacturing the stamping tools are very expensive and time-consuming [1]. Hence, reduction of time in the tooling design phase as well as elimination of expensive physical experiments is considered as objectives which the manufacturers would like to obtain. As a solution for this issue, FEA software has been a rapid and effective tool for design and verification of new product propositions in automotive industries in the last few years. Nevertheless, quality of produced parts is one of the most important issues which need to take into account to satisfy customer's specifications. The stamped parts must respect functional, geometrical aesthetic requirements. Thereby, enhancement of reliability of the design by using numerical simulation is a focus of this research work.

In industrial practice, the industrial actors often cope with several defects occurred on the stamped parts in which shape defects due to springback, thinning and wrinkling are principal problems. The sources provoking these defects are from input

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parameters' variations of the forming process. The variation sources of draw bending process are synthesized in Figure 1.

As a consequence, the variabilities result in poor product quality. In order to enhance the robustness of the sheet metal forming processes or in other words, to minimize the reject rate, the fluctuations must be taken into account in the part and tools design stage.

As mentioned above, the FEM numerical simulation is the solution for shortening the lead-time and saving the cost for the experiments in the sheet metal forming process. Presently, the FEM software can evaluate any virtual forming process with an acceptable accuracy. However, there is still difference between results from numerical simulations and results from physical experiments. The cause of the difference may be due to inconsistent FE models or incorrect inputs parameters or deviation of the input variables [3]. In other words, although the geometry and the material properties of the tools and the sheet blank are fixed, the variations in the method of FE modeling by users may lead to various results [2].

Previously, there were several research works which investigated the effects of numerical factors such as the element size of sheet trip, the hardening law, the precision of modeling tool radii and the dynamic effect on the springback results of the U-draw bending benchmark problem [4]. He and Wagoner [5] investigated the impact of the finite element mesh system of the blank on springback results using the same benchmark problem. The effect of the dynamic term on springback was evaluated by Chung et al. [6]. Numerical factors affecting springback including contact damping parameter, penalty parameter, blank element size, number of corner elements were investigated by Lee and Yang, [2]. For the last few years, a couple of investigations in relation to the effectiveness of numerical models have been also taken into consideration making comparison between numerical predictions and experimental results [7]. Particularly, the influence of numerical parameters comprising the type of the utilized element, the number of integration points, the hardening rule and so forth, with the aim to improve the effectiveness and reliability of the numerical results.

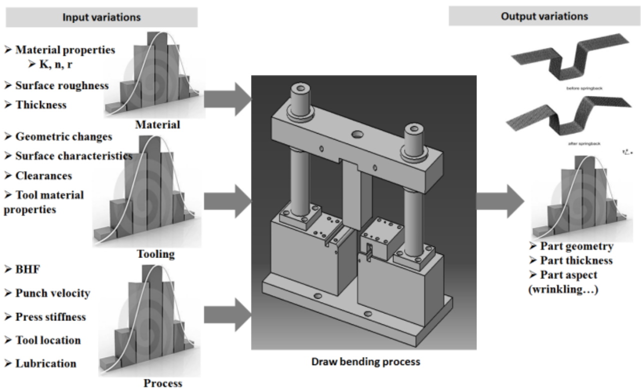

Fig. 1. Draw bending process and its variation sources

Xu et al. [8] analyzed the effect of sensitive factors in a U-bending process of Numisheet'93 benchmark problem using a fully explicit solution scheme in which the impact of integration points number, blank element size and punch velocity was researched.

It can be seen that all mentioned literatures concentrate on considering the effects of numerical parameters on the virtually formed parts, there were hardly any studies concerning evaluation of reliability of FEA software. In other words, qualifying the sensitive level of numerical simulation tools with very small variations of the scattering parameters in the sheet metal forming process is crucial to enhance the robustness of digital programs in the prediction of variability of the process. Since very small variability of the sheet's material properties, the blank thickness and tooling parameters influence on finished part, particularly, springback variation in sheet metal forming process.

Therefore, the purpose of this research work is to focus on evaluation of prediction capability of the stamped part's variation derived from the input parameters' variability using commercial FEA software.

In general, in this study, the objective is to analyze the reliability of FE numerical simulation tool, namely ABAQUS software, when having very small variability of input parameters, so then whether output results, particularly springback variations, are sensitive with the variability or not. Meaning that the software can be sensitive to how small percent of variability is. In the following sections, problem modeling will be presented in which a case study, springback measurements and numerical modeling and simulation will be discussed in Section 2. In section 3, investigation of reliability of numerical simulation will be presented. Evaluation of sensitivity of numerical simulation will be shown in Section 4. The last section is conclusion.

2 Problem Modeling

2.1 Case Study

The U-shaped part, a benchmark problem of NUMISHEET'93 International Conference [10], is investigated in this paper. However, the part's geometrical dimensions are modified according to industrial requirements and the part is named open-channel part. This part is a representative product commonly used in automotive industry to reinforce for body panel or base. A schematic view of die, punch, blank and their dimensions for the draw bending process is shown in Fig. 2 which is used in this study. Table 1 shows dimensions for the draw bending process.

Table 1. Dimensions for the draw bending process

Parameters	W1	W2	W3	W4	R1	R2	G1	Stroke
Dimensions (mm)	57.7	60	150	150	5	10	1.15	60

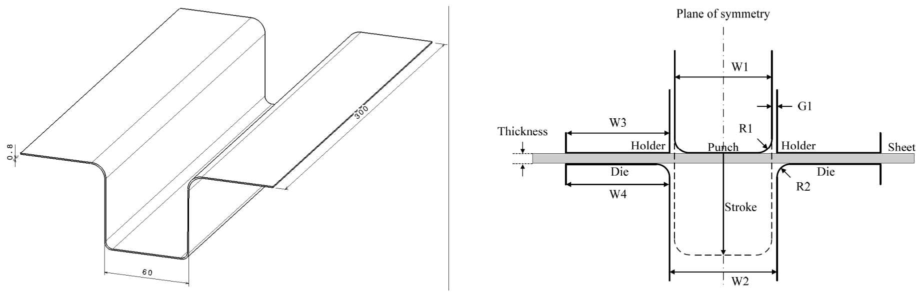

Fig. 2. A schematic view of tools and dimensions for the open-channel part

The simulation work in this study is carried out based on the experimental results of Ledoux et al. [1]. The blank is obtained from rolled sheet of 0.8 mm thick, 300 mm long and 300 mm width. The accuracy of the length and width dimensions of the blank is 0.5 mm. The blank holder force of 90 KN is applied in this case. Blank material is DC04 steel with the material properties presented in Table 2.

Table 2. Blank's material properties [1]

DC04 material	
Young's modulus	206.62 GPa
Yield strength	175 MPa
Poisson's ratio	0.298
Lankford's coefficient	$r_{0°} = 2.09$
	$r_{45°} = 1.56$
	$r_{90°} = 2.72$
Density	7200 kg/m^3
Strain hardening's coefficient	K = 466 MPa
	n = 0.2056

Moreover, experimental measurements prove that part profiles remain symmetric. Therefore, simulation of numerical experiment will be performed on half of the profile.

2.2 Springback Measurements

In order to characterize the total springback distortion, three measurements including the springback of wall opening angle (β_1), the springback of flange angle (β_2) and sidewall curl radius (ρ) are shown in Fig. 3. They describe the variation of the part's cross-sectional shape obtained before and after removing the tools. For calculating the springback measurements, it is necessary to determine the measurements before and after springback. To do so, the least square method is applied to identify the points of A^0, B^0, C^0, D^0 and E^0 on the formed part's profile according to given x and y coordinates.

Based on the known point coordinates, the wall angle (θ_1^0) and the flange angle (θ_2^0) before springback are computed. Similarly, other points of A, B, C, D and E are defined on the part's profile which the tools have been removed.

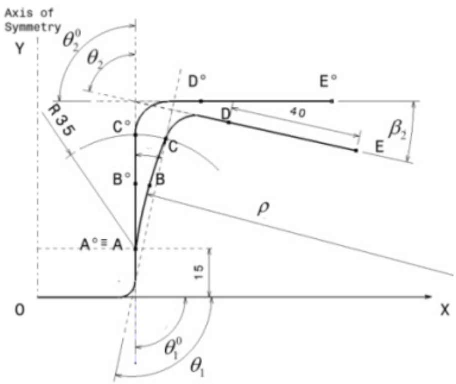

Fig. 3. Schematic view of springback profile and parameters

They are then used to calculate the wall angle (θ1) and the flange angle (θ2) after springback. The side wall curl radius is estimated by a curve fitting technique through three points A, B and C to construct a circular arc.

2.3 Numerical Modeling and Simulation

To predict the springback variations derived from the variability of input parameters, numerical simulation is an efficient solution. The FE simulation of the 3D draw bending process of the open-channel part is carried out by the ABAQUS/CAE 6.11-2. The problem is modeled according to the schema of Fig. 2 and the process parameters and tools configuration are applied as in Table 1. The key characteristics of numerical simulation are shown in Table 3.

Table 3. The key characteristics of numerical simulation

Blank	
Element type	Shell S4R
Number of elements	5340
Integration points	7
Yield function/Plastic potential	Hill48 [9]
Hardening rule	Isotropic, Swift model $\sigma = K(\varepsilon_0 + \varepsilon)^n$
Tools	
Tool type	Analytical rigid surface
General aspect of the code	
3-D draw bending	Dynamic, Explicit
Springback	Static, General
Friction coefficient: 0.15	

As mentioned above, the half of problem is modeled. Hence, boundary conditions and symmetric condition are applied on the half part of the model.

3 Investigation of the Reliability of Numerical Simulation

With the purpose of investigation of sensitive level of numerical simulation software so that a global approach is proposed and illustrated as Figure 4 in which input parameters are run by using method of Design of Experiments (DOE) to make variations, and then, the variation of input parameters are used as input parameters of numerical simulation. As a result, the simulated part will be calculated in the Matlab to define the responses. In this study, only part-to-part variation is considered, namely the blank thickness variation is regarded as an input variable of this investigation.

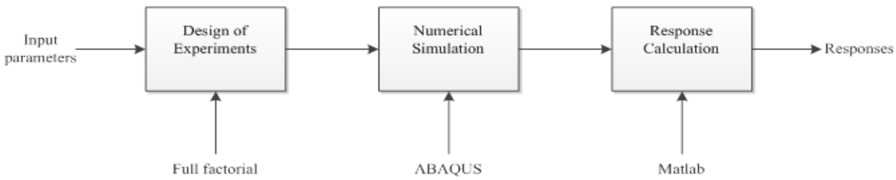

Fig. 4. The globally proposed approach in evaluation of sensitivity of numerical simulation

In particular, the investigated model is demonstrated in Figure 5. Starting from the nominal input parameters of the material, tooling and process as Section 2, numerical simulation of the draw bending process of the open-channel part is run in the ABAQUS/CAE 6.11-2 in which the part shape is performed in two steps of forming and springback step.

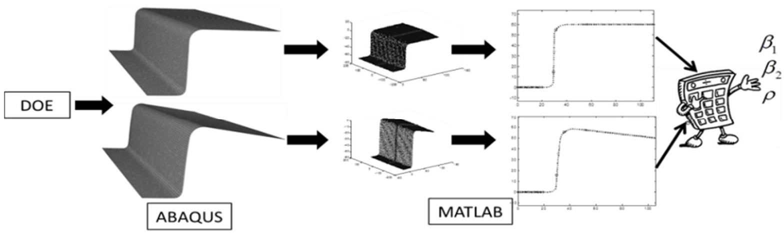

Fig. 5. The investigated model of reliability of numerical simulation

Consequently, nodal coordinates of deformed part are extracted from the ABAQUS. Afterwards, they are used to compute the springback parameters of β_1, β_2, and ρ in the Matlab. After calculation, the results of the part's measurements before and after springback are listed in Table 4.

Table 4. The part's measurements before and after springback

	Before springback		After springback		Springback measurements		
Measurements	θ_1^0	θ_2^0	θ_1	θ_2	β_1	β_2	ρ (mm)
Results	90.5°	90.5°	97.59°	84.93°	7.096°	5.561°	236

A comparison between the numerical simulation result and the experimental result implemented by Ledoux et al. [1], the numerical result is very close to the experimental one. The deviation between experimental and numerical results is less than 1 mm which shows good prediction by FE numerical simulation.

To calculate automatically, the design of experiments, numerical simulation and response calculation are coupled in the workflow of ModeFRONTIER™. The workflow in the ModeFRONTIER™ is presented in Figure 6.

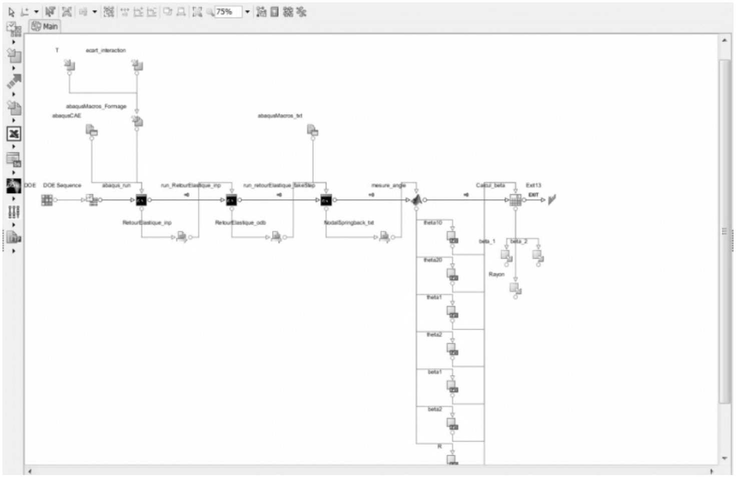

Fig. 6. The workflow of the proposed approach

4 Evaluation of Sensitivity of Numerical Simulation

Sensitivity function is used to evaluate the reliability of the numerical simulation software as below:

- Smaller and bigger value:

$$\alpha = \frac{\partial f}{\partial x}(x_0) = \frac{f(x_0+\Delta_e)-f(x_0-\Delta_e)}{2\Delta_e} \tag{1}$$

- Smaller and nominal value:

$$\alpha = \frac{\partial f}{\partial x}(x_0) = \frac{f(x_0)-f(x_0-\Delta_e)}{\Delta_e} \tag{2}$$

- Nominal and bigger value:

$$\alpha = \frac{\partial f}{\partial x}(x_0) = \frac{f(x_{0+}\Delta_e)-f(x_0)}{\Delta_e} \quad (3)$$

Where, x_0 corresponds to nominal thickness and Δ_e is variation range between thickness values.

Thickness variation parameters and sensitivity values are shown in Table 5. In particular, the variation is expressed through gradual decrease of variation percent of nominal thickness. It is assumed that the thickness in the whole part is constant. The

Table 5. Thickness variation parameters and sensitivity values

Variation (%)	Δe (mm)	Thickness variation (mm)	α(β1) (°/mm)	α(β2) (°/mm)	α(ρ) (mm/mm)
20	0.16	0.64	14.4212	11.3241	-359.3706
		0.8	6.3059	5.1569	-65.7868
		0.96	-1.8094	-1.0104	227.7971
10	0.08	0.72	13.4137	4.4931	-263.4972
		0.8	4.9432	1.2885	33.5350
		0.88	-3.5273	-1.9161	330.5673
5	0.04	0.76	13.8783	1.7104	-92.5804
		0.8	6.9821	2.4945	49.0883
		0.84	0.0859	3.2787	190.7571
2	0.016	0.784	38.6269	4.7084	-284.1957
		0.8	21.9402	5.1717	-67.8929
		0.816	5.2534	5.6349	148.4098
1.5	0.012	0.788	1.2409	-2.5120	115.8318
		0.8	-2.8300	0.2649	126.1214
		0.812	-6.9010	3.0419	136.4111
1	0.008	0.792	4.5147	-9.6161	353.8053
		0.8	-1.9217	-1.9243	287.6912
		0.808	-8.3580	5.7675	221.5770
0.8	0.0064	0.7936	21.0978	9.4679	-848.9659
		0.8	4.1734	9.6291	-433.2124
		0.8064	-12.7511	9.7903	-17.4588
0.5	0.004	0.796	170.8839	42.9871	-2025.5843
		0.8	83.1412	32.0626	-902.5713
		0.804	-4.6014	21.1382	220.4417
0.2	0.0016	0.7984	62.9189	-53.2250	462.2954
		0.8	-136.9051	-38.8243	1393.4893
		0.8016	-336.7291	-24.4236	2324.6832
0.1	0.0008	0.7992	-33.7328	-81.3877	4490.6412
		0.8	-90.2131	24.8825	2733.6190
		0.8008	-146.6935	131.1527	976.5967
0.05	0.0004	0.7996	1453.4986	202.5773	-5962.3799
		0.8	692.7517	174.3740	-5902.7587
		0.8004	-67.9952	146.1708	-5843.1374
0.01	0.00008	0.79992	2023.2555	278.3391	-16901.7565
		0.8	-2675.0272	11.9680	14256.7433
		0.80008	-7373.3098	-254.4031	45415.2431

other parameters of the process are fixed with nominal values. Numerical modeling and simulation of the process still remains as mentioned in Section 2. Output parameters are springback measurements of β_1, β_2 and ρ.

Sensitivity analysis results are shown Figure 7. Observation from sensitivity analysis graphs shows that the sensitivity of numerical simulation software in this case can reach for level of blank thickness variation of 5 % of nominal thickness. It can be seen that three sensitive lines of three springback responses converge at the point of 5% of nominal thickness. Due to the fact that the smaller the variation range, the more closed three sensitive lines are.

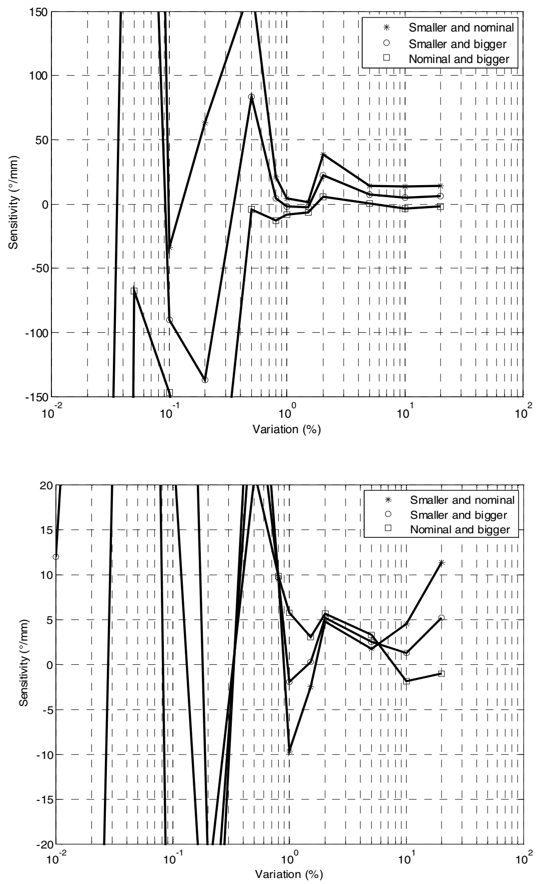

Fig. 7. Sensitivity of numerical simulation α(β1), α(β2), α(ρ) respectively with thickness variation

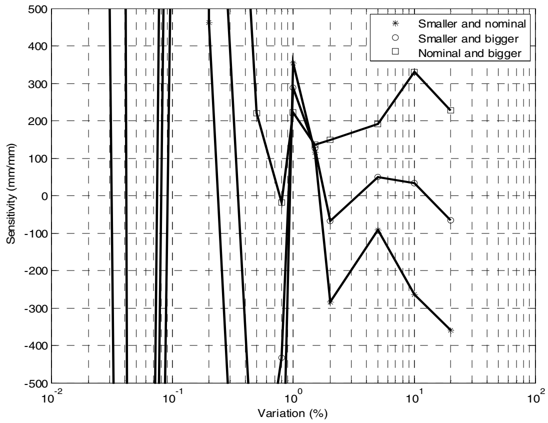

Fig. 7. (*continued*)

5 Conclusion

Numerical modeling and simulation of U-shaped draw bending process has been carried out to show the effect of blank thickness variation on the variability of output response of springback.

Additionally, the paper has been investigated the sensitivity of numerical simulation software, namely ABAQUS, in modeling and simulating the U-shaped draw bending process. The result has shown that the reliability of the software can reach for level of blank thickness variation of 5 % of nominal thickness in this case study. The sensitivity evaluation is built and calculated automatically in the ModeFRONTIER™. The proposed approach has been developing which provides a tool in taking into account the variation of input parameters affecting on output responses in the sheet metal forming process by using FEM contributing to improvement robust parameter design methodology.

This project is being in the research process. Construction of metamodels based on approximating surface response to predict variation of other factors will be employed in the next works.

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Analysis of Automatic Online Lead User Identification

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Abstract. Lead user identification is a systematic approach to uncovering product development opportunities by identifying lead users, individuals or groups actively involved in modifying or developing products for personal benefit. In this paper, a systematic approach called Fast Lead User IDentification (FLUID) based on online data mining, specifically of the Twitter micro-blogging site, is proposed. Topic classification, sentiment and intent of a given tweet or user-metadata can be automatically determined using various text mining techniques. The described FLUID system makes use of such techniques to rank retrieved users based on indexes derived from well-established lead user characteristics. In the initial analysis phase collection of relevant artifacts and contextual inquiry allow for measuring impact of each index toward delineating lead users from other non-lead users. Through refinement based on statistical analysis of expert assessments the effectiveness of the FLUID system is optimized.

Keywords: lead user identification, data mining, micro-blogging, social networks.

1 Introduction

In recent years, research has shown that experienced users driven by the possibility of own benefit contribute greatly to the development and innovation of new and existing products [1]. Often referred to as lead users, they are among the first to see high degree of benefits in adopting products and services and are first to diffuse adaptations, new prototypes or services into the marketplace [1] [2]. Lead users have deep and extensive knowledge of products and services and their needs eventually become general demands of the marketplace [1] [3]. In addressing their needs, lead users apply products and services in unique and novel ways to generate new prototypes or solutions [4]. Luthje [5] characterizes the described lead user behavior with six characteristics: ahead of trend, dissatisfaction, product-related knowledge, use experience, involvement and opinion leadership. Furthermore, product satisfaction, adaptability and evolution can all be observed and learned by studying lead users [5] [6]. Systematic identification allows for reduction in costs incurred during the research and conceptualization stages of the engineering design process. By engaging lead users, enterprises or companies reduce the effort and cost of design and product

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adaptation [7] [8]. It is also a way to judge the feasibility and adaptability of a product in an engineering design process to meet the changing needs or requirements. Additionally, with their extensive knowledge of products and services, lead users can easily be integrated into work groups within enterprises, one of the main reasons being that they do not need extensive on-the-job training.

Two current methods for identifying lead user are screening and netnography. Screening is one the original approaches to identifying lead users, a technique advanced by Eric Van Hippel [6]. During the screening process, experts in the product domain create and map a network of lead users and gather innovation ideas. Based on the preliminary research of the target population, they set up semi-structured telephone interviews to evaluate potential candidates and explore their product related knowledge. In some cases, depending on the feasibility, on-site interviews are performed. Over a lengthy time-period, the screening method results in a small network of verified lead users [8]. An advantage of the described method is to indubitably disassociate lead users from non-lead users by having a direct or over the phone contact with the potential candidates. Through exploratory interviews and on-site visits, experts are able to ascertain if a candidate is a lead user. Several drawbacks are associated with the screening method. The identification process can last a few months and a significant number of potential lead users are overlooked by the screening process, resulting in a small sample efficiency in a large population [8] [6]. There is also high demand on human resources and heavy reliance on self-assessment of respondents [6].

Netnography is a more recent systematic approach to identifying lead users. As the name implies, it is an ethnographic study with the web as the target platform [6]. Initially, relevant user online metadata and discussions are collected through observations of forums or communities. Similarly to the screening method, the approach necessitates expert users to analyze and process the available data to delineate potential lead and non-lead users. Verification is done on the downloaded material and, in contrasts to the screening method, no direct communication is enacted between the experts and the selected lead users [6]. The approach focuses on a much smaller community formed around a common interest, a product or service, allowing it to have a better sample efficiency than the screening approach [6]. Unfortunately, the resource and time costs are as high as with the previous approach. The experts observe and parse through vast amounts of online data, a time consuming effort. Other major drawbacks of this method are the scarcity of online information for a significant number of users on online communities or forums and lack of proper direct verification of lead users. A portion of users is cast out of the analysis process due to lack of substantial online user information, adding to the error margin in uncovering potential lead users. Both methods ask for utilization of expert users, persons that have deep knowledge of the material or service and are capable of analyzing vast amounts of user discussions, comments, attitudes and opinions. The authors aim to reduce resource and time costs by using a fast, automated and systematic approach while retaining high attainment of lead users from a large population.

2 FLUID

Fast Lead User IDentifaction (FLUID) is a systematic approach to finding and identifying lead users. The method aims to automate the process by focusing on the virtual or web based communities and sites and by using data mining algorithms on publicly available information to separate lead users from non-lead users. The selected target platform is the web with the aim to increase the sample efficiency and minimize the errors introduced by relying on self-assessment of respondents. To strengthen the reliability of the results, in the final stages of the approach the authors aim to make use of expert verification of rendered lead users. Netnography has shown that we can detect user needs, desires, experiences, motivations, attitudes and perceptions using available online data [9]. More and more people are also sharing their experiences and opinions on the web. According to Pang [10], 81% of users have done online research on a product, 32% have provided a rating on a product or service via an online rating system and 30% have posted an online comment. In addition, patterns in relationships between the online users can be detected, that can provide more clues in predicting lead user characteristics and behavior [6]. The advantage of the automated data mining tool is the ability to speedily evaluate large quantities of user metadata and activities without relying on interactive human interference. In the approach, the first step is to obtain and consolidate or select data. The next step is preprocessing data, which entails filtering spam and irrelevant data or users. Thereafter data are interpreted and evaluated for knowledge to identify potential lead users. Figure 1 shows the three principal steps in fast lead user identification leading to actualization and also integral impact scoring based on FLUID indexes, described in the following sections.

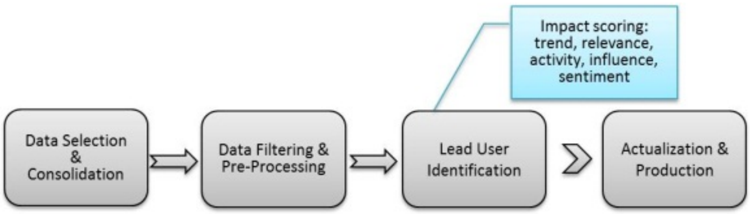

Fig. 1. FLUID system

2.1 Target Platform

For the target platform, the authors selected the micro-blogging site Twitter. Since its creation, the number of users has exponentially increased and currently Twitter represents a large, rich and complex data set. Although it contains enormous amounts of insignificant or spam information [11], data mining Twitter has provided significant amounts of useful qualitative and quantitative data for interpreting user knowledge and behavior [12] [13]. It has been used to successfully predict box office revenues for movies and political election results [14] [15]. Twitter is a real-time, opinion rich resource making it a possible platform for analyzing behavior and attitudes towards products and services. Daily tweets discuss product experience and adaptation and can make companies aware of new components added to the products or replacements and reconfiguration of the existing components [12] [16]. Product use, benefits and potential redesigns, including opinions and feelings, can be gathered through real time tweet monitoring and analysis [12] [13]. Other important factors regarding Twitter are the feature richness and ease of access and use. Majority of the features including tweets and the user metadata can be accessed through the Twitter application interface. Twitter provides a programming method for most of the site features. Extensive user metadata, i.e. description, URL, location, lists etc. may be accessed to better support the classification process. However, data mining micro-blogs like Twitter still poses a challenge. Tweet language is constantly evolving with numerous non-uniform linguistic conventions. Because of the 140 character limit, users make use of nonstandard vocabulary for informal conversations, missing proper names and terms. At the same time, Twitter has specific conventions for marking up words that are valuable for data mining. For example, Twitter user names are prefixed with a @ sign, i.e. @plumb. Hashtags # denote subjects or topics, i.e. #election. Another commonly used convention is RT that stands for retweet, where the text of a user is being echoed. Consequently, data mining methods are adapted to process tweets and Twitter user metadata [12] [13].

2.2 Application

To test the applicability of the FLUID approach, a test platform was built. Initially, the FLUID application takes a product name or a hashtag and searches real time for relevant tweets, e.g. bicycle. All retrieved tweets and included user metadata are stored in the local database to be processed. After retrieval data are analyzed and processed before being displayed. Spammers, promoters, and other automated-script style Twitter accounts are discounted, filtering irrelevant data. In the follow-up steps, parsed tweets and user metadata are ranked based on five proposed criteria or indexes: activity, trend, influence, relevance and sentiment. After several iterations based on a manually selected score threshold, users with a high rank are identified as potential lead users. In the following section, the FLUID ranking criteria are discussed.

2.3 Rank Indexes

Existing research has identified six characteristics of lead users: ahead of trend, dissatisfaction with the product, product related knowledge, use experience, involvement and opinion leadership [6] [7]. The characteristics are reformulated into indexes for automated scoring of user data to facilitate identification of lead users online. The five indexes are as follows: activity, trend, influence, relevance and sentiment. Table 1 shows the mapping of lead user characteristics to FLUID online indexes characterized by Twitter user attributes.

Lead users have an extensive experience using products and see potential benefits of product redesign or modification. They tend to show high level of engagement in product use and development and these traits have been denoted as user involvement. Since user involvement is not limited to the web, in the context of online behavior the authors defined the trait as user online product related activity. The frequency and quality of online discussions or conversations regarding a product are indicators of product related activity. For Twitter users, high product related activity can be observed in the number of relevant statuses, URLs, hashtags, favorites, etc, as shown in Table 1. It can also be observed in the number of relevant networks users form, the number of subscription or member lists and the number of like-minded friends. Activity related actions increase the rank value of a Twitter user in the FLUID application, as enthusiastic and engaged users and consumers are viewed as probable lead users.

Table 1. FLUID Metrics

Lead User Characteristics	# of Statuses	# of Followers	# of Friends	# of Favorites	# of Lists (Member)	# of Rel. Lists (Member)	# of Hashtags	# of Rel. Hashtags	# of Lists (Subs.)	# of Rel. Lists (Subs.)	# of URLs	# of Retweets	Image Relevance	URL Relevance	Description Relevance	Tweet Relevance	Tweet Sentiment	FLUID Indexes
Ahead of Trend				x		x		x		x		x		x				Trend
Knowledge						x		x		x				x		x		Relevance
Use Experience						x		x					x	x	x	x		
Involvement	x	x		x	x	x	x	x			x	x						Activity
Opinion Leadership		x	x						x	x		x		x				Influence
Dissatisfaction																	x	Sentiment

The lead user characteristic, ahead of trend, is also an index component of the FLUID model, called trend. This user characteristic means that a lead user is among the first users to recognize benefits of a product or service and its potential adaptation or redesign. Lead users are among the first to use and modify the product. In the context of online behavior, judging foresight is a challenge due to lack of direct contact with the user, but knowledge and use of new products or services can be observed and is therefore denoted as trend. Twitter examples of such behavior are retweets of new product developments, subscriptions to relevant lists and the number of potential lead user Twitter friends and favorites. Similarly to the activity index, trend-like Twitter actions add to the overall rank score of the user.

The influence component of the FLUID model is inferred from the opinion leadership characteristic of the lead user. Lead users diffuse innovation ideas or prototypes into the marketplace, influencing future product development. In the context of online behavior, user's clout or influence is measured. Online use experience, knowledge, needs sharing and high activity attract like-minded individuals and followers, which helps facilitate circulation of innovation solutions. On the Twitter platform a user's influence and popularity is measured by monitoring the number of product relevant retweets and mentions by other users. In addition, the number of potential lead users' followers is a significant indicator in how far-reaching the user's message is.

Within the web based FLUID model the relevance index is perceived as both product knowledge and experience. Without direct contact or on-site visits there is an inadequate amount of information to determine product knowledge and experience, but online the extent of user's tweet relevance to the target product is measured. Relevant conversations to the target product or service, relevant lists and follower networks are good initial indicators of an assiduous user. The importance of relevance in processing is one of the primary indicators of significance of target related product behavior. On Twitter, user status updates, links and hashtags are analyzed for their relevance. Lead users will often subscribe to lists or discussion boards focused on the target product or service or will find themselves added to those lists by other Twitter users. Relevance of tweets is measured using natural language processing tools to provide a numeric estimate for the index. Filtering and extraction algorithms are applied to discern the essential components, the size of the post, presence of a specific category and keywords for that category. A tweet is relevant when properties i.e. function, and characteristics, i.e. structure, shape of a product can be uncovered in the message. User lists and hashtags are matched up against automatically or manually generated lists and hashtags to give additional indicators of relevance. The relevance scoring is based on the tweet and metadata analysis and contributes to the rank used to identify lead users.

Final important indicator in identification of lead users is sentiment or product related disposition. It is one of the main sparks behind human behavior or actions. It is defined as a thought, view or attitude and it is derived from related research indicating that lead users tend to express a greater amount of dissatisfaction with offered products or services [6]. The sentiment of online posts, in this case tweets, is measured and a noticeable negative sentiment is used to separate lead users from other users. The process makes use of emoticons that approximate human emotions using language characters. Lastly, scores for each index in the application are weighted and combined to give an overall rank of the retrieved user. Manually keyed in rank threshold based on observed difference in scores is used to set lead users apart from non-lead users.

3 FLUID Effectiveness Analysis

3.1 Test Description

A study was conducted to evaluate the ranked results obtained by the FLUID application. The primary goal of the study was to verify the lead and non-lead users discovered by the FLUID tool. The secondary goal of the study was to identify the significance or strength of difference in relevance, trend, influence, activity and sentiment between the two groups of users. For the target product the authors selected bicycle products. In preparation for the study, the FLUID application utilized the Twitter search engine to search for Twitter users using manually chosen relevant bicycle terms and Twitter hashtags, e.g. bicycle, #cycle. Twitter users were aggregated by the FLUID application and ranked using the five indexes. 0.07 % had a distinctly high rank score based on the indexes, which was selected as the threshold designating users as lead users. For the effectiveness analysis 50 users were selected from the total number of users retrieved by the FLUID application. 20 users were uniformly selected from the 0.07% of FLUID users labeled as lead users and 30 from the remaining list of FLUID non-lead users. The test took place at KU Leuven with five experts, knowledgeable in lead user characteristics, evaluating the selected 50 users by their tweets. Before starting the study a brief introduction regarding the study was given to the experts. Next, they were given 14 random tweets of each of the 50 users and were asked to rank on a five point Likert scale whether they agreed or disagreed that the tweets belonged to a lead user. The order of Twitter users was altered for each participant to minimize ordering bias. The results, a lead and non-lead user group, were used in the second part of the study to score and compare user metadata, tweet relevance and tweet sentiment.

3.2 Experimental Results

The experts identified 14 lead users and 36 non-lead users out of the selected list of 50 Twitter users. Twitter users rated with an average score between 4 (agree) and 5 (strongly agree) were noted as lead users. Users with an average score between 1 (strongly disagree) and 4 noted as non-lead users. An interrater reliability analysis for the 5 experts was performed using the Fleiss' Kappa statistic. The strength of the agreement between the experts was found to be substantial, with Fleiss' Kappa for 50 cases with two possible classes (Lead User and Non-Lead User) 0.7124, 95% CI (0.6247, 0.8000). As shown in Table 2, 14 of the 20 FLUID lead users were noted as lead users (LU) by the experts and remaining 36 were noted as non-lead users (NLU).

Table 2. Expert and FLUID results matrix

		Predicted class (FLUID)	
		LU	**NLU**
Evaluated	**LU**	14	0
Class (Experts)	**NLU**	6	30

The next step was to quantify the performance of the model in the case of bicycle products. A confusion matrix was created with two classes for FLUID and experts, shown in Table 2. Calculated precision that a FLUID retrieved lead user is affirmed by experts to be a lead user is 0.7 and calculated recall that a randomly confirmed lead user is retrieved by FLUID is 1. The accuracy of the model base on the results shown in the table is 0.88.

In the second part of the study, the identified lead user metadata were compared to the non-lead user metadata with regard to the five indexes. Significant differences in Twitter user metadata and tweets between the two groups are shown in Table 3. For the influence index, the number of retweets for lead users was considerably greater than for the non-lead users. Lead users are also involved in networks relevant to the target product. Looking at the lists that users are subscribed to by other users, the number of relevant lists that the Twitter user is member of is considerably higher for lead users than for the non-lead users. For the relevance index, lead users' tweets, URLs, descriptions, and images were found to be more relevant to the product domain than the non-lead users'. For the sentiment index, authors found no difference in the overall sentiment in tweets between the two groups. The lead user sentiment ($M=3.17$, $SD=0.14$) was adjudged to be similar to the sentiment of non-lead users ($M=3.10$, $SD=0.17$), $t(29)= 1.52$, $p=0.13$. Lead users did not appear to be more dissatisfied with the bicycle products as expected from the related research [6].

Examining the activity index, the identified lead users tend to share more in-depth information regarding products, but also notably tend to be less active on Twitter. Lead users retrieved by utilizing Twitter search tend to tweet less than non-lead users. No other significant indicators of difference in activity between the two groups were found. Finally, for the trend index, the percent of relevant lists that the user subscribes to is considerably higher for lead users. There was no noticeable difference in the percent of relevant hashtags, taking into account the bias introduced by manual selection of queried hashtags in the FLUID application.

Table 3. Significant Differences for Twitter data

	Lead Users		Non-Lead Users				
	Mean	SD	Mean	SD	T	Df	p
Tweet	2.87	0.29	1.84	0.92	5.95	47	0.000
URL	4.21	0.69	2.64	1.25	5.20	39	0.000
Description	3.83	1.11	2.27	1.18	4.11	20	0.000
Images	2.85	1.29	1.85	1.17	2.43	24	0.022
# of Tweets	1.95	2.71	8.74	11.47	-3.32	43	0.002
# of Retweets	7.57	5.01	3.77	5.00	2.40	48	0.020
Lists (Member)	0.54	0.21	0.18	0.26	4.94	31	0.000
Lists (Subscriptions)	0.62	0.30	0.17	0.31	2.86	17	0.024

4 Discussion

The purpose of the research is to evaluate automatic classification of Twitter data by the FLUID application. For the selected case study, as indicated in the previous section, precision and recall in identifying lead users are 0.7 and 1, respectively, leading to an overall accuracy of the FLUID application of 88% when evaluated by experts. The effectiveness analysis results, shown in Table 2, imply high agreement between the experts and FLUID application on non-lead users and moderate agreement on lead users for bicycle products. The study also shows that the user characteristics can be translated into criteria to categorize online lead users from non-lead users. Relevance, whether of tweets, URLs, favorites or lists is the primary influence factor in separating lead users from other Twitter users. Activity, trend and influence are additional strengthening components in ascertaining the lead user identification. The strength of each index in delineating between the two groups gives a notion of possible correction of weights for the FLUID application in ranking Twitter users for follow up studies. The sentiment of a tweet was found to have no significant impact in separating the two groups. Analyzing Twitter data for relevance and sentiment is challenging. Separate studies should be performed to increase efficiency and verify techniques used. Additionally, with the growth of Twitter, spam messages have become more and more of a problem. A targeted classifier should be used to track down such tweets. Some of the remaining challenges in identifying lead users are limited resources, Twitter data restrictions, and bias introduced in manually selecting queried product names and hashtags. Further studies in other domains with refinements in FLUID weights from the results obtained in the study will have to be performed to validate and improve on the results in identifying lead users. In regards to related research, the FLUID method further supports the netnography method in an online approach to lead user identification. Additionally, it adds a systematic and automatic approach to the method. The FLUID approach can also be one of the initial steps in the screening process to minimize the time costs in mapping a network of potential lead users before an in-person or on-site verification process starts. The model may be applicable to other social networking sites, e.g., Facebook, Myspace, Flickr that may provide access to user posts and also user meta-data, which will require similar mapping to FLUID indexes. Nevertheless, successful data gathering and analysis on social networking sites is dependent on evolving user or site privacy restrictions on available online data.

5 Conclusion

In this paper, a systematic and automated FLUID approach to identifying lead users is described and its performance effectiveness is analyzed on data retrieved from the social networking site Twitter for the bicycle product. These results indicate further need for research on the proposed approach, although they have to be interpreted cautiously. The results are based on a single case study and further refinements through several iterations are necessary. Data mining methods rapidly and effectively extract and classify user discussions and metadata available on Twitter although significant challenges remain. The next step in the FLUID model development is to verify the method with different target products or services and possibly by having on site visits. During on-site visits, context of product use and development can be observed that is difficult to gather through data mining. During the verification stage, the authors look to further ascertain the viability of the approach in identifying the lead users. Identification of lead users and analysis of online discussions on social media sites like Twitter or other online communities provide many opportunities, especially for the private sector. Systematic and automated lead user identification is bound to play an important role in the early stages of product innovation.

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Improving Result Quality in Engineering Design by Better Linking Employee's and Task's Features

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Abstract. Human interference with engineers' activities negatively influences engineering tasks' success. Regarding human influence is therefore a promising approach to improve that success. This Paper examines the aspect of man-induced disturbances in Systematic Engineering Design processes. Based on a lab study done with engineering students and interviews with engineers in industry a model of how to link engineering tasks with the most appropriate problem solving design engineer is developed. To underline the importance of the model, specific background information on Design Theory approaches is given.

Keywords: engineering design, design methodology, result quality of engineering tasks, linking employees and tasks.

1 Introduction

Quality of products is measured by how well requirements derived both from customers' needs and products' development, which is typically comprised of different single tasks e.g. Computer Aided Design (CAD), are met. According to the German VDI 2221 guideline, the quality of the result is on one hand related to the demands of the product development task, and on the other to the competence of the design engineer [1]. Each task demands a certain profile of technical, social and personal competence, and each design engineer possesses a different profile of these competences. If task's demands and competences do not match, inferior product quality can occur. Therefore, to ensure a high quality of the product, it is a first step to find competent design engineers, but more important to find out which of them provides the best fit for the specific product development task. This contributes to a deeper understanding of the relation between the human factor in product development and its consequences for the quality of the result. The paper gives a more detailed introduction of the lab study performed to analyze the scenarios. Furthermore, an insight on how and why the different lab study assignments were compiled, is presented. Finally, the paper examines the conclusions that can be drawn from the results of the three scenarios and proposes a method to evaluate the background of an employee in engineering design, in order to match it with the right kind of task, aiming at the successful solving of engineering tasks.

In chapter two, the state of the art of Systematic Engineering Design and the role of man-induced disturbances in product development along with challenges design

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engineers face in early phases of the product development process are introduced. Chapter three establishes the research on error trees in order to explain the necessity for the presented lab study performed with students of RWTH Aachen University. Based on the lab study and interviews with engineers in industry the need for a model of both engineering tasks and employees in engineering is developed in chapter four, while the two parts of the model are linked in chapter five. Chapter six summarizes the positions of the paper and gives an outlook on further research.

2 State of the Art

2.1 Systematic Engineering Design

Product development as considered by Systematic Engineering Design (SED) is a sequence of distinctive actions starting at the original conception through design and production and leading up to the product's introduction into the manufacturing process. Several methodologies and approaches have been developed in the course of the last fifty years. All that happened in order to systematize product development and to minimize the effect of human action. Research on SED has been undertaken in various countries for about 60 years. As this research progressed simultaneously several methodologies for SED have been developed.

The Theory of Inventive Problem Solving (TRIZ) is focused on early stages of development [2], [3]. Quality Function Deployment was developed in Japan resulting in the "House of Quality" [4], [2] and Axiomatic Design was published in the USA presenting a method in order to achieve high quality products by axiomatically considering independence and least information content [5]. A more holistic methodology of SED was developed in German speaking countries since the mid-20th century. Joint efforts of several groups led to the guideline VDI 2221 [6], [1].

2.2 Methods and Approaches within SED

Despite the different approaches, Systematic Engineering Design techniques can be divided into Discursive Methods, Methods of Analogy Consideration and Heuristic Methods. An overview of methods and their classification is given in Figure 1 [4], [7].

Common with all methods is that humans act with their deficiencies from irrational behavior. All three kinds of approaches make up the entirety of SED problem solving methods.

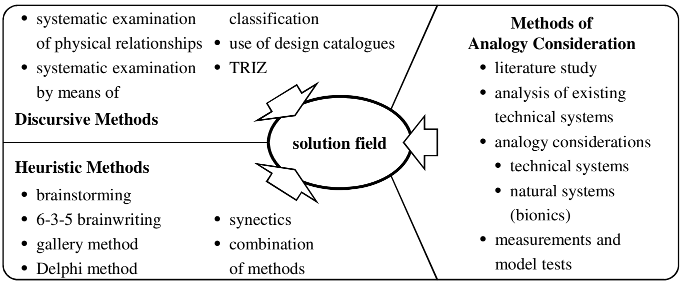

Fig. 1. Methods in Systematic Engineering Design

2.3 Man-Induced Disturbances

Considering the matrix of human error factors in SED by Djaloeis et al. [8], the role of man-induced disturbances was focused on. In order to examine human interferences with SED approaches they have to be named first. According to Dylla, interferences are related to individual as well as external influences [9]. Every design engineer's individual problem solving is initially influenced by his individual background, which is made up by individual personality, acquired knowledge and accumulated education but also results from the emotional situation. In most cases, these influences have to be taken as given. They are always related to external settings, the task and the structure of the organization executing the SED process. They can be kept at bay to a certain extent by well executed project management. Figure 2 shows the relations between SED and individual along with external influences. [9]

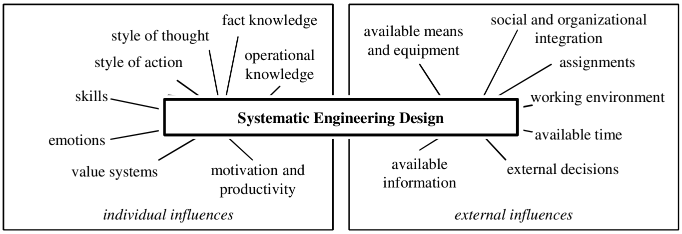

Fig. 2. Individual and external influences on SED

2.4 Challenges in Early Phases of Product Development

Especially for early phases of product development, Bender advocates "opportunistic planning", which includes dynamic changes according to new requirements, partial solutions, and intuition, often based on heuristics [10]. He identifies a detailed problem and requirement analysis as the fundament of product development planning, especially in early stages. After generating possible problem approaches, a systematical evaluation of the most promising principle solutions is advisable. However, the result quality is closely connected to the ability to decompose the general problem into more manageable subproblems. This requires high levels of experience, both theoretical and practical competence, and the ability to dynamically switch between problem-, solution- and process-oriented points of view. Therefore, technical proficiency is highlighted.

2.5 Conclusion

One general aspect of all SED approaches is that they are put into action by human beings who always bring their distinct and unchangeable deficiencies with them [9]. The important influences of human factors are also underlined by research done by Duckwitz, Djaloeis et al [11]. These influences interfere continuously with the proper execution of SED methods. Error trees, which will be introduced in the next chapter, can be used to examine problem solvers' influence on the success of actions.

3 Lab Study

3.1 Error Tree

In product development, the product must conform to the requirements listed in the product specification. The quality requirements as well as their respective acceptance limits on the functional, working and constructional interrelationship levels can be derived [4].

- The functional interrelationship level expresses the intended relation between input and output. Common errors are e.g. failure to understand the main function or naming a physical law or a product component instead of a function.
- On the working interrelationship level, relevant laws of physics as well as geometrical and material constraints are listed. Common errors are e.g. choosing the wrong physical effect.
- The constructional interrelationship level highlights components, joints and assembly points. Common errors are e.g. naming a function or a physical law instead of a defined component, value or dimension or wrong dimensioning.

Pahl et al. elaborate that establishing functional relationships can be challenging, because the high level of abstraction is difficult to handle [4]. Based on the error model of Hacker [12], a three-level error tree was defined. In each of the three relevant systematic engineering levels, the respective requirement R can be evaluated using the following procedure: at first, it is asked whether the designer has included R: if not, it is an error of omission, and if yes, it is asked if the implementation of R exceeded the design range. If yes, it is an error of execution, if no, R is fulfilled. This error tree provides a valid method to categorize and count errors on various levels of systematic design. The above mentioned approach towards error trees was verified in a lab study which will be described in the next chapter.

3.2 Study with Engineering Design Students

In order to examine different influences like (e.g. amount of time or personal background) on the quality of the outcome of a product development process, a lab study was conducted. The participants solved five tasks in the engineering design process, described as followed. First task was to conceive the structure of the product with the help of a picture of the crankset. For guidance the participants got an example of a structure with the task definition. Focus of this task was the examination of the human capability in abstraction of a given issue and structuring a given product. In the second task, based on the same picture, the function of each part had to be conceived and displayed in a hierarchical structure. Then subsequently the structures had to be connected by the participants to show the coherences between parts and functions. Beyond the pure abstraction of the bicycle crankset the participants had to develop functions. In the third task an improved solution of the crankset had to be designed by the participants. Creative development was required. For the fourth task the participants were handed an incomplete technical drawing of a part of the crankset with a lot of freedoms in design. The part had to be modeled in CAD software. Demanded skills were handling of the software, but mostly the self-reliant recognition of the problem and the modeling of the part. In the fifth and last task CAD parts had to be assembled in CAD software. Central requirements to the participants were finding reasonable connection types, self-reliant picking of an assembly order and handling the software. To get an insight into systematic interrelationships of participants' backgrounds and performance in the given engineering tasks, three scenarios analyzing both background data and results were set up.

3.3 Scenarios

In this chapter scenarios are laid out for all four groups of participants and the results will be interpreted. Scenario A examines in what way the personal backgrounds, which are independent from the test and only depend on the participant, are connected to the result quality of the design process. To test the correlations between test data the provided results were split into three scenarios. Spearman's rank correlation coefficient was calculated bivariate for the ordinal scaled data in different categories for each scenario. Spearman's rank correlation is used because the variables are nonlinear to each other. Furthermore Spearman's rank correlation is robust against outliers. The scenarios are as followed:

Hypothesis A (correlation between Background and Results)
Hypothesis A examines the correlation between the backgrounds of each participant, gathered before the experiment, and the results achieved by the participants in the test. The evaluation in SPSS (IBM Statistical Product and Service Solutions), a software package used for statistical analysis, also states the correlation in the backgrounds and in the results itself, which lead to conclusions for types of problem solvers. In detail the following criteria are analyzed: As part of an often used intelligence test results from a test for spatial awareness are used [13]. The test was performed by the participants before the main test. Different rotated dice had to be matched to a set of dice. The results were converted into grades from 1 to 4, where 4 is the best grade and 1 the worst. Other background information is experience with technical drawings, engineering design, CAD and with the item examined in the test, the crankset of a bicycle. Again a scale from 1 to 4 was used by the participants, where very much experience was rated with a value of 4. On the site of the results the quality of the solution was rated. The rating was done regarding aspects of completeness, correctness and cleanness of the displayed results. Best results got a 4. Worst results a 1. Scenario A could be confirmed with the test results.

Figure 3 shows an excerpt of the result from the lab study. It is easy to see, that there is a strong relation between the average subjectively perceived spatial perception and the actual result from the above described engineering tasks. Similar results were drawn from the other tasks conducted in the lab study.

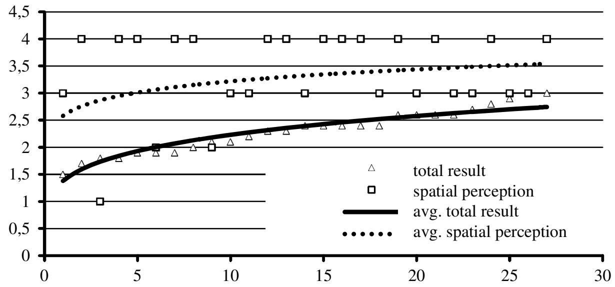

Fig. 3. Interrelationship between average spatial perception and results in lab study

Hypothesis B (correlation between backgrounds and task load)

Hypothesis B examines the correlation between personal backgrounds of the participants and subjective task load. The same criterions as with hypothesis A were used. A scale from 1 to 4 was used by the participants, where very much experience was rated with 4. In the following the task load criteria are introduced. They were recorded on standardized questionnaires from the NASA TLX method [14]. On the questionnaires the participants could score their task load on a scale from 1 to 10. For the evaluation the score was converted to a scale from 1 to 4. The task load was recorded together for tasks one and two and separately for the task three to five. The NASA TLX measures mental demands, physical demands, temporal demands, own performance, effort and frustration. Results delivered ambiguous data for this scenario.

Hypothesis C (Correlation between task load and results)

Hypothesis C evaluates the correlation between subjective task load and the result quality. The criteria were recorded on standardized questionnaires from the NASA TLX method [14] exactly like hypothesis B. On the side of the results the quality of the solution was rated. The rating was done regarding aspects of completeness, correctness and cleanness of the results. Best results got a 4. Worst results a 1. Results delivered unclear data for this scenario. Figure 4 exemplarily displays the relationship between task load expressed through temporal demand and results. Further details on the results of the scenarios are summarized by Hinsch et al. [15].

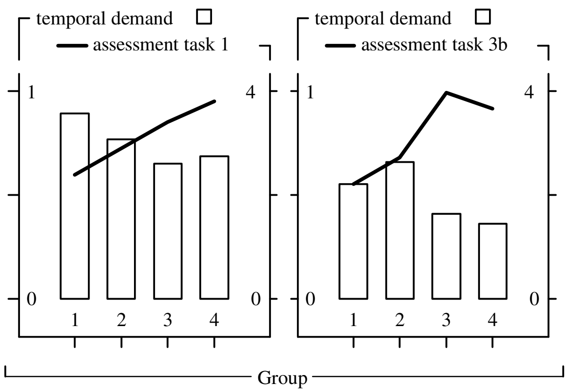

Fig. 4. Interrelationship between temporal demand and results in lab study

Additional research by Djaloeis et al. [11] confirmed that there is an unclear, though trending, relation between available time and subjective workload: especially a paradoxical relation between frustration and quality of the result was highlighted. These results provide an approach for improving an existing actor-oriented workflow simulation model. A first theoretical approach was conducted by Duckwitz et al. [16], with the intention to sustainably increase the predictive accuracy of the simulation model as a planning tool for project managers in design projects.

4 Need for an Employee and Task Model

Participants in a set of interviews held in engineering companies as well as the lab study results confirmed strong influences of man induced disturbances and the choice of problem solver on SED task execution. Thus, SED task execution requires a well thought choice of problem solver and therefore models of both tasks and employees.

4.1 Task

Adapting a model from Schreyögg, a task can be categorized by five scales – variability, novelty, interdependence, unambiguousness and knowledge/skills [17]. Variability is defined as differences in the conditions of the performance of work over time. A more variable task frequently changes its conditions of successful task execution over time, where a less variable task features fewer changes. Novelty is examined from the number of exceptions that the task executioner maybe confronted with. A new task will force a high number of exceptions. Interdependence measures the dependence to other tasks before or after the task viewed as well as the dependence to other people. A higher rating in interdependence states a high dependence on other tasks and people.

Unambiguousness rates how explicit the task is or can be defined. A higher rating in this scale results in a more defined task with less room for interpretation. Added to the mentioned four directly adapted scales from Schreyögg the scale knowledge/skills defines what knowledge is demanded by the task and how much the knowledge influences the task execution. The demands are scaled in a range from 0 to 4. The factors were validated by examining 35 typical engineering tasks and exercise assignments from university. The tasks were executed in final theses since 2008 in cooperation with the industry. For each task five items were evaluated. In total only 25 questions have to be answered in order to describe a task.

4.2 Employee

The employee model is adapted from a personality test – the NEO-FFI [18]. The five scales in the employee model are agreeableness, openness for experience, conscientiousness, problem solving and competence. The first three scales are directly measured with the personality test. Employees with high scores on the scale compatibility are altruistic, compassionate, understanding and sympathetic. They tend to interpersonal trust, cooperation, compliance and they have a strong need for harmony. Subjects with high scores on openness to experience are characterized by a high degree of appreciation for new experiences, prefer variety, are inquisitive, creative, imaginative and independent in their judgment. They have varied cultural interests and are interested in public events. The conscientiousness scale differs neat, reliable, hard-working, disciplined, punctual, meticulous, ambitious and systematic of careless and indifferent persons. The scale problem solving is based on research on problem solving among engineers. Subjects with a higher rating in problem solving deliver better results in most cases. The scale competence is based on common tests for evaluation of IQ and EQ as well as expertise. The questionnaires for employees are more extensive compared to the task questionnaires. This is done because the variety of employee characteristics typically exceeds task variety, as all tasks originate in product design.

5 Linking of Task and Employee Model

Figure 5 displays the linking of task and employee model. For each of the five sectors attached to each pentagon, the link is established by first conducting surveys with predefined questionnaires. The results are stored in databases. Through a correlation matrix that is established by intense statistical analysis (like the above described) and thoroughly based on the lab study's results the link is created. All five links together form the model. The implemented software prototype features an easy to use interface that helps people from the management level to assign the right task to the right employee.

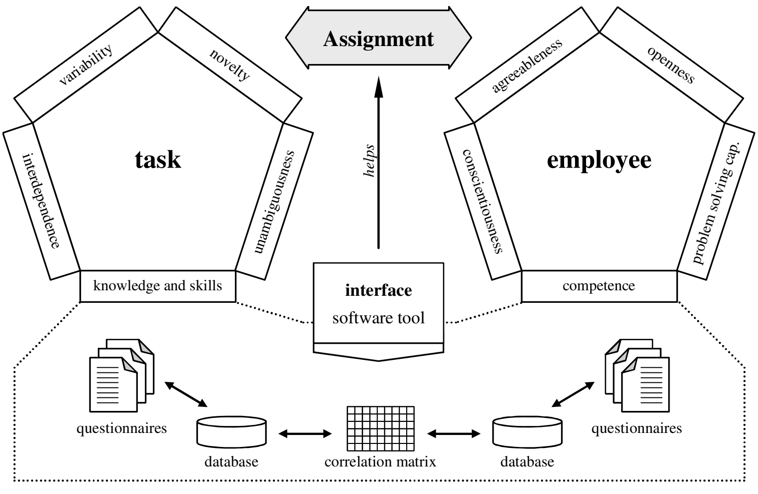

Fig. 5. Application of task and employee model and assignment scheme

The correlation within the prototype is calculated in an Excel based matrix, while the applying engineer will only enter the given values into a software-based form. The matrix then calculates the best match based on the given entries and proposes an employee-task combination to be chosen. The values concerning the employee can be imported from already existing systems to evaluate employees. In order to best consider these systems in the development of the tool, a survey on practical application of these systems will shortly be done in engineering companies.

6 Conclusion and Outlook

This paper intends to underline the importance of considering human influence in engineering task execution. Therefore it first gave a short insight into Systematic Engineering Design approaches and methods. Next, it subsequently presented error trees to examine the effects of the influences along with a lab study based on these error trees. The results of the lab study contributed to the establishment of a model on how to meet the challenges from human influence in engineering tasks. Finally, the model was introduced and presented in its current state. The model is subject of current research and will be broadly enhanced. While further developing the model, the background of its development as presented in this paper will again be used to underline features of the model. E.g. insights into interrelationships between engineers' problem solving will be taken from the analysis of lab study results. Next, the factors of the model as presented here are developed supported by an extensive series of interviews with engineers in the field. Thus, the validity and applicability of the model can be granted. Last, task and employee linking will be enhanced from the current state as already outlined. Once finished, the applicable model will increase engineering tasks' success, as negative effects of human influence will be reduced.

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Internal Innovation Communities from a User's Perspective: How to Foster Motivation for Participation

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Abstract. In order to further include the employees' creativity in the innovation processes, companies provide social software platforms for internal innovation communities to share, discuss and evaluate ideas. The main challenge for organizing such communities is to foster motivation for participation. In this paper, motivation theories are put in context with an innovation community concept developed at the automotive manufacturer Dr. Ing. h.c. F. Porsche AG. Firstly, an interview study analysis of this concept is used to identify new relevant expectations, hopes, needs and abilities of employees. Secondly, measures proposed in the past are evaluated. With the help of 20 semi-structured interviews it can be shown that each of the employees is unique and has own motivational deficiencies. Thus it is important that a concept for fostering motivation includes several measures which motivate the various users to participate. These measures are integrated into a holistic concept presented in this paper.

Keywords: tools for innovation, collaboration, innovation community, user motivation, enterprise 2.0.

1 Introduction

Researching the open innovation paradigm, *Chesbrough* suggests that organizations should integrate new sources for innovative product ideas from outside into their innovation processes [5]. However, *Gassmann and Enkel* found that limited absorptive capacities make it challenging to transfer external knowledge through organization boundaries [8]. Only recently more and more companies identify their own employees from various divisions inside the company as useful sources for new product ideas. Often, however, the accumulated knowledge and creativity necessary for generating such ideas is spread out widely through the organization. From a perspective of knowledge management these findings implicate two major tasks. Firstly, effective processes and tools for collaboration have to be provided through a software platform. Secondly, a culture of participation, curiosity and knowledge sharing has to be lived.

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2 State of the Art

2.1 Research on Innovation Communities

Koch and Richter suggest that Social Software is suitable for collaboration and knowledge sharing especially in the case of large organizations [11]. As can be seen on popular internet applications, people are able and willing to share knowledge (e.g. on Wikipedia.org), discuss issues (e.g. on Facebook.com) and evaluate products (e.g. on Amazon.com) through social network functionalities. These typical functionalities for communication, collaboration and knowledge sharing can be transferred and adapted to an organization's internal platform for an innovation community, enabling employees to share, discuss and evaluate new product ideas. The Innovation Jam carried out by IBM in 2006 shows the potential of such platforms. *Bjelland and Wood* give an overview on the results of this online brainstorming session initiated by the IBM Top Management with the aim to bring together the creativity of more than 300.000 employees. As a result, in only 72 hours 150.000 employees, family members, business partners, clients and university researchers generated 46.000 ideas resulting in 10 new business units [4]. Since then *Reinhardt and others* have developed a variety of concepts for processes, structures and IT landscapes for social networks to support collaborative idea generation within organizations. However, after installation in organizations many of such innovation communities lack user participation.

One main reason for that can be found in studies of *Albers et al*: While in recent decades more and more effort was put into the development of computer tools for product engineering, the role of humans was neglected [2]. In order to organize a community for effective idea generation, the user has to be put in the center of a community concept. The innovation potential of an internal community can only be fully utilized if the user's expectations, hopes, needs and abilities are met. Hence, user acceptance is believed to be one of the keys to the success of any tool that is supposed to support the design process. This is why motivation theories from social sciences are in this paper put in the context of an innovation community platform developed at the automotive manufacturer Dr. Ing. h.c. F. Porsche AG.

2.2 Research on Motivation

Thus far, research has rarely considered the role of motivation in the context of community innovation. *Schattke* and *Kehr* analyzed motivation in innovation communities with 'the compensatory model of work motivation and volition'. [13] *Kehr's* model includes three components: Explicit motives, implicit motives and perceived abilities. [9] Explicit motives can be expressed by a person, they are consciously accessible and they constitute the reason for their actions. In contrast to that, implicit motives lead to behavioral impulses and are subconscious. Additionally, perceived abilities are the basis for people to perform certain acts. [9] With regard to implicit motives *McClelland* differentiates between the need for affiliation, the need for achievement and the need for power. The need for affiliation describes the desire of people to enter new social relationships and stay in touch with their friends. The need for achievement prompts people to explore what they are able to, so they can grow with new challenges and expand their own limits. People who are motivated by the need of power aspire to have power and to keep it. They focus mainly on strength and control. Each of the types of need can appear more or less dominant to different individuals. [12]

Kehr states, that if explicit and implicit motives of a person are congruent, the person is enabled to be intrinsically motivated. If the perceived abilities also match these motives, the person can immerse into a 'flow' experience. [9] This is a state, in which a person has undivided attention to a task, a changed sense of time and no disturbing thoughts. [6] *Von Cube* relates 'flow' to the experience of mastering a challenge and go beyond one's expectations as in mountain climbing or complex problem solving. [7] This element is also addressed in 'the compensatory model of work motivation and volition'. It is found within the need for achievement.

For the purpose of an innovation community platform, where participation is voluntary, it is necessary to make sure that the users are able to have a flow experience. They need to be motivated explicitly as well as implicitly and must be enabled by their perceived abilities. Although *Kehr* offers different approaches to motivate people who have deficiencies in one of the three components of his model, *Schattke* and *Kehr* mainly concentrate on implicit motives and the need for affiliation, achievement and power. From these types of need the Authors derive recommendations for measures to motivate different types of employees.

A person who has deficiencies in explicit motives is not convinced that the action is required. Such a Person can be motivated by measures that focus on cognitive aspects. These are e.g. argumentation for the necessity of the action, setting goals and solving of conflicts of objectives. [10] A person who has deficiencies in implicit motives can be motivated by stimulating the needs for affiliation, achievement and power. Depending on the personal preferences, the need for affiliation can be stimulated by teamwork, the need for achievement can be addressed by challenging assignments and the need for power can be satisfied by the chance to earn prestige and responsibility. [10] A person who has deficiencies in perceived abilities is not able to solve the task with his abilities. These deficiencies can be overcome by making the task easier or by improving the person's abilities by assistance. [10]

3 Development of an Integrated Concept

3.1 Aim of Research

The authors are convinced that humans and their individual factors should be positioned in the center of product engineering when developing new methods and processes (see also [1]). In the case of an innovation community, an undefined number of users can be involved. Every one of them is a unique individual and will respond differently to measures of community management. Thus, when implementing a community platform, it is crucial to motivate all these different types of users. While approaches for stimulating implicit motives already exist [10], this paper aims at the identification of new relevant expectations, hopes (explicit motivation) and abilities (perceived abilities) of employees, the evaluation of existing measures for fostering (implicit) motivation, the development of new measures for innovation community management and the integration of these measures into one holistic concept.

3.2 Methodology

'The compensatory model of work motivation and volition' offers different perspectives on the motivation of users for participation within the community. Because of its broad approach this model has been chosen to support the framework for the further interview study analysis and the development of the concept introduced in this paper.

The interview study was conducted with the automotive manufacturer Dr. Ing. h.c. F. Porsche AG. Two workshops with innovation management experts have been held to identify relevant aspects for the following interviews. In addition, two innovation community platforms for demonstrational and test purposes were introduced to provide interviewees with a deeper understanding of variations in basic features of such platforms. Semi-structured interviews with 20 employees including current and potential users of an innovation community form the basis for the identification of relevant motives and the evaluation of possible management measures. Questions asked during the interviews concern the three areas explicit motives, implicit motives and perceived abilities. Thereby probable reasons for a lack of explicit motivation or perceived abilities have been identified and first potential solutions have been derived. Regarding implicit motivation 15 possible features for innovation community platforms were presented to the interviewees, who were asked to rank these according to how much they would like to use them. On the basis of the interview study, measures have been developed to foster motivation. Newly identified and evaluated measures are then checked for consistency because several measures can cause conflicts between various objectives. Those are identified and solved through a holistic concept.

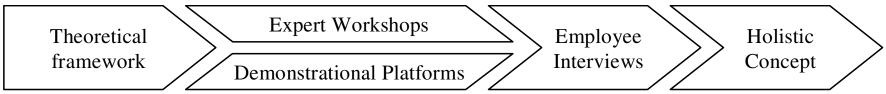

Fig. 1. Overview of this paper's research

4 Findings

4.1 Explicit Motives

Explicit motives are consciously accessible and the cognitive reason for people to undertake an action. Two major aspects of these motives were found in the experts workshops. Firstly, knowing about the relevance of the innovation community in a company and secondly, understanding the relevance of the specific innovation task that is to be solved by the community.

Relevance of the Innovation Community

The interviews revealed that "the projects [the employees are] working on don't leave a lot of time. If [they] spend time working in the community [...] it should be valuable for the company." [Interviewee 15] Furthermore they say that "working in the community is definitely not prioritized." [Interviewee 5] In summary because of the lack of time it is important for the users that ideas can be efficiently added. In addition, reasons for the relevance of an innovation community need to be obvious. Therefore it is important that the employees see the necessity for innovation on the one hand and the suitability of a community to generate innovation on the other hand.

Relevance of the Innovation Task

The attention of an innovation community can be led by specific innovation tasks. Even if an employee is convinced by the relevance of an innovation community, it is further necessary to give arguments why the particular innovation task is important. One interview partner who worked in a workshop with a test community platform says that "in order to generate an additional value for the company, [he] always tried to solve the given task." [Interviewee 15] Furthermore an interview partner explains that "the main point is what the benefit for the [company] is." [Interviewee 2] In summary the users expect the tasks to be within a strategically relevant area and on a question, on which answers from the community can make a noticeable impact.

4.2 Implicit Motives

Implicit motives can be strengthened by stimulating the needs for affiliation, achievement and power. This can be accomplished by implementing specific functions in the innovation community platform. In the expert workshops, in literature and in case studies from existing platforms such functions were collected. After an introduction of the different functions that stimulate the need for affiliation, achievement and power, the results of the evaluation are analyzed and visualized in this chapter.

Functions to Stimulate the Need for Affiliation, Achievement and Power

Functions to stimulate the need for affiliation must address the desire of people to establish new relationships and stay in touch with existing relationships. Therefore functions for communication are important to people who are motivated by the need for affiliation. Examples for this kind of functions are the possibility to send personal messages and a chat function. Furthermore it can be shown to users who else is online in the community. [13] In addition, further functions can include the possibility to set up personal profiles and to link with colleagues.

Functions to stimulate the need for achievement are effective if they give the employees the chance to engage in new challenges and improve their skills. Therefore a function for asking experienced members for feedback can be interesting. Ratings given from others also provide feedback on one's achievement. [13] Furthermore tools for visualization give the community members the chance to give feedback more easily and improve the quality of their posts. The personal skills can be improved by following categories in order to learn more about specific topics.

Functions to stimulate the need for power are supposed to give the employees the chance to gain prestige. This can for example be reached with the name and the portrait of the idea generator placed next to his idea. Motivation of employees that focus on career can be achieved through a function to inform the supervisor by automatically forwarding own ideas. Power can also be gained by becoming a moderator. Employees can be motivated by having their ideas compared to others in a ranking and earning a title like 'innovator of the month'. [13] Additional statistics provide the possibility to compete with others.

Evaluation and Visualization of the Functions

Fifteen potential users were asked to rank the suggested functions by their personal preference. The result of that analysis can be seen in figure 2.

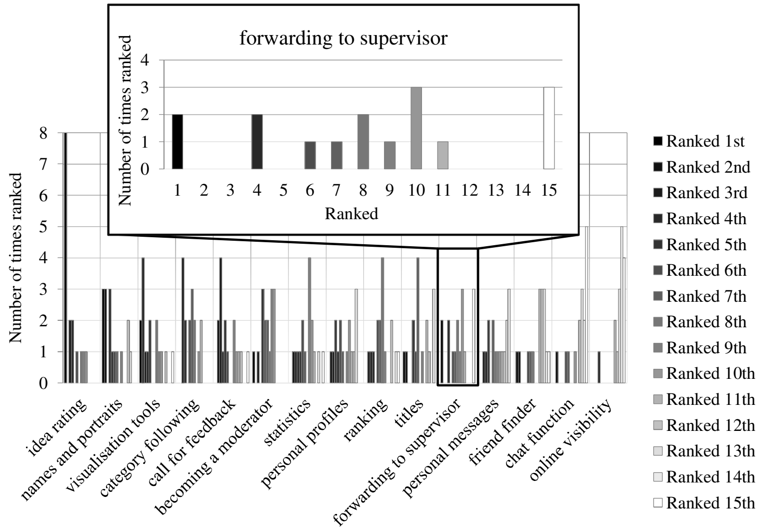

Fig. 2. Ranking of functions according to personal preferences of interviewees

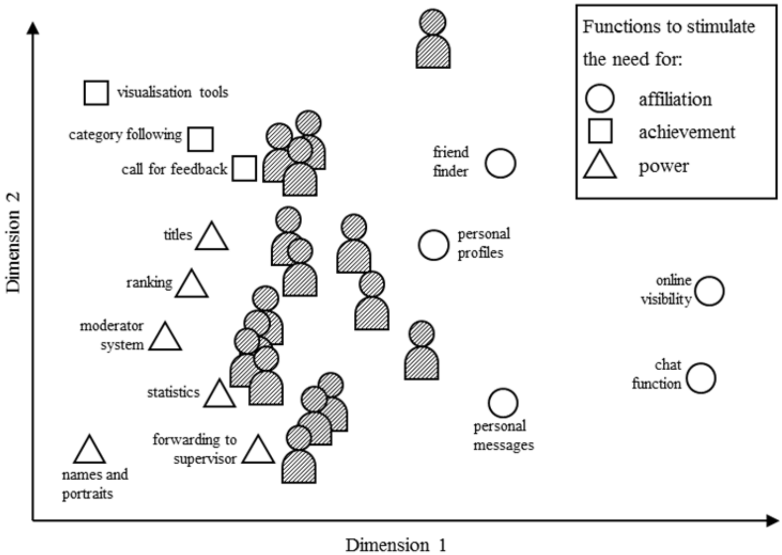

Fig. 3. Multidimensional unfolding to visualize the personal preferences towards different functions within a community platform

Except the function 'rating ideas', which is a basic function and expected by the interviewees, the distribution of the ranking is heterogeneous. The function for automatic idea 'forwarding to supervisors' is for example ranked first by two employees and ranked last by three others. One possible explanation for such discrepancy is that power motivated users focus on that function, whereas employees who are motivated by the need for affiliation and achievement do not consider this function as important.

If the decision whether to implement certain functions in the community platform or not was based on the averaged rating of the potential users, functions would not be taken into account although they are most important to some users. In addition in figure 3 the data is visualized by multidimensional unfolding. This statistic method allows to project objects and subjects by their similarity in a two dimensional space. [3] Thus functions that are ranked high by an interviewee are placed close to him, whereas functions that he dislikes have a larger distance to him.

By looking at figure 3 it can be seen that similar functions like the 'chat function' and the 'online visibility' function are placed close to each other. Furthermore the functions that stimulate the need for affiliation are clustered, as well as the functions that stimulate the need for power and achievement.

4.3 Perceived Abilities

Usability

Most interviewees stated that they have experience with internet applications like Wikipedia, Facebook and Amazon. However they say that "even small technical difficulties can demotivate potential users." [Interviewee 16] For example the community platforms for demonstrational and test purposes had a few deficiencies in this area, which "threw [users] back in [their] motivation." [Interviewee 15] Furthermore an interviewee says "even though [he] consider[s the innovation community] as very important, [he expects] that the access and the handling with the community platform is very easy and uncomplicated." [Interviewee 16] In addition care should be taken that the "effort is as low as possible to work" [Interviewee 10] in the community platform and "ideas [can] be entered efficiently." [Interviewee 5] In summary the interviewees expect an intuitive community platform with a comfortable access.

Selection of Innovation Tasks

One interviewee is "sure, that [he] can contribute to some innovation tasks more than to others, based on [his] experience." [Interviewee 3] Another interviewee "believe[s] that everyone has his favorite topics." [Interviewee 15]. By the sample of interviewees it was confirmed that different users have individual knowledge, specific technology or market expertise and personal intellectual skills. Depending on the area, topic and the question of the innovation task, users felt more or less creative. If a task makes it too hard for a user to contribute at all, he might get frustrated. Thus, an innovation task is only motivating, as long as it appears solvable to users. On the other hand, users who are driven by the need for achievement might get bored if a given task is too simple and lets them only generate ideas which are already obvious. For such users the optimal level of excitement can be reached, when a task appears challenging and demands just the very best effort of the user to solve.

5 Application in an Example Case

At the example of a community concept developed at Dr. Ing. h.c. F. Porsche AG it is shown how the findings from Chapter 4 can be applied on a community platform. Firstly measures are recommended, secondly they are analyzed in a holistic context.

5.1 Measures to Foster Motivation for Participation

Five major issues have been identified in the interview study: The user's understanding of the relevance of an innovation community as well as the specific innovation tasks, providing functions to stimulate the users' implicit motives, ensuring usability of the software and the adequate selection of innovation tasks. In the example case these issues are addressed with the following recommendations:

1. In order to show to the users the relevance of the innovation community platform it is recommended, that the top management publishes statements for innovation communities in the platform, articles are printed in the company magazine and the CEO sends an e-mail to the users directly calling for participation. Furthermore the priority in working in the platform can be improved if the top management also participates in the community. In addition, videos of successful cases from the past can be presented to show the suitability of a community to generate innovation.
2. In order to show the users the relevance of the specific innovation tasks it is recommended that the tasks are related to the organization's strategy, endorsed by statistics and studies explaining why each task is going to be important for the future.
3. Considering that every potential member of the community is an individual, the innovation community platform should offer a multitude of different functions to motivate all kinds of users. On the other hand, there are hardly any users who want to use every possible function. As a consequence every member should be able to decide on his own if he wants to use a function or not, e.g. rankings.
4. For high usability the access to the community platform should be quickly found, for example via a link on the intranet homepage. After the computer login, an additional login request for the community platform should be avoided. A video explaining the platform and answers to frequently asked questions can help inexperienced users. To identify difficulties, the community platform should be established in several steps, starting with testers who are not easily frustrated.
5. Since every user will define his perceived abilities differently, it is suggested, that several innovation tasks are given to the community at the same time. The users can then decide which task they would like to work on. Just like different goals are chosen by mountain climbers according to their own physical fitness, different tasks should cover various levels of complexity and various topics. In addition, a 'free ideas' task should be opened to address ideas which don't match given topics.

5.2 Holistic Concept on Motivation in an Innovation Community Platform

Since the employees have different motivational deficits the recommended measures address all three components of 'the compensatory model of work motivation and volition'. These various measures have to be checked for consistency. It is recommended that the community platform has a large number of different functions. However, it should be easy and uncomplicated to work with.

One interviewee describes one testing platform as "extremely confusing." [Interviewee 16] Another interviewee says about the same testing platform, that "it is a matter of taste, what is too much [or] too few. [Apparently, he is] already used to other community platforms" [Interviewee 3] and, "because [he has] seen a lot of platforms, [he is] able to imagine something behind all the functions." [Interviewee 3]

Thus different users with different experience perceive the usability of the same platform more or less easy to handle.

In order to equip the platform with interesting functions but prevent an overload, an analogy to smartphones may be considered. Smartphones can have a lot of different functions. Their handling, however, is perceived intuitive. One reason for that is that there are only a small number of functions installed, when delivered. Once a user gains more experience, he can then enhance the smartphone through downloading and installing new applications of his choice. This logic can be transferred to innovation communities. Like smartphones functions the community platforms functions should be modular. In the beginning, every user should only see basic functions to ensure a good usability. However, he should then be able to customize the platform according to his needs. From the user's view, such self-determination is important for the acceptance of the platform. That is why as few functions as possible should be enforced upon a user or withheld from him.

6 Conclusion and Outlook

The findings on the basis of 'the compensatory model of work motivation and volition' indicate the complexity of motivating users to participate in an innovation community. Since every user is unique and responds differently to measures of community management, a 'one-size-fits-all'-approach is rarely adequate. With the example case it is illustrated how motivation for participation can be fostered. A broad set of measures regarding layout design, processes and communication of a community platform is recommended. Furthermore a modular platform is proposed which can be individually configured by the users according to their motives and abilities.

Kehr's 'compensatory model of work motivation and volition' showed to be suitable to analyze motivation in innovation communities. For future research on human factors further theories from the social sciences may be considered. In order to solidify the findings and validate the described measures for the example case further analysis on cases from other organizations should be carried out . The presented concept needs to be further developed and additional objectives and requirements within the context of organizations have to be considered, This includes intellectual property management, information technology security, data protection, human resources, cost optimization and processes of moderation, transfer and implementation of ideas. Whilst research on innovation communities has started only recently and methods and processes for community management will become more and more enhanced in the future, putting humans in the centre will be the most important success factor.

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Determining Granularity Level in Product Design Architecture

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Abstract. Product architecture represents components grouped into modules that can be assembled later to constitute a specific variant. Literature provides Methods of clustering components into weakly related modules with strong interconnections between components within modules. The number of modules and their hierarchical relationships shape product architecture and determine the balance between modular design and components integration. A novel hierarchical clustering approach, based on the biological Cladistics analysis, has been developed to cluster Design Structure Matrix (DSM) widely used to promote modularity. It evaluates different granularity levels of the resulting hierarchy and finds the best granularity level for maximum modularity. An automotive Body-in-White of 38 different components is used as a case study. Results showed the superiority of the recommended modularity pattern and synthesized product architecture over other clustering techniques.

Keywords: Product Design, Architecture, Modularity, Granularity.

1 Introduction

Product architecture defines the components of that product in terms of their function and the topology of their interfaces. Product architecture allows further detailed design, testing, manufacturing, supplying, etc. of those components [1]. In an era characterized by proliferation of product variety and mass customization, family of products and product platforms are typical solutions for product design and manufacturing [2]. A modular architecture instigates the appropriate product structure consisting of a group of modules, each with distinguishable function(s), with minimal interaction. Many types of modularity can be identified in a product architecture [1], 1) bus modularity where all modules are connected to a single common module, 2) sectional modularity where product variants are built from specific combinations of modules with a unified interface, 3) scalable modularity where some components with scalable parameters are combined with standard components.

Granularity level of a product refers to the number of decomposition stages of its components' hierarchy and which components exist at each stage. Granularity level of modular product architecture is of prime importance. Sharing common modules across many product variants facilitates economy of scale, while modules differentiation increases product variants and enables economy of scope. Effective trade-off between the two types of economies depends on the appropriate identification of

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common and different modules and their interaction. A product architecture, especially in a setup of family of products, should consider the appropriate level of aggregation [3].

This paper introduces a new model that is capable of determining the appropriate level of granularity for a product design, as well as the structure of its architecture, based on the interactions among its components. The model also includes a new clustering tool to group components into modules in a hierarchical structure revealing the appropriate product architecture.

2 Product Modularity

Product components are usually grouped into modules assembled according to a specific design architecture to facilitate future design changes, product variety, mass customization and manufacturing processes using delayed product differentiation [4]. Design Structure Matrix (DSM) is the most common tool used to represent interactions among components (component-based DSM) in a system [5]. DSM elements are usually binary; however, other values can be used to express the intensity of component interactions. In binary DSMs, '1' indicates interaction existence, while '0' indicates lack of interaction. Grouping product components into modules can be accomplished by clustering DSM into blocks of '1' elements.

There are few techniques available to cluster a DSM for modularity. The differences between those techniques are mainly in the clustering objective function. Coordination cost minimization was one of the first methods used for clustering [6], in which each DSM element is placed in an individual cluster and bids evaluated from all other clusters. Clustering is a tradeoff between the costs of a component being within vs. outside a cluster. The maximum number of components in a cluster was predetermined to prevent large clusters formation, and iterations were performed using simulated annealing.

Minimal Description Length (MDL) is another objective function introduced to cluster a DSM [7]. MDL is an evaluation function that compares clustered DSMs to a targeted DSM structure and considers their mismatched elements. Although the method allows the possibility of having overlaps among modules and performing bus clustering, it is highly dependent on the target DSM and its clustering scheme. The objective of clustering process was to minimize MDL, while GAs were used to generate chromosomes for clusters. Number of clusters is determined beforehand based on the given targeted DSM structure. A clustering efficiency (CE) index was also used to direct DSM clustering process [8]. CE is a weighed count of zero elements inside clusters and non-zero elements outside clusters. A neural network optimization approach was used for clusters generation. If the number of clusters is not predefined, the model would form fewer clusters than desired. One problem with applying automated clustering algorithms to some complex DSMs is the difficulty of extracting the relevant information from the data, and conveying it to the user [9].

The review of existing clustering techniques and modularity measures reveals two points. First, the objective function for DSM clustering is normally closely related to the existence of interactions within and between the resulting clusters. Chiriac et al. [10] compared modularity of several products based on different indices, and all of them were consistent and yielded the same results. Since many formulae of modularity indices exist without clear advantages, the simplest formulation would always be preferable. In this paper, a modified clustering efficiency (CE) index [8] formula is adopted in a much simpler form.

Second, available DSM clustering techniques reveal only one dimensional modules formation, even when compared to bus modularity architecture. Yu et al. [7] imposed bus architecture on the clustering process based on prior designer knowledge. The true nature of product architecture and its granularity is difficult to be revealed using clustered DSM only, especially for large matrices representing complex systems [9], without human intervention.

This paper introduces a new DSM clustering technique for product modularity. The technique finds the best granularity level of modular product architecture without forcing a specific modularity structure or pre-defining the number of modules or number of components per module.

3 Product Architecture Granularity Model

This new model uses hierarchal clustering to divide a DSM into the best modular architecture. Cladistics, a classification tool extensively used in Biology [11], reveals the evolution hypothesis and speciation scheme of a studied group of entities. Cladistics was first introduced to propose evolution hypotheses to the world of artifacts in ElMaraghy et al. [12]. Cladistics analysis was applied to the extracted features of automobile engine blocks using historical data to study their evolution and plan their future designs. Those variants have a total of 10 characters/features as shown in Fig.1, in which (1) refers to presence of a character (derived state), while (0) refers to the absence of that character (primitive state).

Cladogram construction is performed to obtain the most parsimonious data representation with the minimum information content. It is referred to as the cladogram length, which is the number of characters appearing on the branches of the cladistic tree. Fig.1 shows that the total number of derived character states (1) is 25, which is the upper value of the information content, while the number of characters is 10, which is the lower value. The presented cladogram has a length of 17 derived characters, i.e. there is a reduction of (26-17=9) in the information content. A handful of specialized software is dedicated to cladogram construction such as Hennig86, PAUP, NONA, PeeWee, Phylip, etc. and can perform very fast clustering on huge data [13]. NONA is used in this paper for cladogram construction.

Cladogram construction process is modified to allow for DSM clustering where relationships are considered as characters. The self-relationships of components to themselves are represented by the '1' diagonal elements of the original DSM. To determine the best granularity level on a resulting cladogram, a simple modularity index (MI) is used to specify the depth of the cladogram topology that is equivalent to the best granularity level and given in equation 1.

$$MI = I + Z \quad (1)$$

Where I is the number of '1' elements in the DSM outside formed clusters, and Z is the number of zero elements of those clusters. The aim is to minimize the value of MI. MI value changes from a granularity level to another depending on the developed clusters. Best granularity level corresponds to the minimum value of MI.

Characters and States Description

	Characters	States	Description
1	Material	0	Aluminium
		1	Cast Iron
2	Cylinders Arrangement	0	Inline with Ø=0
		1	V-Banks with Ø=60° or 90°
3	Wheel Drive Type	0	Front- (transverse position engine)
		1	Rear- engine mounts are on block sides (longitudinal position engine)
4	Deck End	0	Open- block made by die casting
		1	Closed- block made by sand casting
5	Cylinders Closeness	0	Siamese cylinders
		1	Separated cylinders
6	Skirt (Crank Case)	0	Assembled to the block
		1	Integrated with the block
7	Camshaft Housing	0	Absent from block (over head cam)
		1	Camshaft and Pushrods housing exists in block (over head valve)
8	Water Pump	0	Completely separable from the block
		1	Pump housing integrated in the block
9	Oil Pump	0	Completely separable from the block
		1	Mounted on the block
10	Deck Height	0	Low deck. stroke length<bore diameter
		1	High deck. stroke length>bore diameter

Characters and States at Each Engine

	1	2	3	4	5	6	7	8	9	10
Buick215	0	1	0	1	0	1	1	1	0	0
711M	1	0	1	1	1	0	1	0	1	0
LS2	0	1	1	0	0	1	1	1	1	0
Mopar2.4	0	0	0	0	0	0	0	1	1	1
QR20DE	0	0	0	0	1	0	0	1	0	0
4A-GEU	1	0	1	0	0	1	0	0	1	0

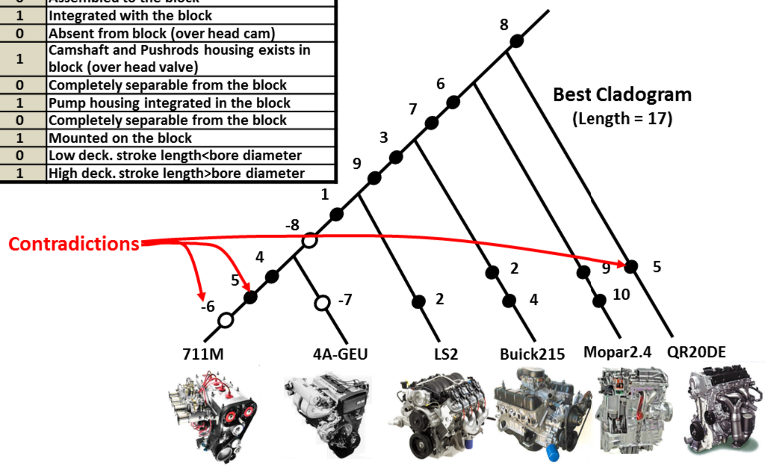

Fig. 1. An example of a set of engine blocks showing the hierarchal clustering technique of Cladistics analysis. Adapted from [12]

4 Automotive Body-in-White Case Study

This case study was published in [8, 14] to evaluate their modularity measures and clustering technique, which use neural networks for optimization. A body-in-white (BIW) is a structure of large number of metal parts to be welded in the body shop in preparation for painting later in the paint shop (Fig.2). The DSM that presents relationships among BIW components is given in Fig.3. The BIW components in the DSM are listed alphabetically. Self-relationships of components are replaced with '1' elements so they can be used as an input to the proposed cladistics clustering analysis.

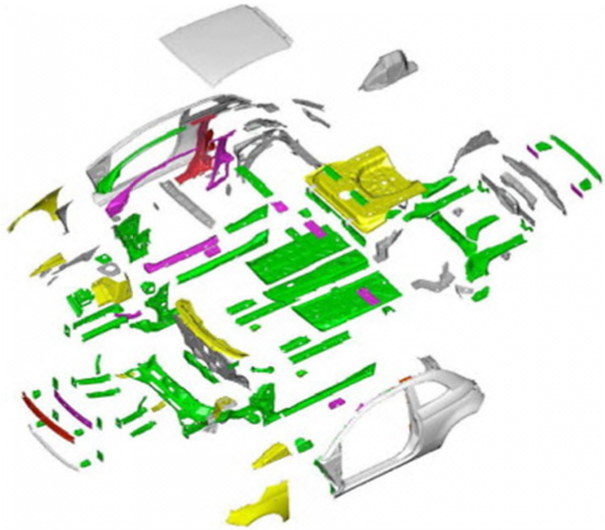

Fig. 2. An exploded view of automotive BIW components [15]

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Adapter A-pillar roof rail	1	1	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Adapter B-pillar roof rail	2	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
A-pillar inner	3	1	0	1	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
A-pillar reinforcement	4	1	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Back panel	5	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
Back panel side	6	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Back panel upper	7	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Body side	8	1	1	0	1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1	1	0	0	0
B-Pillar	9	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
Channel	10	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Cowl	11	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Crosstrack rear floor	12	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
Dash cross member	13	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dash panel	14	0	0	1	1	0	0	0	0	0	1	1	0	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Floor panel	15	0	0	1	0	0	0	0	1	0	0	0	0	0	1	1	0	1	0	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
Front header	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Front side rail	17	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Front suspension housing	18	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Heelkick	19	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	1	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0
Rear floor panel	20	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0
Rear floor side	21	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	1	1
Rear header	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Rear panel inner lower	23	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	1
Rear panel Inner Upper	24	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Rear side floor	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	0	1	1	1	0	0	0	0	0	0	0	1
Rear side rail	26	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	1	1
Rear side rail center	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0
Rear side rail frt	28	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	1
Reinforcement rocker rear	29	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	1	1	1	0	0	0	0	0	0	0	1
Rocker	30	0	0	1	1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	1	0	1	1	1	1	0	0	0	1	1	0	0	0
Roof bow	31	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
Roof panel	32	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0
Roof rail	33	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
Seat crossmember front	34	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0
Seat crossmember rear	35	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
Shotgun	36	1	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Spare wheel well	37	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
Wheelhouse	38	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	1

Fig. 3. The DSM of automotive BIW case study (Adapted from [8])

5 Results and Discussion

The DSM of the BIW has been used to construct a cladogram using NONA cladistics software. The resulting cladogram has a length of 127 steps and shown in Fig.4. Cladogram topology shows 10 possible levels of granularity between the top root level and the terminal level of individual components. To determine the best granularity level, Modularity Index (MI) is calculated for each possible granularity level presented by the cladogram topology. The ordered DSM is used to draw cluster boundaries at each level to identify the '1' elements outside cluster boundaries and the '0' elements inside those boundaries. Results show that level 6 scores the least MI=160, hence, it is the best granularity level. It has 9 modules, module {36, 1, 11, 3, 4}, module {9, 2, 35 ,34}, module {30, 8, 29, 28, 25, 19}, module {27, 15}, module {38, 23, 24}, module {17, 14, 18, 13, 10}, module {26, 21, 5, 7, 6}, module {20, 12, 37} and finally module {33, 32, 31, 16, 22}.

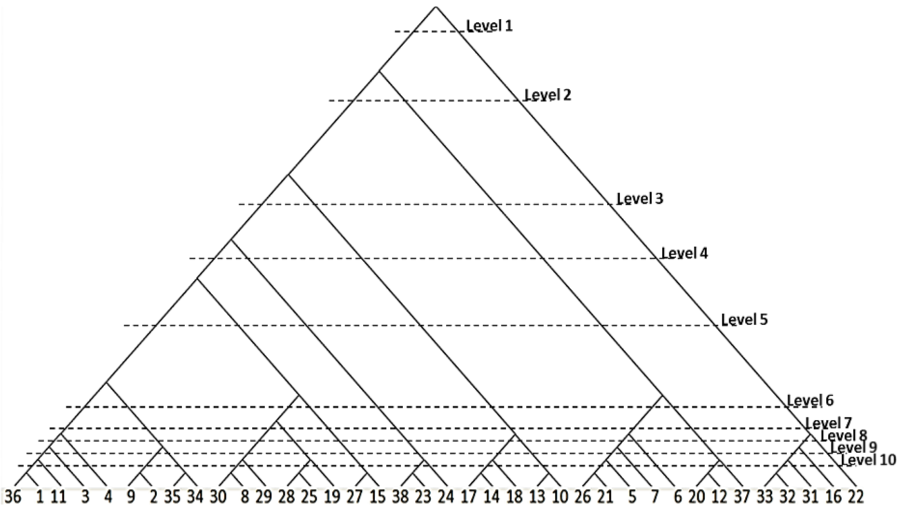

Fig. 4. Cladogram showing the different architecture granularity levels and component modules of the BIW case study

Cladogram topology above dotted line of level 6 in Fig.4 is the granularity map of the desired BIW product architecture. It can be converted to a product architecture layout similar to a Bill-of-Material (BOM) tree in Fig.5 by adding nodes of subassemblies at each level to illustrate unions of component modules. Modules {38, 1, 11, 3, 4} and {9, 2, 35, 34} exist at the bottom of the tree indicating that these are core modules with the most relationships with other modules. They have the least probability of change over product generations and the highest potential of being used as a product platform. The MI of clustering results obtained by Pandremenos and Chryssolouris [8] is 204, a higher value than MI=160 obtained from the proposed cladogram based method. Therefore, the clustering model presented in this paper

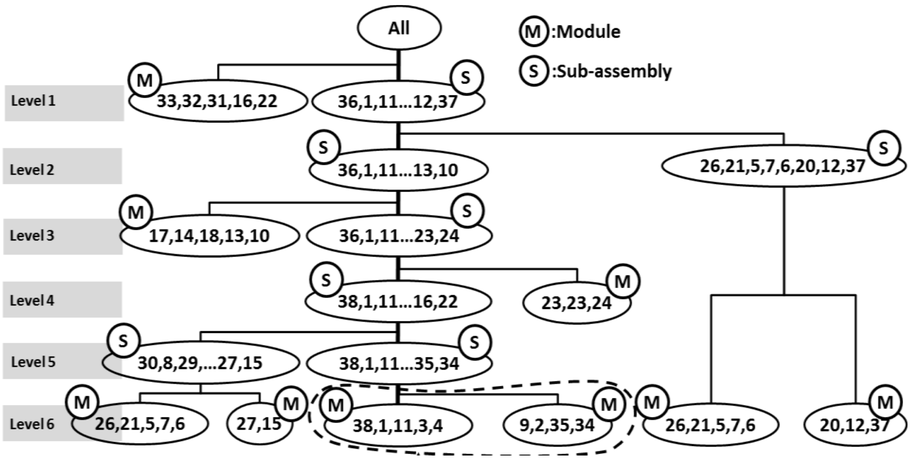

Fig. 5. The BIW architecture showing the obtained best granularity level and its modules

produces more efficient clustering compared to the latest models proposed in the literature [8]. In addition, the method is also capable of determining the architecture structure including number of granularity levels, components, modules and subassemblies at each level of the BIW case study.

6 Conclusions

System architecture represents the main design of system components layout and their interactions. In addition, a modular architecture is extremely useful for designing product variants especially for mass customization, since it facilitates variants customizing using modules removal, addition and switching. The interactions among components are the driver for grouping components into specific modules. The main objective of components clustering is to maximize component integration within each module and minimize interactions among modules.

This paper presented a new clustering model that uses cladistics, a hierarchical classification tool commonly used in biology, to 1) find the architecture structure of analyzed product design, 2) group product components into the optimum number of modules, and 3) specify the best granularity level of the system that minimizes the overall interactions between modules and subassemblies at all granularity levels.

A case study of 38 sheet metal parts to be welded together to form an automotive Body-in-White (BIW) is analyzed using the new model. Results showed that: 1) Hierarchal clustering of products using cladistics is able to reveal their architecture, 2) the new model determines the optimal granularity level of the system, 3) Modularity results, based on the new model, are superior to those reported in literature.

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Developing Modular Product Families with Perspectives for the Product Program

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Abstract. Reducing internal variety is a major challenge for industrial enterprises. Several approaches have been presented in literature supporting the development of modular product families in order to accomplish variety reduction. The Integrated PKT-Approach for Developing Modular Product Families integrates aspects of design for variety with technical-functional and product - strategic modularization methods. It furthermore proposes how to embed product family development into a holistic strategy for the specific corporate product program.

Keywords: Product family, product program, design for variety, modularization.

1 Strategic Background of Product Family Development

The product development phase determines to which extent a product meets the challenges of modern market situations. It is important to address contradictory requirements and to balance compromises. Globally intense pricing competition as well as the megatrend of individualization is reflected in the conflicting customer requirements of low prices and personalized, highly variant products. These requirements result in two product development strategies. On the one hand, the aim is to develop standard mass-market products to offer competitive prices - the focus being on the advantage of large quantities of the same products. On the other hand, to be able to make a profit, a high number of individualized products can be a successful way to meet individual customer requirements. Both strategies involve chances and risks. In product development, the strategy of developing modular product families is a promising way for combining the advantages, such as individual customer demands, with low costs, to offer competitive and robust product programs.

2 An Example of a Product Family

A family of herbicide spraying systems is used to demonstrate the use of tools and methods in the following. The MANKAR-Roll family by Mantis ULV consists of Ultra Low Volume (ULV) Spraying Systems that enable eco-efficient distribution of

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herbicides. The existing product families consist of twelve actively advertised variants as well as 24 additional variants provided on special request (Fig. 1). For example, these variants adjust the spraying systems to the individual application conditions of the customers working within professional in-row cultivations or public places via different spray widths or sizes of wheels.

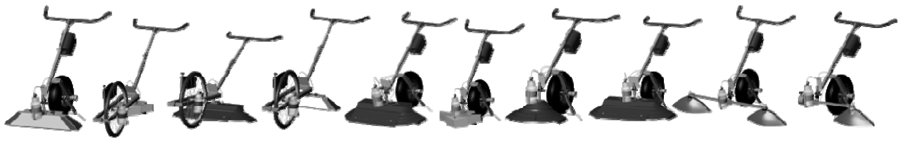

Fig. 1. Product variants of the product family of herbicide spraying system MANKAR-Roll [1]

3 Methods Supporting the Development of Modular Product Families

To support the development of modular product families different scientific approaches have been developed. Approaches on modularization deal with the regrouping of product components either according to technical-functional (e.g. [2] and [3]) or according to product-strategic (e.g. [4]) module drivers. Product variety is reconsidered more detailed in approaches on design for variety (e.g. [5]) as well as in product architecture approaches (e.g. [6]). Researching these approaches in theory or even by partly conducting them in workshops with industrial practitioners and students as well as applying them on industrial examples, experiences on their convenience could be gained. Fig. 2 (left) shows how the Design Structure Matrix [2, 7] is applied to the herbicide spraying system. Spatial, energetic, informatics and material couplings between all components are allocated. The matrix is then re-sorted so that the couplings are shifted to the diagonal. This forms clusters that indicate possible modules. The DSM is a powerful tool in understanding the technical-functional conditions for a modular structure. It was enhanced by integrating the view of organization in Structural Complexity Management using even matrices to analyze the couplings between people and documents in the company [8]. The Module Indication Matrix (MIM) as a tool within MFD [4] deals with product-strategic module drivers, describing the strategic reasons why components should be integrated into modules. Fig. 2 (right) shows an example of the MIM applied to the family of herbicide spraying systems. Here the components are allocated to the module drivers that they are affected by. Modules are designated as components sharing similar module drivers or module driver patterns. Experiences in workshops and case studies showed that method users appreciate and need the support that both tools (DSM and MIM) provide in understanding technical-functional and product-strategic module drivers. However, when working with matrix-based approaches, product related visualizations that enable more intuitive perception are missing. The methods give no direct indication of how to reduce component variety within the product family.

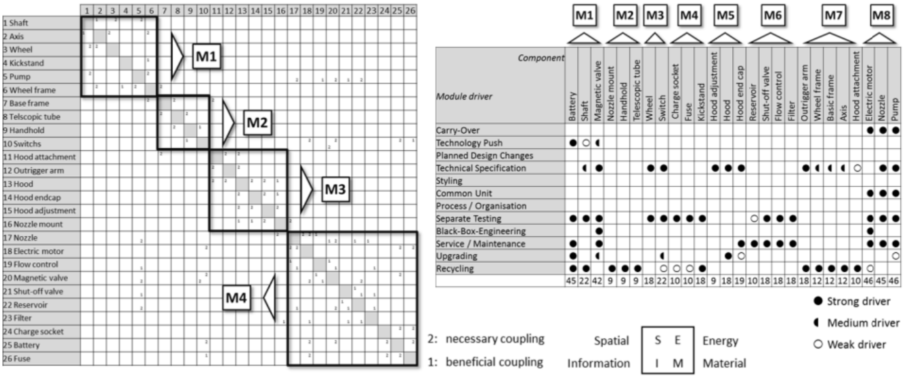

Fig. 2. DSM (left) and MIM (right) of the family of herbicide spraying systems

4 The Integrated PKT-Approach for Developing Modular Product Families

Combining the strengths of the approaches analyzed before and reacting on potential weaknesses, the *Integrated PKT-Approach for Developing Modular Product Families* [1] was developed at the Institute PKT at Hamburg University of Technology (TUHH). This approach for reducing internal variety has the following aims:

- Combining the product-oriented view with the process-oriented view of product program variety
- Integrating technical-functional and product-strategic module drivers along the product life phases
- Redesign of components to enable a variety-optimized product structure
- Fostering team discussion and integration of experts by specific product family related visualizations
- Support for reducing variety tailored to corporate needs.

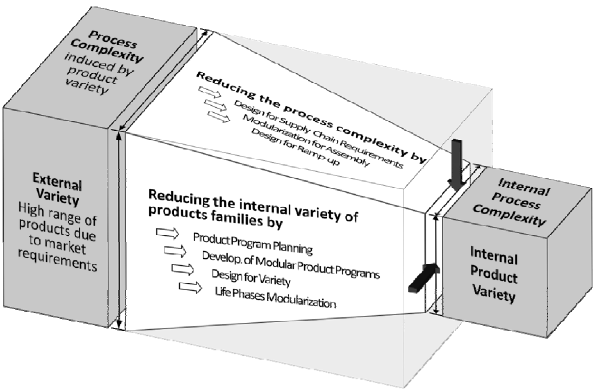

Fig. 3. The Integrated PKT-Approach for Developing Modular Product Families [9]

Several method units are integrated within an approach reaching towards that aim (Fig. 3). Two of them, *Design for Variety* and *Life Phases Modularization*, are presented below. In section 5 tools for *Product Program Planning* and the *Development of Modular Product Programs* are described.

4.1 Design for Variety

Design for Variety [10,11] aims to bring the product families closer to an ideal of a variety-oriented product structure derived from literature research:

- Clear differentiation between standard components and variant components
- Reduction of the variant components to the carrier of a differentiating properties
- One-to-one mapping between differentiating properties and variant components
- Minimal degree of coupling of variant components to other components.

In the first step of the method, the external market-based and internal company v arieties of the product family are analyzed. A Tree of External Variety (TEV) aids analysis of the external variety (Fig. 4). This tree visualizes the selection process of the customer by linking variant product properties relevant to customers and the offered product variants.

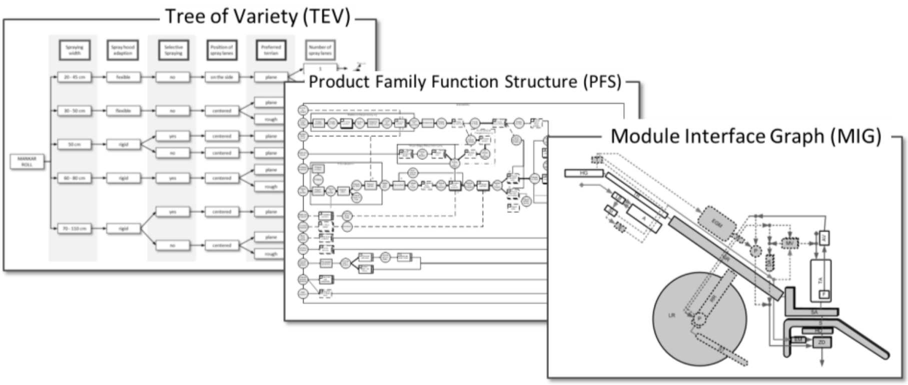

Fig. 4. Tools for the analysis of product variety [9]

Internal variety is analyzed at the levels of functions, working principles and components. The variety of functions is shown in the Product Family Functional structure (PFS) that makes representation of variant and optional functions possible. The Module Interface Graph (MIG) is used to visualize and analyses the variety of components and connecting flows (Fig. 4). All this information is visualized in the Variety Allocation Model (VAM, Fig. 5). The connections between the four levels demonstrate the allocations between differentiating properties, functions, working principles and components. In this way, the VAM allows analysis of the degree of fulfillment of the ideal of a variety-oriented product structure described before. For variant conformity, any weak points in the design can be identified at all levels of abstraction. Thus, the VAM is the basis for solution finding. In Fig. 5 (left) the differentiating property 'Selective Spraying' influences various functions, working principles and components that were influenced by other differentiating properties in turn. Realizing this property via a magnetic clutch instead of a magnetic valve a solution was found with fewer interdependencies between the differentiating properties (Fig. 5, right). By this multiplication effects of variance are avoided, with the result that each component is required in only a small number of variants and configuration of the product family is simplified.

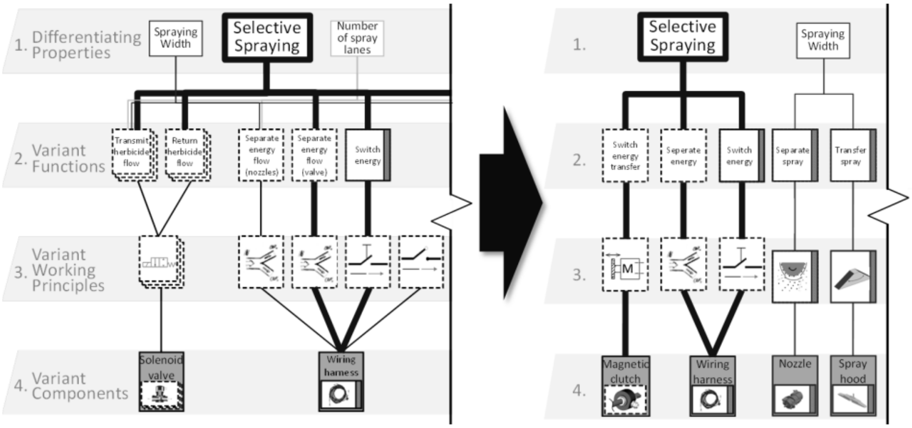

Fig. 5. Applying the Variety Allocation Model (VAM) as a tool to optimize the product family of herbicide spraying systems [9, 10]

4.2 Life Phases Modularization

Life Phases Modularization [10, 12] transfers the results of *Design for Variety* for each relevant product life phase to a continual module structure, while checking consistency and adjustment. Product family structure requirements can be better met by considering different product family structures for individual phases. The procedure is divided into the following steps:

1. Development of a technical-functional modularization
2. Development of modularizations for all stakeholders and product life phases
3. Combination of modularizations
4. Derivation of the modular product family structure.

The starting point is the technical-functional modularization of the product development phase. Modules are provided that are largely decoupled to reduce the complexity of the development task and allow parallel development of modules. Technical functional approaches (Section 3), such as that described by Stone [3] or the DSM [2,7], can be applied at this step. The development of modularization perspectives for all relevant product life phases is made by module drivers associated with individual life phases. For instance, the production phase is mapped by the module driver 'Separate

Testing' (Fig. 6). The module drivers are a concept known from Modular Function Deployment (Section 3, [4]) that has been supplemented with concrete specifications to develop modules. For the module driver 'Separate Testing', the tests carried out demonstrate the product-specific specifications. In network diagrams, these specifications are linked to the components of the product. The preparation of modules is made by grouping the components that relate to a common module driver specification into one module. Subsequent to the development of modular product family structures for the individual life phases, the modularizations are visualized in a MIG to check consistency between life phases and find conflicts. It was found that the same module structure cannot be realized for all life phases because of the contradictory criteria. It is important that the module structures of the individual phases are adapted and continuous but not 100 % congruent. For assembly, it may be advantageous to install a module that is as large as possible. For purchase, it may be necessary to buy this module in the form of smaller modules from different suppliers which, in a well-adapted structure, must not be contradictory. The Module Process Chart (MPC) transparently combines the perspectives of different life phases and makes the coordination process more clear (Fig. 6).

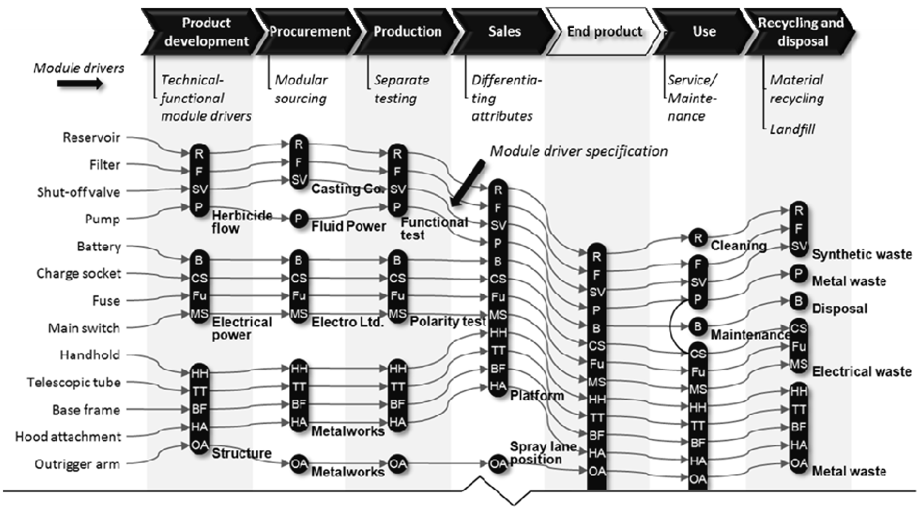

Fig. 6. The Module Process Chart (MPC) as a tool for allocating module drivers and module driver specifications to modules [10,12]

4.3 Results from Industrial Application

The redesign of a family of herbicide spraying systems by the method units *Design for Variety* and *Life Phases Modularization* led to a new product family concept based on 32 instead of 46 components in total (reduction of 31%). The number of variant components was reduced from 31 to 14 (reduction of 55%). Fig. 7 (left) shows how the new product family concept enables easy configuration. Furthermore the MIGs of the existing and new product family concept (Fig. 7, right) show which components were standardized (white). Similar results were achieved in six further industrial case studies that were performed for evaluating the approach (Fig. 8).

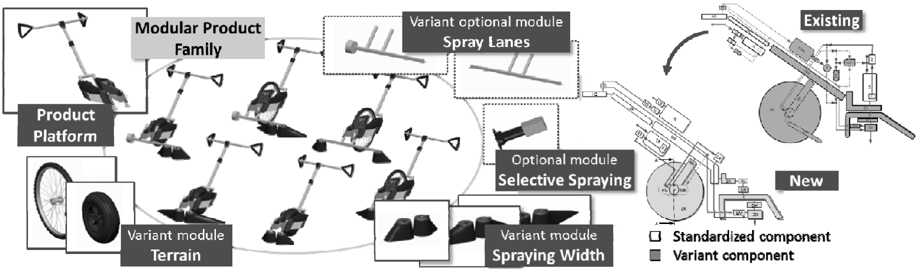

Fig. 7. Configurational concept of the new product family of herbicide spraying system (left) and MIGs showing the optimization of component variety (right) [1]

For the total number of components the product families consist of, a reduction of 52% could be gained in average. In average 85% of product family components were variant before and only 48% after the optimization. The share of standardized components was enhanced from 15% to 47% in average. Performing evaluation in industrial case studies further need for research was identified concerning applicability and usability of the integrated PKT-approach [13]. A major need of the companies is to open the focus of activities for reducing variety from focus on single product families to a holistic corporate product program strategy.

		Herbicide spraying systems	Displays	Operation devices	Fork carrier	Gas inlet valves	Hatracks	Gas detection devices
Components in total	Existing	46	83	73	49	53	21	37
	New	32	17	28	28	22	13	27
Variant components	Existing	31	82	71	43	47	21	19
	New	14	12	13	19	9	4	14
Standardized components	Existing	15	1	2	6	6	0	18
	New	18	5	15	9	13	9	13

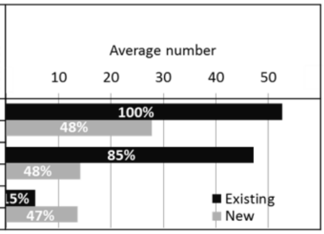

Fig. 8. Achieved results in reducing variety of diverse product families (industrial case studies)

5 Perspectives for the Product Program

In order to gain a product program balanced between standardization and differentiation according to the specific corporate context, product family development needs to be embedded within a corporate product program strategy. This strategy is influenced by a market-driven product program planning on one hand and the development of modular product programs based on the carry-over potential on the other hand.

5.1 Product Program Planning

The method unit of *Product Program Planning* consists of two major phases [14]. The first phase uses a new portfolio model which shows hierarchy and economic key figures of the whole program as a status analysis. The visualization called the Program Structuring Model (PSM) is shown in Fig. 9. In addition to the dimensions, traffic light colors can be added to represent the margin of each hierarchical level. After analysis of internal and external trend factors, scenarios to the future structure of the product program are elaborated in a workshop and visualized by the model. Based on the developed scenarios, in the second phase of the method strategic carryover-components are conceptualized to the product program. Aim of this phase is a maximization of potential carryover-components, internally of product families as well as crossing different product families.

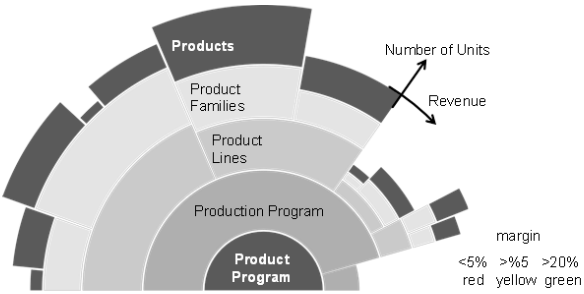

Fig. 9. Program Structuring Model (PSM) [14]

The developed carryover concepts are visualized in the Carryover Assignment Plan (CAP), Fig. 10. Outcomes of the method are the planned variety of the program represented by a TEV and product concepts including carryover-candidates visualized by MIGs. The outcomes represent also the modular product structure of the life phase "product planning". For the next step, the CAP gives the information whether carryover components can be realized rather within or across product families.

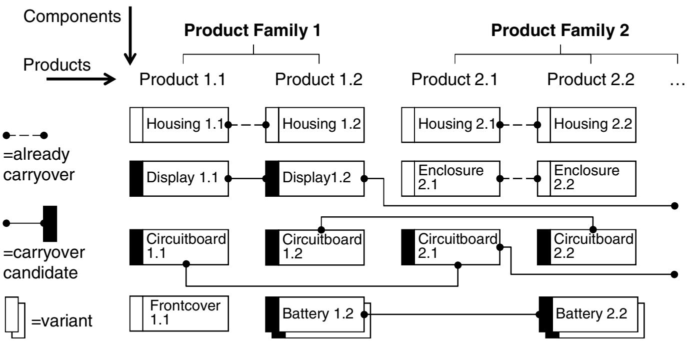

Fig. 10. Carryover Assignment Plan (CAP) [14]

5.2 Development of Modular Product Programs

There are different strategies how to develop a modular product program. Initially, activities can be subdivided into activities within and across product families. This helps to allocate and name different activities. These activities mean product design activities that raise product commonality. Depending on the product program, there might be high potential for product family internal commonality. In this case, it is recommended that a classical product family oriented platform strategy is followed (Fig. 11, left). Other product programs might have high potential for carryover of parts, components and modules across product families. They should be designed as a configurable modular system of smaller modules with a strong focus on carryover across product families (Fig. 11, right). A lot of product programs might show potential for both directions of commonality – within and across product families (Fig. 11, middle). During *Product Program Planning* this potential is analyzed using the CAP (Fig. 10) which gives direct indication for which product structure strategy the product program shows best potential to internal variety, see the indicator in Fig. 11. After choice of product structure strategy the design tasks can be performed accordingly within and/or across product families. These design tasks are performed as projects supported by *Design for Variety* and *Life Phase Modularization*, as described above.

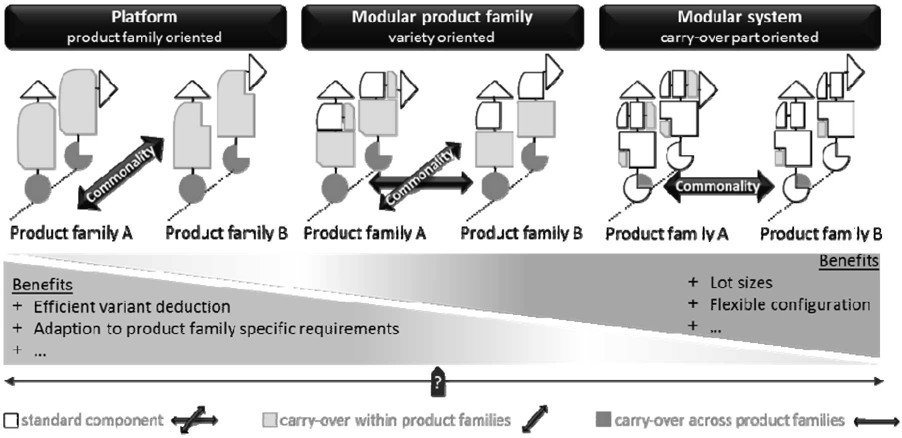

Fig. 11. Product structure strategies and indication of potential [15]

6 Summary and Prospects

Reducing internal variety is a challenge that touches all life phases of a product family, particularly product development. To give a support in product development the *Integrated PKT-Approach for Developing Modular Product Families* was derived from literature research and industrial case studies. The branch-specific knowledge, experience and creativity of a company's engineers are integrated using graphical tools to foster discussion and exchange of concepts. This is also supported by incorporating the method units into workshop-based procedures, focusing on interdisciplinary exchange within the company. In 7 case studies, a reduction in components of about 52% on average was achieved by applying the method units *Design for Variety* and *Life Phases Modularization*. Even more significant is the reduction from 85% to 48% in the share of variant components achieved. Method units for *Product Program Planning and Development* enable a market-oriented product program planning as well as choice of product structure strategy according to the specific corporate carryover potential. By this product family development is embedded within a holistic corporate strategy. In future the method units *Product Program Planning* and *Development of Modular Product Programs* will be evaluated through industrial cases.

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A Modular Dynamic Products Platforms Design Model

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Abstract. Mass customization is an effective means to economically produce the wide product variety that the market now demands. The product platform strategy has emerged as an important enabler, where common components used across different product variants are maximized to decrease design and manufacturing cost. A model for designing optimal products platforms was developed. It determines the best number, combinations, and composition of modular product platforms. It defines the optimum hierarchy of relations between the platform components and enables delayed product differentiation to achieve economy of scope. Unlike designing product platforms using common components, the new model enables customization of the platforms themselves to suit the dynamically changing and evolving product families. It uses a mathematical nonlinear and linear mixed integer programming approach. A case study of a family of touch screen computer tablets is used to illustrate the application and advantages of the newly developed dynamic product platform design model.

Keywords: Products Platforms Design, Modular, Dynamic.

1 Introduction

Products variety is increasing in response to customers' demands for new features and functionalities. This is in addition to fluctuating market conditions of supply and demands. Therefore, effective concepts and methodologies are needed to enable Mass Customization while keeping cost down and quality high in order to remain competitive.

The product architecture concept and its impact on industrial corporations were discussed [1]. A clear differentiation between Modular and integral product architectures were delineated and categories of modularity (such as slots, bus, and sectional types) were identified.

2 Literature Review

In the Product Platform Formation, the research field includes, but is not limited to, commonality measures and indices and optimization using different criteria (e.g. maximum commonality and minimum functionality loss). Platforms have been

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categorized depending upon modularity, scalability and functionality. defined Product Platform as a: set of subsystems and interfaces that form a common structure, from which a stream of derivative products can be efficiently produced and developed [2]. Another paper discussed the main concept of product platforms, but called it Product Families Architecture [3]. The authors clearly defined the concept of "Modular Product Platforms", which can produce different products by varying some modular components. described another platform type they called Scalable Platform [4]. A Compromise Design Support Problem Formulation was proposed to design a product family of universal electric motors by varying some scalable parameters. This method can provide motors with very similar structures but with variable performances.

Design Structure Matrix (DSM) method was used with a partitioning and genetic algorithms; to produce clear common platforms for complex products and groups interactions and applied it to Gas turbines, 22 cross-functional teams' communication in GM corporation [5]. A multi agent model was developed to solve the platform configuration problem, where the functional model of the product was the primary concern and the hierarchy and the precedence of the components were ignored [6]. This model does not handle large product families.

A non-linear mathematical formulation dealt with the multiple platform configurations problem was proposed; to configure single and multiple platforms by adding or removing components to the platform; to form the final product but unfortunately their results could not be replicated [7]. This model needs the number of platforms to be defined a priori and yields negative costs when the maximum number of platforms is reached. The model includes number of plane cuts which neither improve the solution time nor guarantees optimality. In that paper, this model will be completely reformulated to avoid all previous drawbacks. Then the concept of platform hierarchy will also be proposed to assist in the assembly of duplicate components that have multiple variants and/or different assembly positions.

3 Modular Products Dynamic Platforms Formation

Many products have a modular nature such as power tools, toasters, microwaves, computer tablets, and computers consist of numerous components and modules. Multiple products with different structure and specifications are produced by interchanging these modules and components to target different market segments.

The proposed model aims at combining different concepts into one holistic model. The concepts include: changeable product families [8], changeable product platforms [9], delayed product differentiation, simultaneous assembly and disassembly processes, and the newly proposed platform hierarchy concept. It employs an innovative concept of a "Changeable modular platform configuration" where some modules may be removed or added after initial assembly to maximize responsiveness to changing customers and market demands. The Dynamic Products Platforms Design Model (DPPD) is mathematically described next.

3.1 The Mathematical Model

As shown in Figure 1, the DPPD model describes many criteria which are considered crucial in the platform concept including the most recent criterion related to the hierarchy of the obtained platforms. Most platform design models in the literature discuss the product platform as a group of individual components without clearly defining the relations between the components of the platforms.

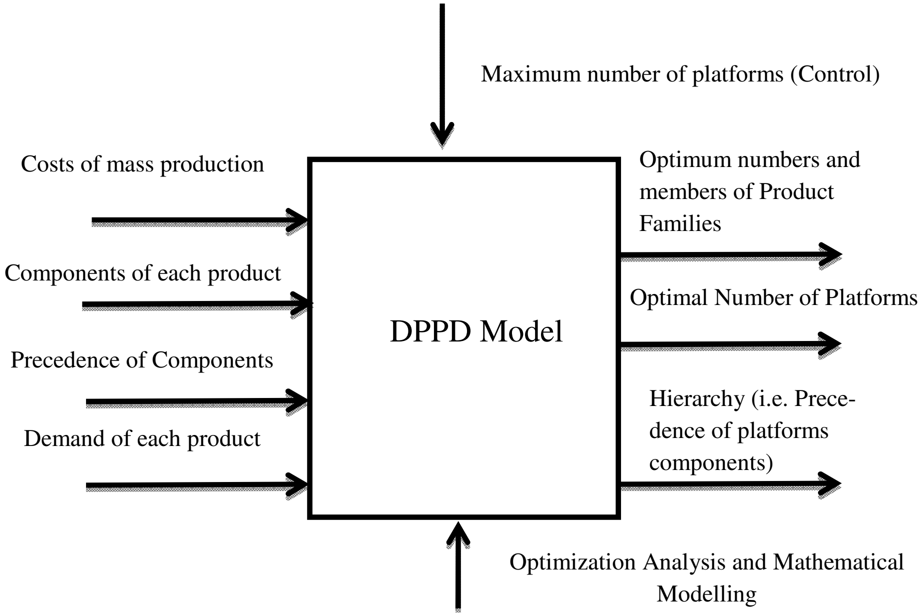


Fig. 1. IDEF0 of the Dynamic Products Platforms Design

The clear definition of the relations between platforms components is very essential especially when one component can be assembled in different places (i.e. bolts, nuts and specially designed parts). The objective function of the proposed model has four main terms:

- The first term describes the cost of the components and their mass production assembly.
- The second term describes the cost of adding components needed to obtain a new product in a manual station or stations that are not dedicated for mass production.
- The third term describes the cost of removing components needed to obtain a new product in a manual station or stations that are not dedicated for mass production.
- The fourth term is used to add cost for each platform if the platform is used (i.e. costs associated mainly with training workers on new assembly processes/ products)

The objective function (c) is the total cost of the above four cost items.

Assume that:

$cost_p$: Cost of assembling single component j into platform

c_d: Cost of component d

c_{ad} : Labor cost of the assembly of a component d to a platform in station that does other operations

c_{rd}: Labor cost of disassembly of a component d from a platform in station that does other operations.

c : Cost of labor training to assemble a certain platform.

M: large integer number

$$v_{jk} = \begin{cases} 1, & \text{if product k contains component j} \\ 0, & \text{otherwise} \end{cases}$$

$$P_{kjd} = \begin{cases} 1, & \text{if component j precedes component d in product k} \\ 0, & \text{otherwise} \end{cases}$$

The decision variables are:

$$y_{ik} = \begin{cases} 1, & \text{if product k is clustered to platform i} \\ 0, & \text{otherwise} \end{cases}$$

$$a_{ijdk} = \begin{cases} 1, & \text{if component d is assembled after component j in platform i to form product k} \\ 0, & \text{otherwise} \end{cases}$$

$$r_{ijdk} = \begin{cases} 1, & \text{if component d is disassembled from component j in platform i to form product k} \\ 0, & \text{otherwise} \end{cases}$$

$$p_i = \begin{cases} 1, & \text{if platform i exists} \\ 0, & \text{otherwise} \end{cases}$$

$$s_{ijd} = \begin{cases} 1, & \text{if component d is assembled after component j in platform i} \\ 0, & \text{otherwise} \end{cases}$$

The objective function is given by:

Min Cost c =

$$\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{d=1}^{m}\sum_{k=1}^{n}(cost_p + c_d)s_{ijd}\,y_{ik}d_k + \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{d=1}^{m}\sum_{k=1}^{n}(c_{ad} + c_d)\,a_{ijdk}y_{ik}d_k + \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{d=1}^{m}\sum_{k=1}^{n}(c_{rd})\,r_{ijdk}y_{ik}d_k + \sum_{i=1}^{l} cp_i \qquad (1)$$

The objective function obtained is nonlinear. This will significantly increase the time needed to solve real products and platforms with large number of components and products. Therefore, a basic linearization scheme is adopted from [10]. Each two binary variables are substituted by one variable (shown below) and two constraints (shown within the model itself) as follows:

$$zx_{ijdk} = s_{ijd}y_{ik} \tag{2}$$

$$zy_{ijdk} = a_{ijdk}y_{id} \tag{3}$$

$$zz_{ijdk} = r_{ijdk}y_{id} \tag{4}$$

Hence, the objective function will be:

Min Cost c =

$$\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{d=1}^{m}\sum_{k=1}^{n}\left(cost_p + c_d\right)zx_{ijdk}\,d_k + \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{d=1}^{m}\sum_{k=1}^{n}(c_{ad} + c_d)\ zy_{ijdk}d_k + \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{d=1}^{m}\sum_{k=1}^{n}(c_{rd})zz_{ijdk}d_k + \sum_{i=1}^{l}cp_i \tag{5}$$

Subject to:

$$Ms_{ijd} \geq zx_{ijdk} \tag{6}$$

$$zx_{ijdk} \geq y_{ik} + M(s_{ijd} - 1) \tag{7}$$

$$Ma_{ijdk} \geq zy_{ijdk} \tag{8}$$

$$zy_{ijdk} \geq y_{ik} + M(a_{ijdk} - 1) \tag{9}$$

$$Mr_{ijdk} \geq zz_{ijdk} \tag{10}$$

$$zz_{ijdk} \geq y_{ik} + M(r_{ijdk} - 1) \tag{11}$$

$$\sum_{i=1}^{l} y_{ik} = 1\ ,\ k = 1, \dots, n \tag{12}$$

$$a_{ijdk} + M(3 - v_{jk} - v_{dk} - P_{kjd} + s_{ijd}) \geq y_{ik} \tag{13}$$

$$a_{ijdk} \leq My_{ik} \tag{14}$$

$$r_{ijdk} + M(1 - s_{ijd} + P_{kjd}) \geq y_{ik} \tag{15}$$

$$\sum_{k=1}^{n} y_{ik} \geq p_i,\ i = 1, \dots, l \tag{16}$$

$$\sum_{k=1}^{n} y_{ik} \leq Mp_i,\ i = 1, \dots, l \tag{17}$$

$$\sum_{d=1}^{m} s_{ijd} \leq 2,\ i = 1, \dots, l \tag{18}$$

$$\sum_{k=1}^{n} y_{ik} \geq s_{ijd} \tag{19}$$

$$zx_{ijdk}, zy_{ijdk}, zz_{ijdk}, p_i, s_{ijd}, y_{ik}, a_{ijdk}, r_{ijdk} = \{0,1\} \tag{20}$$

Constraints 6 to 11 are necessary to linearize the three quantities ($s_{ijd}y_{ik}$, $a_{ijdk}y_{id}$, $r_{ijdk}y_{id}$). The set of constraints (12) ensures that every product belongs to only one family and one platform. Constraints set (13) assembles new component d to component j in a certain platform i to form product k, if components d and j belong to that product, and j precedes d in the original product precedence matrix, and not in the obtained platform. Constraints set (14) prevents assembling any component to a platform i, if the product k is not in platform i. Constraint (15) removes component d from component j in platform I to form product k, if the product is in the family served by that platform, and component d is not in product k. The existence of a certain platform and, hence, addition of its associated fixed costs is determined by constraints (16-17). Constraint set (18) is component and product dependent, where the constraint determines the maximum number of components that can co-exist (assembled) to a parent component. Constraint set (19) ensures that if a platform does not serve any product family then all its components should vanish. Finally, constraint set (20) forces all variables to be binary.

The newly introduced platform hierarchy concept in this paper needs a modification in the structure and hierarchy of data set of the products. Hence, in the proposed dynamic platform model, a new dummy component with zero cost is added to each product to enable the model to account for the first component in any given product (e.g. steel mid frame components in the following tablet's case study).

4 Case Study

A case study of touch screen tablets product family consisting of six product variants is used to demonstrate the developed dynamic platform formulation model. The tablets have different structures and different components, hence different precedence constraints as shown in Figure 2. The mathematical model was programmed using AMPL language and solved using CPLEX 11.2.1 solver. The inputs to the model were as follows:

- cost_p = \$2.5
- c_{ad} = \$4.25
- c_{rd} = \$4.25
- c = \$900
- Total demand (number of tablets to be produced) for the six products respectively = [9000 700 8000 400 9000 500]
- Maximum number of platforms = 1 and 6 (two scenarios were analyzed)

Figure 2 shows the precedence sequence for assembling the different components of the touch screen tablet family. The motherboard used has three different variations; the speaker is designed so that it has two different possible assembly locations: either after the assembly of the battery, or just after the power button. The dummy component is an imaginary component used to decrease number of terms and their complexity in the objective function. Table 1 enumerates the components used in each tablet, and their costs as well.

4.1 Discussion

The model was solved for single and multiple assembly lines. In the single assembly line, the product platform structure contains five main components: steel mid frame, power button, display, front panel assembly, and the speaker assembly in position 1.

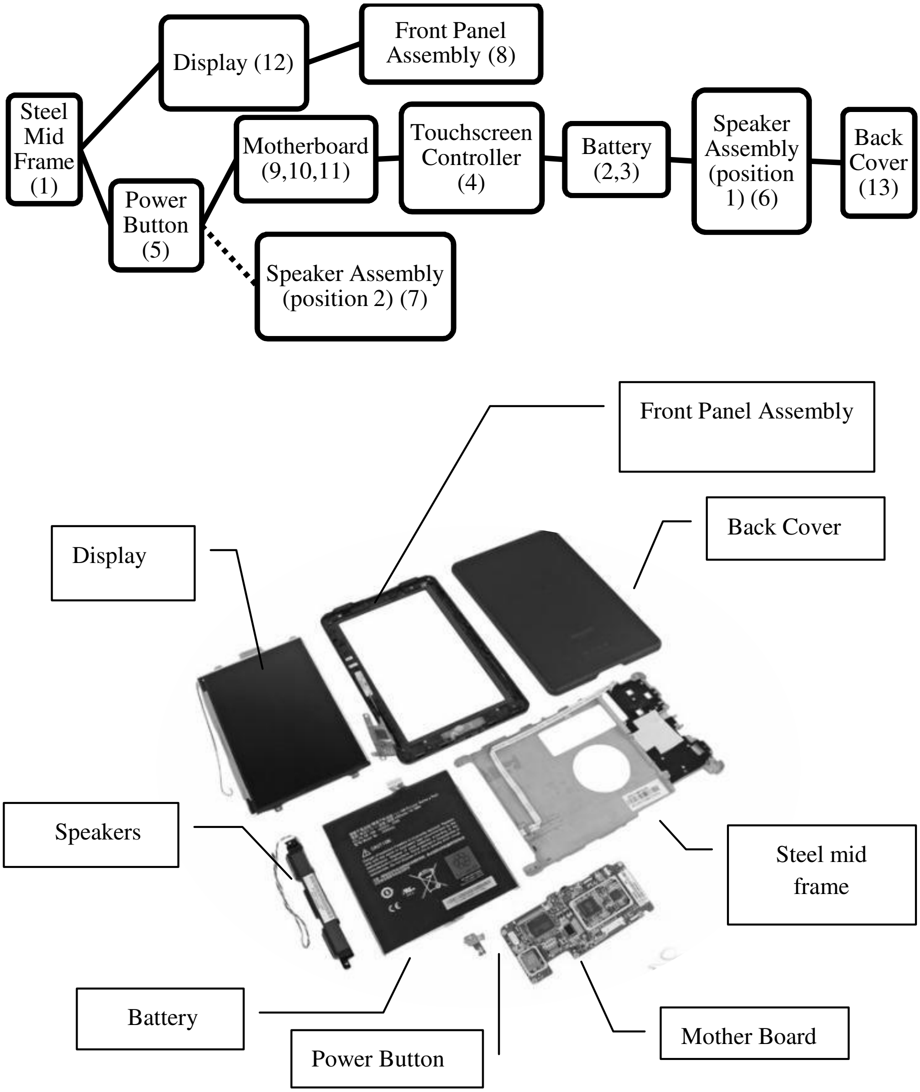


Fig. 2. General precedence diagram of the tablets family

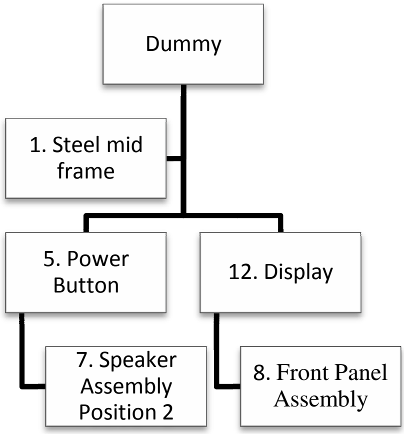
In Table 2, the model described clearly the position of the speaker assembly – since it had two positions – and decided to attach it to the power button. This is suitable for products 1, 3, 5. For products 2, 4, 6, the speaker assembly will be removed from its position and added after the assembly of the battery. Then, according to the composition of each product, the components will be added as the product platform advances through the assembly line. The next step is to allow the maximum number of components in the platform to be the total number of product variants. This increases the model flexibility in assigning the products to more platforms and assembly lines, to minimize the cost of products components, assembly, and disassembly. The total cost dropped by 2.89 % as a result. In that case, the model found that assigning each product to a separate assembly line is more economic than creating one unified platform for all of them.

This would be expected if the cost of initiating the assembly line is small compared to the expected cost of the components, mass produced platforms, and their combined assembly and disassembly operations. It is worth noting that by changing any input factor (e.g. product demand, assemblies' precedencies, and costs), all product platforms and product families change accordingly and evolve flexibly and easily. The obtained product platforms possess more shared components across the tablet family; this is the key to delayed product differentiation. Use of the model decreased the number of differentiating elements in the mass production phase, so the delayed differentiation process has become more efficient. The computation time using 3.12 Ghz Xeon Processor and 4 GB RAM computer was less than 1 second for the one platform, and less than 5 seconds for the 6 platforms, which proves the efficiency of the model and its potential ability to handle more complex products.

Table 1. Costs and composition of each tablet

		Cost($)	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
1	Steel mid frame	**4**	x	x	x	x	x	x
2	Battery 1 (4400 mAh)	**16.5**	x			x		x
3	Battery 2 (8000 mAh)	**30**		x	x		x	
4	Touchscreen controller	**3**	x	x	x	x	x	x
5	Power Button	**2.5**	x	x	x	x	x	x
6	Speaker Assembly Position 1	**10**		x		x		x
7	Speaker Assembly Position 2	**10**	x		x		x	
8	Front Panel Assembly	**42**	x	x	x	x	x	x
9	Mother Board 1 (default)	**64.5**	x			x	x	
10	Mother Board 2 (High memory)	**80**		x				x
11	Mother Board 3 (High storage capacity)	**90**			x			
12	Display	**45**	x	x	x	x	x	x
13	Back Cover	**6**	x	x	x	x	x	x

Table 2. One and multiple platform configuration

One Platform (i.e. one assembly line)	**Cost ($)**	**Maximum allowable Platforms (i.e. 6 platforms)**	**Cost ($)**
Platform Hierarchy for all products 	6459430	Each product has its independent platform (i.e. the product itself) and separate line of assembly.	6272630

5 Conclusions and Future Work

Innovative and efficient product platform design and assembly strategies are essential for enabling mass product customization. A new mathematical model was introduced to merge many different product platform design aspects using a new platform hierarchy concept for Dynamic Products Platforms Design (DPPD). It allows both the addition and removal of components / modules to satisfy customers and market demands. The model utilizes the principle of assembling components shared by most product variants, which can be disassembled later to produce different variants. It defines the optimum position of each component in the dynamic product platform. The merger of different aspects of the product platform design (precedencies, demands, costs, platform hierarchy and combined assembly and disassembly) enhances the efficiency of delayed product differentiation and increase the flexibility of forming product platforms from assembly costs perspective. For future work, different performance criteria (e.g. maintainability, torques, speeds... etc.) would be explored.

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Design Automation with the Characteristics Properties Model and Property Driven Design for Redesign

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Abstract. This paper presents a framework consisting of a mathematical model and an algorithm for representation, analysis and exploration of the design space in redesign problems. The framework develops and extends the existing formalism of the Characteristics Properties Model (CPM) and Property Driven Design (PDD). A platform independent quantitative model based on formal logic is presented to map the characteristics and properties, as well as the relations and dependencies between them, along with the necessary conditions for solution evaluation. The model is based on generalization of existing mathematical design models and is supported by the development of an algorithm enabling property driven design. The resulting framework offers a rich and flexible syntax and vocabulary along with a mathematical and computational tool applicable to mechanical product redesign.

Keywords: Redesign, first order logic, design automation, simulation based design, characteristics properties model, property driven design.

1 Redesign and Adaptive Design

Most design problems encountered in industry are related to redesign or adaptation of an existing product design [1]. Redesign, and adaptive design are common and widely practiced design tasks, wherein – starting from an existing solution – the designer creates a product to meet new requirement, needs and constraints [1]. The resulting product may be adapted for different requirements, or be an improved product version for the existing requirement. Redesign is also used for different versions of the product to address different segments in the market. With advances in the manufacturing systems, shift from mass production to customized production, and global markets with specific demands, adaptive design and redesign are increasingly practiced. This allows the company to better adapt its product with regard to performance, functionality, economic constraints or ethnographic preference, as required in a new market.

While most of the literature in product design addresses methodologies and methods for original design, the most common design activity remains to be redesign or adaptive design. The model presented in this article addresses these design problems

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and assumes that earlier information about the product is readily available in form of simulation based non-physical models and the solution principle and design space is well understood from previous experiences in similar projects.

CPM/PDD is conceived with goals of consolidation of the knowledge from design theory and methodologies; integration of existing models and strategies into a common framework; facilitating the integration of simulation based design and design automation in everyday design activities of practitioners [2]. The resulting ease of formalization of CPM/PDD due to consideration of these elements lends itself to the possibility of adapting it for the application in redesign problems.

The degree of abstraction and detail in redesign tasks is significantly different from other design tasks. Redesign is characterized by a high level of concreteness exhibited by detailed models with quantifiable characteristics resulting from the existing product documentation or design experience. In a redesign task information from earlier design project(s) is available, providing an idea of the design space already explored, which may be used to enhance the search for alternative solutions. The CPM/PDD framework can be developed and extended to provide a formalized support for design simulation and automation for such redesign problems. The following sections in the paper respectively provide an introduction to CPM/PDD model, a systematic, mathematical and logical CPM based model for modeling redesign and an algorithmic iterative method for carrying out design space search for the solutions to a redesign problem at hand. Further, an illustrative example is presented.

2 Characteristics Property Model and Property Driven Design

The *Characteristics-Properties Modeling* (CPM), respectively *Property-Driven Development* (PDD) approach is a rather recently developed approach to systematic product development [2, 3]. Therein, CPM comprises the product model, while PDD embodies the systematic scheme for the process of product development. The approach specifically aims at integrating knowledge about design from well-established design theory as well as existing modeling approaches and techniques into a common framework. Formalization is endorsed, so as to ease implementation in computer-based tools.

The fundamental characteristic of the approach is the clear separation between *characteristics* of a product and its *properties*:

- **Characteristics (C_i)** "describe the shape and the structure of a product (e.g. geometry, BOM, materials etc.) and can be directly established, assigned and modified by the designer";
- **Properties (P_j)** "describe the current behavior of a product (e.g. weight, manufacturability, function, cost, user friendliness etc.) and cannot be directly established by the designer; they can only be indirectly influenced by changing the depending characteristics" [4]. They are the indicator of the actual performance of the product, resulting from a given set of characteristics.

- **Required Properties (PR_j)** describe the properties that have to be fulfilled by the designed artifact. Required properties are the reference values which are fixed while considering a customer's preferences.

Product development strives to define a set of product characteristics such that the established product properties are sufficiently close to a set of required properties ($\mathbf{PR_j}$), i.e. the difference $\mathbf{\Delta P_j = RP_j - P_j \rightarrow 0}$. Thus, minimization of $\mathbf{\Delta P_j}$ is in fact driving the development process.

Relations ($\mathbf{R_j}$) relate the characteristics to the properties through the laws of physical behavior and tangible/intangible principles. Relations may be deduced from physical objects (models, mockups, and prototypes) or they may be made in a non-physical model (mathematical, numerical, computer-based, graphical, etc.). They may be differentiated in:

- *Analysis*: Based on a set of known or given characteristics (structural parameters) the respective embodied properties are analytically determined through e.g. experiments, simulation, calculations etc.
- *Synthesis*: Based on a set of given ($\mathbf{P_j}$) or required properties ($\mathbf{RP_j}$) the product's specific characteristics and corresponding values are established. The designer may use calculation, tables, catalogues, experience etc. in order to determine the specific characteristics, to achieve the desired properties.

In Figure 1 these two basic relations are modeled. Dependencies ($\mathbf{D_x}$) address the interdependencies between individual characteristics. External conditions ($\mathbf{EC_j}$) need to be respected during the analysis and synthesis, as they directly constrain the available solution space.

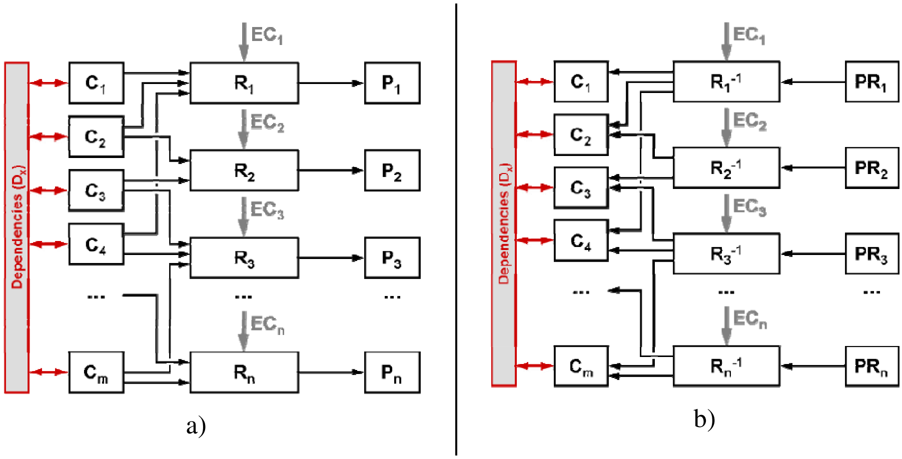

Fig. 1. Model of the central analysis a) and synthesis b) steps, after [2]

The starting point of PDD (i.e. application of the described CPM theory) is a comprehensive requirements list, based on which the required properties (**RP$_j$**) are derived. The product characteristics and respective values – embodying the product properties – are gradually established, in order to meet the required properties. Essentially, this is facilitated through synthesis steps. Synthesis is thus regarded to be the essential activity during product development. However, in PDD, synthesis is frequently accompanied by analysis and evaluative steps to give more and more precise information about the conceived product's properties (function, behavior etc.).

3 Mathematical Characteristics Properties Model for Redesign

Different mathematical models exist in literature on modeling in design. Often these models describe a specific task with a specialized context and application and provide no link to a general framework in the design theory and methodology. Yvars [5] models the parametric design activity during detail design as a constraint satisfaction problem in the form of $\{V, D, C\}$. Modeling of the parameter design and robust design activities has been proposed by different authors [5–8]. Dantan et al. [9] propose a model which enables specification, modeling and analysis of tolerancing activities using a model based on quantifiers ("there exists, $\exists$" and "for all, $\forall$").

A generalization of the above models (discussed in the previous paragraph) is possible by extending the definition of the quantifiers as given by Dantan et al [9]. An extended design model for redesign problems using the available syntax of formal logic can be formulated and applied to CPM. The notion of predicates and conditional evaluation available in formal logic can be extended to model relationships between different parts of the CPM as described in the preceding section. The following section describes the model in detail with relevance to the parameter design of mechanical systems.

3.1 Changes to CPM Nomenclature

To facilitate the mathematical expression, the nomenclature of the CPM as described in [2, 3] is modified as follows. The mathematical representation of the individual characteristics C_i , properties P_j , relations R_k , dependencies D_x and external conditions EC_n are henceforth used in italics instead of upper case letter. The upper case denominations will henceforth be utilized for sets of individual terms as described below.

3.2 Mathematical Model

The following text describes the general structure of the mathematical model of the characteristics properties model (mCPM). General definitions of the terms 'characteristics', 'properties', 'required properties', 'relations' have been described in the previous section. The following text defines these terms mathematically.

Characteristics

The state of information in the product design in the later design state is in a degree of maturity that it can be represented to a large extent through quantitative data sets. The characteristics c_i belong to the set of the characteristics of the model $\boldsymbol{C}$. Characteristics may be quantitatively represented in form of dependent and independent variables.

The characteristics are defined as:

$$\boldsymbol{C} = \{c_1, c_2, \dots, c_i\} \tag{1}$$

Each characteristic may be assigned one or a set of values which may be categorized into symbolic, numeric, discrete, or continuous type. From a viewpoint of definition, they may be categorized into symbolic or numeric, whereas from the viewpoint of continuity, these values may be categorized into discrete or continuous variables. Depending upon the nature of their value(s), a characteristic may be represented by a set or a tuple.

Properties

The properties p_j belong to the set of the properties $\boldsymbol{P}$. The set of properties is defined as:

$$\boldsymbol{P} = \{p_1, p_2, \dots, p_j\} \tag{2}$$

Required Properties

The required properties are the properties that are to be achieved in order for the design process to succeed. Required properties RP_j belong to the set of the required properties $\boldsymbol{RP}$ which is defined as:

$$\boldsymbol{PR} = \{pr_1, pr_2, \dots, pr_j\} \tag{3}$$

The type of values of each individual rp_i is same as the type of corresponding p_i.

Design Space

The characteristics are the variables to which values must be assigned. These assignments are taken from the design space. For redesign, this denotes the n-dimensional space in which the solution is to be searched. Parts of design space have been explored during the earlier design activity for similar products. It is not entirely known but a partial understanding of the space is present from existing solutions corresponding to their specific required properties. The design space is defined as:

$$\boldsymbol{D} = \left(d_{c_1}, d_{c_2}, \dots, d_{c_i}\right) \tag{4}$$

$$c_i \in d_{c_i}: c_{i_{min}} \leq d_{c_i} \geq c_{i_{max}} \tag{5}$$

where D is the starting domain for the design problem. It contains the existing solutions and the unexplored space that a designer intends to explore for possible solutions corresponding to the required properties.

Relations

Relations provide the fundamental quantitative boundaries to constrain the design space for the expected solution. A relation or a set of relations may be required to model a specific property. In case of non-physical models, the whole set of the relations forms the analytical model of the product which can then be evaluated for properties in the presence of the given required properties. From a mathematical point of view, the relations are a function of characteristics and properties. In order to facilitate design automation or simulation, they may include required properties in form of an equality or non-equality. They are represented as a set of relations $\boldsymbol{R}$ with individual relations r_i:

$$\boldsymbol{R} = \{r_{1,} r_2 \dots r_k\} \tag{6}$$

The relations may be of any of the following general types:

- Discrete i.e. of a catalog type, where choice between two or more discrete entities of numeric or symbolic nature is required;
- Continuous, where all the variables involved are continuous real numbers;
- Mixed, where both the continuous and discrete variables are present;
- Based on relational database necessitating the use of rule based database selection;
- Complex relations involving the use of expressions dealing with complex numbers; i.e. numbers having real and complex parts;
- The relations may be of explicit type or of implicit type.

The general form of relations may therefore be expressed as:

$$r_i = f(\bar{C}, p_i) : \bar{C} \subseteq C, p_i \subseteq P, f(\bar{C}, p_i) \in \mathbb{R}^\infty \vee \mathbb{C}^\infty \vee \mathbb{Z}^\infty \tag{7}$$

$$r_i = \begin{cases} IF \dots & THEN \dots \\ ELSEIF \dots & THEN \dots \end{cases} \tag{8}$$

$$r_i = \begin{cases} f(\bar{C}, p_i, rp_i) \leq 0 \\ f(\bar{C}, p_i, rp_i) \geq 0 \\ f(\bar{C}, p_i, rp_i) = 0 \end{cases} \tag{9}$$

The terms of sets with bar accent $\bar{C}$ denote that a specific relation may contain only a partial list of the members of that set. One or many relations may be required to model a specific property.

Dependencies

Each relation r_i contains a subset of characteristics $\bar{C}$ from the set C. The characteristics present in a given relation are dependent on each other as defined in a given relation. These dependencies may be established between the characteristics in a given relation or between the characteristics and the property being modeled by a relation. A dependency involving different characteristics may also be present across different relations. This is often the case making the design problem a multi-objective constraint satisfaction and optimization problem.

Solutions

The values of characteristics for which the relations are satisfied are declared to be a solution. This necessitates that these values should be from design space and the difference between $\boldsymbol{PR}$ and $\boldsymbol{P}$ should be the minimum acceptable. For a given design problem the set of solutions $\boldsymbol{S}$ may be defined as:

$$\boldsymbol{S} = \{s_{1,}s_2 \dots s_l\} \tag{10}$$

$$s_i = \{s_{c_1}, s_{c_2} \dots, s_{c_i}\} \tag{11}$$

$$\boldsymbol{s_i} \subseteq \boldsymbol{D}, s_{c_i} \subseteq d_{c_i} \tag{12}$$

Mathematically the condition for a successful solution is described as:

$$\exists s_i | s_i \subseteq \boldsymbol{D} \tag{13}$$

$$\boldsymbol{S} = \{\cup_{s_i \in S} s_i \vDash \exists \boldsymbol{C} \ \boldsymbol{R}(\boldsymbol{C}, \boldsymbol{P}, \boldsymbol{RP})\} \tag{14}$$

The above expression lays down the basis of the standard parameter design by verifying that for a solution to be valid, all the characteristics must have valid value(s) from design space and that all the relations must be satisfied according to the required properties.

Having defined the necessary mathematical elements for CPM and the conditions for a successful solution, the next section describes an algorithm based on PDD for rapid visualization of design space for the solutions.

4 PDD Based Design Space Search Algorithm

According to [3] the PDD process consists of four main steps:

1. Establish the required properties $\boldsymbol{RP}$ and selecting initial set of characteristics $\boldsymbol{C}$
2. Analysis of the properties $\boldsymbol{P}$ based on the assigned characteristics
3. Comparison of the calculated properties w.r.t. required properties $\boldsymbol{RP}$
4. Reducing the magnitude of difference vector between $\boldsymbol{RP}$ and $\boldsymbol{P}$

Based on these four steps, an algorithm is proposed to apply the CPM/PDD search for finding solutions in a design space via rapid visualization. The algorithm has been programmed in Mathematica® and is platform independent. It utilizes the mCPM model in conjunction with formal logic to search a given design space for a number of solutions that satisfy the required properties.

Fig. 2 illustrates the flowchart of the developed algorithm. The algorithm is divided into three main parts (1-3). Part 1 corresponds to the first step in PDD wherein the designer specifies the set of $\boldsymbol{PR}$ to be fulfilled. This is accompanied by linking them to the design space and a list of solutions known earlier. This results into the assignment of initial values to the set of characteristics. The algorithm then systematically divides the given design space into subspaces for the analysis of the characteristics. These steps are carried out via interval arithmetic and mixed integer programming and branch and bound technique.

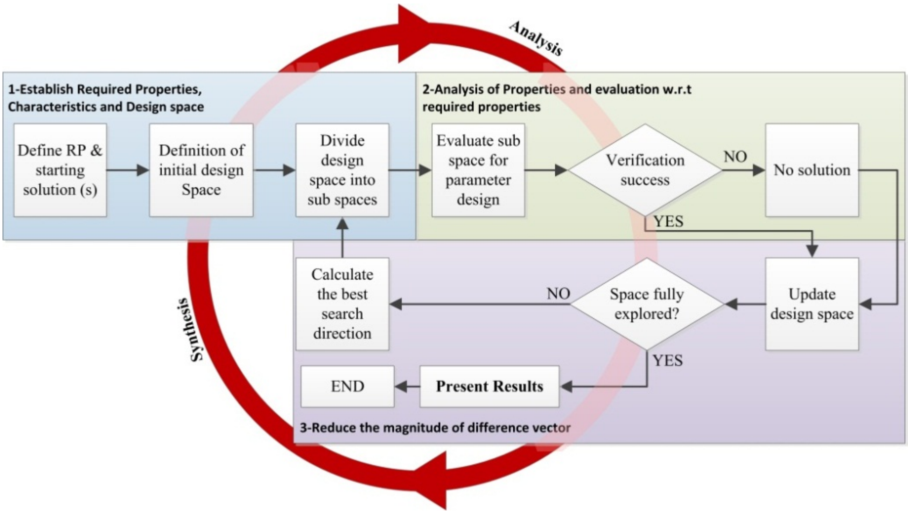

Fig. 2. PDD based design space search algorithm

The second step comprises the step 2 and 3 of PDD. Herein the algorithm analyses the subsets of the design space to calculate the properties via specified relations. These properties are evaluated against the required properties. The outcome of this step is the evaluation if the part of the design space under analysis holds a valid solution. The evaluation takes place by iterative application of equation 14. This requires evaluation of the quantified expressions. As the scope of this paper consists of parametric design therefore the algorithm is limited to resolution of existential quantifier only. This is resolved via optimization based constraint propagation as minimization or maximization of relations with inequalities.

The results from the step two are used in the step three of algorithm. This step corresponds with the last synthesis step of PDD. Results of the design space analysis are used to reduce the design space. The space without solutions is disregarded and the space with solutions is added to the set of solutions. The algorithm then proceeds to select the best direction to search for the properties. This is a directed search which prefers the direction according to the minimum distance between the required properties $\boldsymbol{PR}$ and the evaluated properties $\boldsymbol{P}$ of the analyzed design space i.e.:

$$\min_{diff}(diff\colon diff = |\boldsymbol{PR} - \boldsymbol{P}|) \tag{15}$$

The results of the algorithm are obtained in form of the explored design space which is stored and manipulated in form of an n-dimensional hypercube having dimensions equal to the number of the characteristics. For analysis, the parts of the n-dimensional hypercube may be projected to a 3 dimensional projection space, allowing the designer to visually analyze the solution space for the number of alternative solutions available. The alternatives can then be analyzed for the adaption to a certain preference via the information available in the hypercube. The algorithm can be programmed to run until all the design space is explored or until a given number of solutions are found.

5 Application

The developed framework is illustrated by an example problem of a structure design adapted from earlier research work (see [10]) as shown in Fig. 3. Contrary to the earlier version, the example is made complex by decoupling the dependencies between the two beams in terms of a fixed pin joint location and beam dimensions. The objective is to find out the values for the dimensional characteristics of two beams (length L_i, width w_i, thickness t_i : i=1, 2) as well as the positioning of the pin joints and materials to support a weight W). The example has 8 characteristics, 5 properties (system mass, max. stress, max. force, cost, and factor of safety) and 7 relations linking the characteristics to properties. The relations are non-linear and there is a strong dependency between the characteristics. The mathematical model contains continuous as well as discrete variables representing different characteristics and properties.

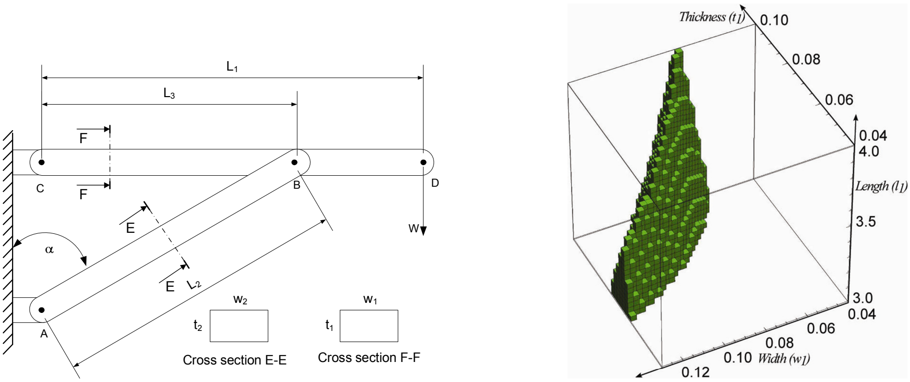

Fig. 3. Mechanical structure example with domain visualization

The white cube in the Figure 4 is the starting design space whereas the green cubes correspond to the parametric solutions. Starting from an earlier point based solution, a number of alternative solutions are generated that satisfy the required properties and allow the designer to choose the suitable solution.

6 Conclusions

CPM/PDD models products and product development processes in a flexible yet formalized way which is further developed in this paper for computer aided-design in redesign problems. These problems are routine design problems characterized by iterative design processes and activities to adapt an existing product to varying requirements with intensive CAx involvement. CPM is adapted for providing the basic product model and design process. However in order to apply CPM on CAx level, a mathematical model and an algorithmic process is required. This paper proposes a mathematical model and algorithm that intends to unify the two different views of design theory and methodology and computer aided design automation.

The model and algorithm developed in this paper is based upon a generalization of existing mathematical models. It is flexible and may be developed further to encompass other considerations such as robust design and uncertainty management.

The performance of the algorithm for using the model however currently depends heavily on the number of characteristics. Due to being a branch and bound method the computational complexity of calculation increases and results in high computational effort. It is currently being improved through direct integration with heuristic techniques. The model is also currently applicable only in situations of redesign and adaptive design i.e. where the design space is understood; where non-physical models (analytical/parametric/simulation based) can be constructed from the knowledge of the relations between different characteristics and the properties.

The model can also be further developed and integrated with other concepts in CPM to provide a unified view of different downstream activities in design such as parameter design, tolerance design and analysis, robust design and manufacturing process selection which are interlinked with each other.

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The Implications of the Skin Model Concept for Computer Aided Tolerancing

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Abstract. During product origination many deviations occur which manifest in unreliable functional behaviour and reduced product quality. Thus, the observable geometric deviations have to be limited by geometric tolerances of function-relevant part features. In this context the standards for Geometrical Product Specification and Verification (GPS) provide helpful tools for geometric tolerancing. A basic concept within these standards is the skin model concept which can be understood as a model of the physical interface between the workpiece and its environment. Recent research tries to translate this concept into discrete geometry and focuses upon the technical aspects related to generating skin model shapes, whereas the implications of this concept and emerging simulation possibilities for the geometric variations management process stay disregarded. Therefore, this paper highlights the consequences of the skin model concept and modern simulation tools for the computer aided tolerancing process and the management of geometric deviations during product development.

Keywords: Skin model, geometric variations management, tolerance management, computer aided tolerancing.

1 Geometrical Variations Management during Product Development

Geometrical variations management is an important issue in all phases of the product life cycle, especial in product design [1,2]. The main reason is that even though modern manufacturing processes achieve steadily increasing accuracy, geometric deviations are observable on every manufactured part, which are covered by the axiom of manufacturing imprecision and the axiom of measurement uncertainty [3,4]. These geometric deviations can have huge influences on the functional behaviour as well as the product quality. In engineering design there is therefore a necessity to manage and to control these geometric deviations along the whole product life cycle [5] and thus to limit the observable geometric

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deviations by geometric tolerances of function-relevant part features during product development. In this context it is acknowledged that approximately 70% of the manufacturing costs are related to insufficient tolerance requirements [6,7] since tight tolerances lead to high manufacturing costs due to additional manufacturing steps, slow and cost-intensive machining, and additional measuring expenditure [8]. Against this background, it is of high interest to identify tolerances which assure the functional behaviour of the product during use causing as low as possible costs. These activities, which can be referred to as tolerance management or geometric variations management, help to increase the competitive capability of modern quality-aware companies and should be integrated in a complete and coherent tolerancing process [5].

In order to assure cost-effective product design, manufacturing, and inspection as well as adequate product quality, the tolerance activities should be incorporated into the early conceptual design stage (following [9]) [1,10]. Quite few approaches have been developed for this, such as e. g. the Integrated Tolerancing Process proposed by Dantan et al. [1], a design synthesis process proposed by Roy et al. [11] and a concurrent design method for functional tolerance proposed by Heng at al. [10].

In these early engineering design stages only little information about the final product geometry is available, whereas in later stages of product development the whole part geometry is known and could be used for tolerance analysis. Nevertheless, this geometry information is not taken into account by many current tolerance analysis models since severe simplifications are made and the part deviations are reduced to dimensional and orientation defects [12,13].

However, nowadays computer aided tools support the product designer during product development as well as in many other phases of the product life cycle. Though, many of these established computer models for simulation and analysis disregard environmental impacts and imperfections of manufacturing processes [12], their accuracy and capability for taking uncertainties and geometric deviations into account steadily increases. This trend is challenging for product developers and organisations since the available tools need to be integrated efficiently within existing product development processes. Especial in computer aided tolerancing during product development where the allowable limits of geometric deviations have to be set and a huge cost responsibility is predominant, the application of suitable methods and their efficient integration into the tolerancing process is crucial [14]. Therefore, this paper proposes an approach for performing tolerance analysis in later design stages based on the skin model concept which is a basic concept of the standards for Geometrical Product Specification and Verification (GPS). Since this approach is based on the workpiece geometry, we denote it as an approach for *geometry-based* computer aided tolerancing.

This paper is structured as follows: in the next section the standards for GPS as well as the skin model concept are briefly highlighted. Thereafter, the proposed approach for skin model inspired tolerance analysis is explained. Following that, the ideas are illustrated in a simple case study. Finally, we summarize our results and give an outlook for future research.

2 Geometrical Product Specification and Verification

As mentioned before, the main aim of the tolerancing activities is to ensure the proper function of every manufactured product despite geometric deviations of its parts and to finally satisfy the customer demands by defining and setting limits for these deviations. For this purpose, the standards for Geometrical Product Specification and Verification [3] offer beneficial tools to the product developer for setting geometric tolerances and hence simplify geometric variations management.

2.1 The Concept of GPS

Geometrical Product Specification and Verification are standards for the description of workpieces, so that they can be manufactured and measured independently as single parts or assembly groups [3]. Certain requirements regarding the geometry of a workpiece or a number of workpieces are known as GPS that comprise size and dimensions, geometric tolerances and geometrical surface finishes [3]. However, the concept of GPS includes four different kinds of standards, different kinds of geometric features, workpiece features as a result of different manufacturing processes and different stages of product development [3].

2.2 The Skin Model Concept

The standards for GPS offer a toolbox for geometric variations management to the designer for defining the range of tolerable geometric deviations of a part's set of features. These allowed geometric deviations are adapted to the functional requirements of the part [3]. In this regard, a part is initially defined by its nominal geometry with perfect shape and ideal dimensions, which is called the *nominal model* (see Figure 1 (a)) and can be identified as a finite model [12]. However, the nominal model can impossibly be manufactured or measured, since every manufacturing process is inherently imprecise and every measuring process involves uncertainties [3,4]. Therefore, the *skin model concept* (see Figure 1 (b)) is developed within the GPS standards, which comprises the deviations brought in by manufacturing, measurement and assembly processes [3]. Hence, the skin model is a model of the physical interface between the workpiece and its environment [3]. It exists in the mind of the product developer and represents an infinite model [12]. It can be seen as a tool for the designer to envision the deviations of the part's shape as well as to set geometric tolerances.

Geometrical operations such as partition, extraction, filtration, association, collection and construction are required to obtain certain ideal or non-ideal geometrical features. These operations are the basis of the GeoSpelling model [2] and are also described and defined by GPS standards. They can be applied to the nominal model as well as to the skin model [3,15]. Based on this, a comparison procedure between the skin model and measurement results can be defined [3]. Here, parallel procedures of specification and measurement of manufactured workpieces are performed in order to check if the measured workpiece complies with the design intent [3].

(a) Nominal Model (b) Skin Model

Fig. 1. Difference between the Nominal Model and the Skin Model

However, the skin model concept itself is an infinite model and is not related to any kind of geometry representation [12]. Recent research activities, though, try to translate this concept into discrete geometry [4,16] and to create possible and realistic outcomes of the workpiece involving geometric deviations which may be referred to as skin model shapes. The idea behind creating these skin model shapes is visualizing manufacturing dependent geometric deviations and simulating their effects on the product behaviour during the later stages of the product life cycle. These approaches enable the product developer to identify critical design issues as well as the impacts of geometric tolerances and therefore help to optimize geometric variations management. In doing so, simulation models can be developed based on the skin model concept which can support the product designer in tolerance simulation as it is an important tool in product development [14]. But, however, so far no general framework for the integration of these approaches in the product development and tolerancing process, especial tolerance analysis, exists.

3 Implications of the Skin Model Concept on Computer Aided Tolerancing

The basic design tasks in geometric tolerancing are *tolerance specification*, *tolerance allocation* and *tolerance analysis* [17]. During tolerance specification, the questions of which types of tolerances are required and which datums and references should be used to ensure the proper function of the product have to be answered. During tolerance allocation values for these selected tolerance types have to be identified. Finally, a tolerance validation has to be performed in order to ensure that the selected tolerances and their values ensure that the product meets its requirements and conforms to the design intent. This validation is referred to as tolerance analysis. *Tolerance synthesis*, however, can be regarded as tolerance optimization taking into account inspection and manufacturing facets and is an iterative process of tolerance allocation, tolerance analysis and adjustment of tolerance values. Computer Aided Tolerancing tries to solve these highlighted tolerancing questions with the support of computer modelling and analysis.

Nowadays, the product design process and thus also computer aided tolerancing is still performed based on the nominal model [12], i. e. severe simplifications about the reality are made. This paper, thus, focuses on how skin model inspired simulation models could be integrated in computer aided tolerancing and how their application in tolerance analysis could be structured.

Since these approaches are based on the workpiece geometry, we denote them as geometry-based tolerancing, which starts as soon as geometric information about the workpieces are available (see Figure 2). The geometry-based CAT builds up on the design intent and the functional requirements just like the tolerancing process itself. Based on this information, tolerance specification and tolerance allocation can be performed. Thereafter, the tolerance analysis is conducted. For this purpose, skin model shapes, that are likely outcomes of the workpiece surface regarding the manufacturing process, are generated using either results of manufacturing process simulations or mathematical approaches such as e. g. proposed by Zhang et al. [4], Schleich et al. [16] or Stoll et al. [18]. These skin model shapes represent deviated shapes of the workpiece that fulfil all tolerance requirements, i. e. usually a virtual inspection routine has to be employed to ensure this. These skin model shapes are then assembled virtually employing assembly simulations, as for example developed in [18] or [19]. Furthermore, usage simulations employing finite element methods, elastic multibody simulations or similar simulation techniques are employed and applied to the single or assembled skin model shapes [20,21]. Due to this simulation chain, obviously, geometric deviations from all stages of manufacturing, assembly and use, which may lead to reduced product quality or malfunction, are represented and taken into account. Finally, the functional key characteristics are checked for conformance with the design intent and the functional requirements as explained in ISO 17450-1 where the simulation results can be considered as virtual measurement results. Based on this comparison, a conclusion whether or not the specified geometric tolerances (and even specified operating windows) assure the product function can be drawn. If it can be seen that all simulated assemblies pass the check for conformance then the specified tolerances can be added as functional tolerances. Otherwise, the tolerance allocation and maybe even the tolerance specification steps have to be repeated as well as the tolerance analysis.

This computer aided tolerance analysis procedure reflects the reality in this sense that possible outcomes of the workpieces are successively generated, inspected, and assembled. Thereafter, a functional check is performed whether or not the product fulfils the requirements. By adjusting the tolerances, the functional behaviour and the quality of the product can be influenced virtually. The capability of this approach, of course, depends strongly on the power of the simulation models employed for virtual manufacturing, virtual assembly, and virtual use. However, since the capability of computer aided engineering systems is steadily increasing, it seems to be only a matter of time until powerful simulation models and techniques for these purposes are available.

Furthermore, it should be mentioned that this approach does not depend on any mathematical tolerance representation or tolerancing standard. Of course,

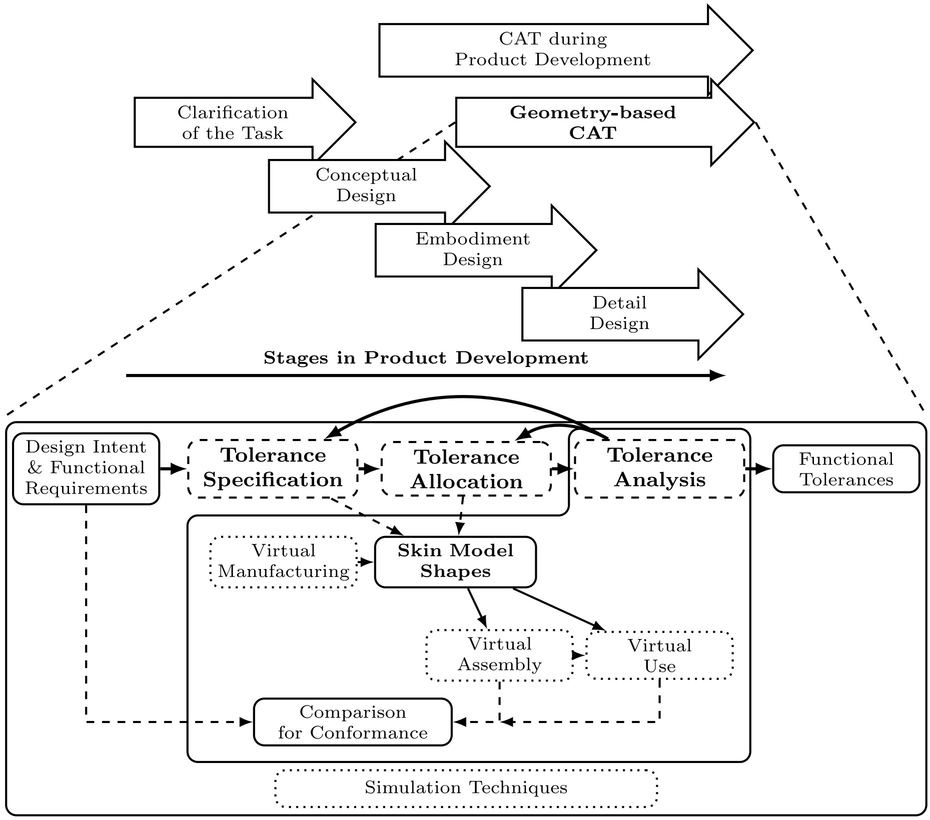


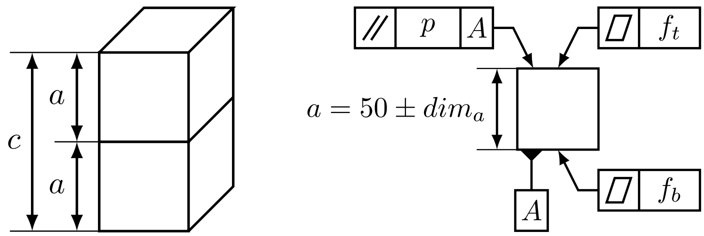
Fig. 2. Skin Model inspired Framework for Computer Aided Tolerancing

the generated skin model shapes have to be checked for tolerance requirements. In order to perform this, various tolerancing standards may be applied. However, the proposed general tolerance analysis procedure stays unaffected with regard to the selected tolerancing standards.

The application of a skin model based approach for computer aided tolerancing can decrease costly tolerancing errors in product development since it reflects the designers native view on the product origination process enabling the consideration of all sources of geometric deviations. It thus offers a contribution to integrated product development.

4 Case Study

The proposed skin model inspired tolerance analysis process is now illustrated in a case study. For this purpose a simple tolerance stack-up of two identical solid cubes as illustrated in Figure 3 (a) serves as an example. The functional key characteristic c is the height of the assembly consisting of both cubes.



(a) Tolerance Stack-Up (b) Specified Tolerances

Fig. 3. Example Assembly

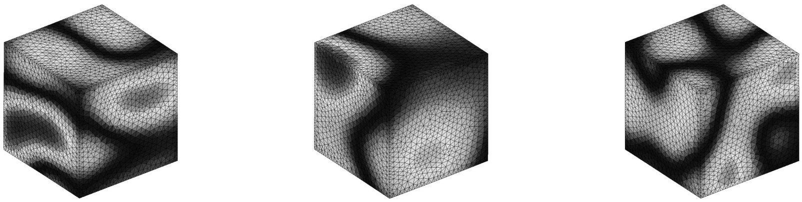


Fig. 4. Three Skin Model Shapes of the Cube

Some tolerances as can be seen from Figure 3 (b) are applied to the cube in order to assure the functional key characteristic c lying in an interval of $[100.00; 100.25]$.

The tolerance analysis procedure can now be performed based on skin model shapes. Firstly, we therefore create $N = 1,500$ skin model shapes of the cube employing a random field approach as e. g. proposed in [16], i. e. a surface mesh of the nominal part is created by a proprietary software tool and then deformed in the surface normal direction by spatially correlated random variables. For the Gaussian random field parameters we choose correlation lengths of $l_\rho = \{1; 15; 30\}$, a mean of $\mu = 0$ and standard deviations of $\sigma = \{0.1; 0.15\}$. The created skin model shapes are then virtually inspected in order to determine their geometric deviations. Figure 4 shows three skin model shapes of the cube where the grayscales indicate the geometric deviations. It should be mentioned that these skin model shapes show only random deviations. Systematic deviations, of course, are depending on the manufacturing process, which is assumed to be not known yet.

These skin model shapes are then assembled to obtain the assembly as shown in Figure 3 (a). In this case we use an assembly simulation based on the minimization of the convex hull volume between the cubes and perform $5,000$ assembly simulations where random skin model shapes of the population with $N = 1,500$ are assembled (note that we have $m = \frac{(N-1)\cdot N}{2} = 1,124,250$ possible assemblies). Thereafter, the functional key characteristic c of the assembly is measured. This measurement is performed by determining the maximum height of the assembly. Three exemplary results of the assembly simulation can be seen from Figure 5.

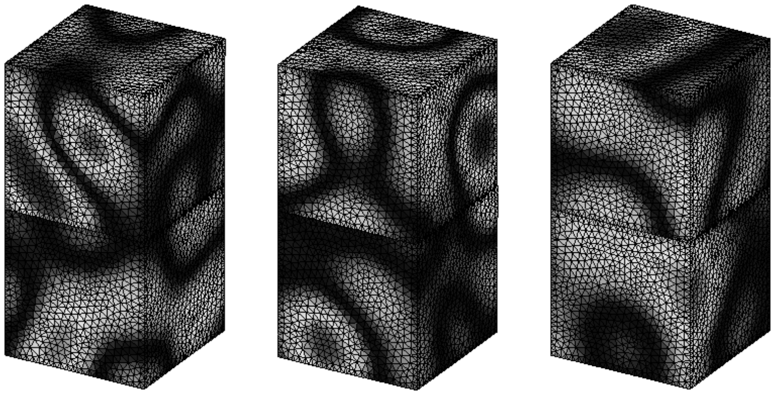
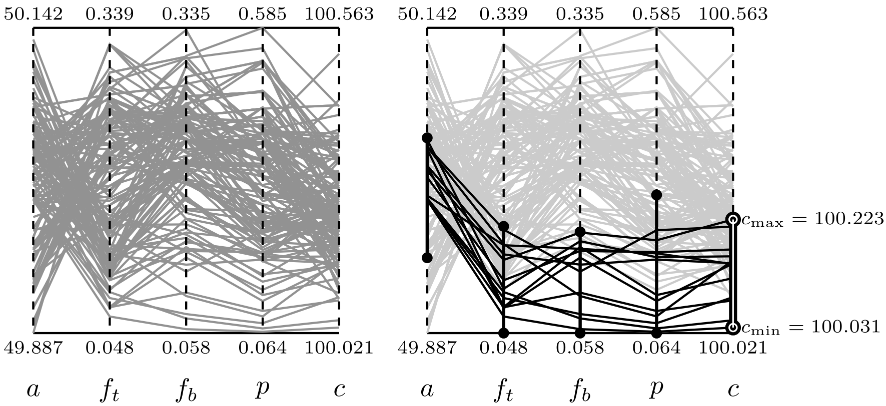


Fig. 5. Three resulting Assemblies



(a) No Tolerance Requirements (b) Applied Tolerance Requirements

Fig. 6. Results of the Case Study

Figure 6 (a) shows 150 randomly selected results where the tolerances and the resulting value of c are plotted in a so-called parallel coordinates plot. By defining values for the tolerance requirements, the effect of these specifications on the functional characteristic c can be determined. For example, if we choose values of $dim_a = 0.05$, $f_t = f_b = 0.15$ and $p = 0.3$, the functional characteristic c lies within an interval of $[\min(c) = 100.031; \max(c) = 100.223]$ (see Figure 6 (b)) and thus conforms to the original specification. It can be seen that the flatness tolerances f_t and f_b as well as the parallelism tolerance p help to assure the functional requirements. However, based on the proposed approach the effects of adjusting these tolerances on the functional characteristic can easily be analysed.

5 Summary and Conclusion

Geometric deviations are observable on every manufactured part. Since these deviations affect the functional behaviour of technical products, geometrical product specification is inevitable and tolerance specifications have to be set during product development in order to assure proper functioning and product quality targets. However, many commonly used tolerance analysis methods disregard form defects of workpieces and take only dimensional and orientation defects into account.

The skin model as a basic concept within the GPS standards as well as increasing capabilities in computer aided engineering such as sophisticated simulation methods change the established tolerancing models and processes. Therefore, a framework for geometry-based computer aided tolerancing is proposed which comprises the skin model concept and the related comparison for conformance as well as new simulation possibilities. This framework enables the product developer to integrate gathered knowledge and experience as well as modern simulation techniques into the tolerancing process. Furthermore, based thereon a straightforward tolerance analysis process is derived. The aim of ensuring the product quality by geometric tolerancing and variations management can hence be achieved more accurate and within a shorter period of time.

However, to develop an integrative tolerance simulation framework for computer aided tolerancing based on the presented ideas, various improvements in the field of tolerance simulation have to be accomplished in the future.

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Can a Pre-sketching Activity Improve Idea Generation?

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Abstract. This paper examines the influence of a pre-sketching activity on the quantity and novelty of the design solutions. A controlled experiment is used to investigate the influence of pre-sketching activity on quantity and novelty of the concepts. Two student groups sketched solutions for the same design problem; with one group given a pre-sketch activity before the design problem. Results reveal that this short pre-sketching activity positively affects the novelty of the solutions of the design problem (p-value=0.05 for novel means). Further, while the findings suggest that the pre-sketching activity resulted in more concepts generated, this was not found to be statistically significant (p-value=0.22). Therefore, it is recommended that idea generation methods be augmented with short pre-sketching activities before the sessions.

Keywords: pre-sketching, design experiment, idea generation.

1 Motivation to Study Idea Generation Activities

Several idea generation techniques support early stage conceptual design synthesis activities, such as brainstorming, brain sketching, C-sketch, Gallery method, and 6-3-5. Four metrics can be used to evaluate and compare different idea generation methods: quality, quantity, variety and novelty [1–3]. This paper explores novelty and quantity metrics as they are affected by the introduction of a “pre-sketching” activity to an idea generation session. Pre-sketching is a sketching exercise performed immediately before ideating on the actual design problem. This proposed augmentation to existing ideation techniques is based on the premise that sketching activities can have a positive impact on ideation. For instance, sketching allows the evaluation of design ideas in terms of level of creativity and enables designers to obtain feedback on their designs [4]. Graphical representations are preferred over textual representation based on the fact that they produce higher quality and novel ideas [5]. Previous experiments suggest that sketching and graphical representations increase the quantity of ideas [6]. The pre-sketching activity is used to “prime” the designer to be thinking visually when they are presented with the new design problem.

Researchers have explored the influence of using different idea generation methods on the quantity, quality, novelty and variety of solutions [7,8]. However, the influence that different types of sketching activities, such as sketching ideas for a novel design problem and sketching artifacts from memory, have on generating novel concepts for other design problems is relatively unexplored. Thus, this paper investigates the impact that pre-sketching activities have on the quantity and novelty of ideas generated by students. To this end, this paper focuses on these research questions:

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- What is the influence of pre-sketching activity on the quantity of design solutions?
- What is the influence of pre-sketching activity on the novelty of design solutions?

To answer these questions, a user study was conducted in a senior level mechanical engineering design class at Clemson University in the Fall 2011 semester. The class was divided into two groups of roughly the same number of students. One group was given a pre-sketch activity while the other group was not given any pre-sketch activity. The results from the two experimental groups are compared with respect to quantity and novelty.

2 Prior Research on Warm-Up Exercises

Researchers have studied the impact that various pre-exercises have on ideation. In one experiment, students were given pictures of toys/creatures and were asked to produce new toys/creatures by retrieving a picture from each category. The instructions emphasized both novelty and quantity. This research shows there was not a significant difference in the quantity but introducing examples can constrain generation of imaginative ideas [9]. In another experiment, analogical thinking was explored which showed that subjects can use a story analogy to guide generation of an analogous solution to the target problem [10]. The study suggests that analogical thinking may play a role in creative problem solving and provide information about the mental processes involved in analogical problem solving. In these two studies, examples were provided to students to determine the impact that analogy or fixation had on ideation.

Alternatively, others have studied how different types of training impact ideation and problem solving. In one experiment, students were given two unbalanced equations to balance them with coefficient as a warm up exercise and then given other chemical equations to solve. The results show that students learned how to rethink and change some features in their drawings to reflect on other equations [11]. Thus, graphical training immediately before an exercise had positive impact. The idea of doing "warm-up" exercises is common practice in athletics to prepare the body for the physical toll of the activities [12]. Here, we introduce an analog to these warm-ups through a pre-sketching activity to have the students practice the activity of sketching before addressing the design problem.

3 Sketching in Idea Generation

Sketching is considered the principal approach by which engineers visualize the solutions and it concretizes the thinking [13]. Designers sketch to externalize their concepts and where the drawings provide visual clues for refinement and revision [14]. Alternatively, one might define a sketch as a rough drawing that addresses one or more requirements in design. In engineering domains such as software, architecture, and mechanical design, graphical communication plays a key role throughout the design process [15]. Sketching facilitates the evolution of concepts into products, thereby having a positive impact on the quality of the solution as well as the designer [19].

In order to conduct empirical studies on ideation, one must address what should be measured and how it should be measured to evaluate the process or the outcome of the ideation [1]. Subsequently, much focus has been placed on evaluating the impact of sketching exercises on the designers. In one study, it was found that the quantity of sketches overall increases the likelihood of generated quality solutions [16]. Essentially, the sketches are used as quick surrogates for evaluating the potential for ideation and other design activities to generate solutions. Analyzing these sketches poses a challenge and thus researchers have developed wide variety of metrics that may be used for analyzing these sketches.

Quantity is most often measured while analyzing sketches [5,11], yet researchers count elements differently. For example, quantity might be a count of the number of distinct sketches generated [19,20] or it could be a count of only those sketches that represent solutions that satisfy targeted functions [8]. The quantity of ideas is important in creativity studies because it is a measure of fluency with the assumption that generating multiple ideas increases the chance generating better ideas [1].

Examples of other metrics include quality, novelty, and variety, but again they are used differently [5,7]. Novelty might be the frequency at which a complete idea is found in a collection [7] or it might be based on the unanticipated solutions to functions and sub functions [5]. Each of these different measures evaluates the solution found within the sketch, rather than on the sketch itself.

4 Experiment Design

This experiment evaluates whether a pre-sketching activity has impact on novelty and quantity of solutions generated. To this end, two groups of students from senior mechanical engineering (ME) design course were given a problem for which to sketch solutions. In addition, one of the groups was given a “pre” treatment where they were instructed to generate sketches prior to the idea generation session. Two hypotheses are tested: (1) the students who participated in the pre-sketching activity will generate a greater quantity of concepts than those with no pre-sketching activity and (2) the number of novel concepts from the experimental group will be greater than the controlled group. These hypotheses are an extension of [1]which suggest that any intervention influencing the designer or the design process will be reflected in the output. As a result, if the outcome is a greater number and more novel solutions, then it will be assumed that the intervention had a positive impact.

Many studies have been done using a population of undergraduate students for design activity research [9,11,27]. Therefore it is valid to use students for this particular study. Moreover, these senior students are less than five months from being considered practicing engineers or novices. Thirty-one students participated in this study. Characteristics such as personality, race, age, sex, or religion were out of scope for this study as students were randomly assigned to the experimental groups to avoid self-selection concerns. The students in this senior level class had previously completed the conceptual design phase of a semester long project to design wind tunnels for local elementary schools, thus giving the students similar baseline experiences in design. Finally the students who participated in this activity were given extra credit within the course to ensure appropriate levels of effort in the study. This type of in class activity is common in the course and was therefore not considered an intrusive activity for the students.

4.1 Sketching "Warm Up" Activity and Design Problem

The pre-sketch exercise administered to the experimental group was to sketch a dream home in Alaska. This problem was chosen based on its simplicity and familiarity to the students, to encourage flow of ideas and with the intention to "jump-start" the imagination of the participants. Specifically, it was felt that drawing a "dream home" in an "exotic" location would challenge the students without requiring them to address explicit design requirements. The activity was developed so it would not be another challenging design problem in itself, but rather an accessible sketching activity. The experimental group was not given detailed instructions on how to sketch or render the "dream home", allowing the students to provide perspective drawings, orthographic views or schematic drawings. They were given 10 minutes to complete the warm-up sketching task. The design problem (Fig. 1) give to both groups was to design a carpentry nail remover.

> While in his home workshop, a carpenter occasionally needs to remove an unwanted nail from a given project. For this project, the carpenter needs to remove a nail and replace it without causing damage to his almost completed project. Normally he might use the classic pry technique; however, the nail is in such a confined place that the pry will not work. The only angle he can approach the nail removal is along the axis of the nail. You are a designer at a Hobbyist Tools Inc. and have 30 minutes to design a nail removing device keeping the following requirements in mind. The device should: (1) Not damage the material, (2) Remove the nail parallel to its axis, (3) Remove the nail from a 4"x 4" space, (4) Be designed with a hobbyist carpenter's budget in mind, (5) Be designed for high production rates of a tool company, and (6) Not enlarge nail hole during removal

Fig. 1. Related Design Problem given to all participants

None of the students have seen this problem before in other design classes, though this design problem has been used in other experimental studies [24]. Thus, the scale and challenge of the design problem have been previously tested and found suitable for senior ME students. The problem does not have a current commercial solution (unsolved), yet is easily accessible in understanding for the students (familiar). All students in the course have completed the ME lab sequence that includes basic fabrication and woodworking. Therefore, they should be nominally familiar with challenges associated with removing nails from wood.

4.2 Execution

Students were drawn from the course. The experiment was conducted in familiar, though segregated settings, during the regular scheduled course time period. Thus, discomfort in unfamiliar settings was reduced in the experiment. Students had sufficient workspace to remove social inhibition. Students worked independently and were not allowed to talk. No additional sketching training was administered before the experiment.

The experimental group had 16 students and the control group had 15 students. Both groups were given thirty minutes to sketch solutions to the nail-removing problem. The students were not explicitly instructed to generate solutions based on quality, quantity, novelty, or variety to avoid biasing the results towards one of these metrics. After the instructions were given, students could ask clarification questions.

Each student was instructed to sketch only a single solution per page provided. A pilot run of the experiment suggested that a dozen sketch sheets would be sufficient for student idea generation within the given time period. All sketches, including the pre-sketch activity results, and a post-experiment survey were collected, though only the sketches generated were used for experimental analysis.

5 Protocol for Analyzing Design Solution Sketches

This experiment focused on quantity and novelty as metrics to analyze the sketches.. Quantity is studied to ensure that a pre-sketching activity does not negatively impact the number of sketches that are generated by designers. Novelty is the metric used to evaluate the positive impact of the activity. Variety and quality analysis are reserved for future studies. To test the hypotheses, the results of each group are compared.

Quantity is based on the total number of sketches generated for each individual as solutions to the nail removal design problem for both the controlled group and the experimental group. Each sketch was documented on a separate sketch sheet by the individual, allowing for a simple quantity count of each sketch sheet that was completed for each individual. Only pages with sketches that addressed one or more requirements were considered. For example if a page contained a drawing not related or addressing the problem statement, it was not added to the count.

Novelty is defined as an unexpected idea that satisfies one or more requirements of the design problem. Novel solutions are sought in idea generation methods as they can help designers to shift from evolutionary to revolutionary design. To objectively evaluate the sketches generated by participants for novelty of solutions, a protocol was defined to score each sketch according to how novel specific elements of the sketch are. In this protocol, similar to that of [5], a collection of predicted solution fragments for the defined set of requirements in the nail removal problem, are developed a priori to avoid biasing. These fragments are represented in a morphological matrix (Table 1). The collection was drawn from the previous experiment using this design problem [24] and augmented by the authors. The sketches generated by the students are compared against the means in the morphological matrix. A fragment in a sketch that could not be mapped to one in the chart is deemed "novel". Each sketch has a novelty score as the sum of the number of novel fragments found with a maximum score of five.

Table 1. Morphological Chart for Novelty Concepts

Sub-Functions	**Means**				
Secure Head of Nail	Adhesive	Magnet	Matching Drill Bit Size	Claws	
Generate Axial Force	Power Screw	Hydraulic or Pneumatic Piston	Manual Rotational Motion	Ball Screw	Human Force
Apply Axial Force	Linear Guide	Linear Bearings	Gear	Pushing Nail	Lever
Adjust to Different Nail Sizes	Several Drill Bit Sizes	Self-Adjusting Mechanism			
Not Damage Material	Specify a Material	Pushing Nail			

6 Analysis and Results

Seventy sketches were generated by the experimental group and fifty-seven sketches from the controlled group. An ANOVA test is performed to determine if the two groups are statically equivalent in the quantity of concepts generated. The p-value found is 0.283. Further in the analysis of the experiment, an outlier was found who generated five sketches with a much higher score for novelty compared to students in the controlled group. The ANOVA test was performed again with a p-value of 0.228. In both analyses, it is shown that the pre-sketching activity does not have a significant impact on the quantity, thus supporting the first hypothesis.

For novelty, an evaluator assigns a score of 0 or 1 for each sub-function addressed in the sketch (0 if found in Table 1; 1 if not found). If a function is not addressed, it is scored a 0 also. The level of detail is not of interest and is not addressed in this study. An example sketch from a student in the experimental group is shown in Fig. 1. When evaluated against the protocol for novelty, this sketch received the score (0,0,0,0,0) as all means used are found in Table 1. For example, "Handle" meets sub-function S2 with means Human force, "Clamp" meets sub-function S1 (Secure head of nail) by means of acting as claws, the edges can adjust to different nail sizes, therefore it meets sub-function S4 with the mean self-adjusting mechanism, and "Gear" meets sub-function S3.

If a novel means is found, the matrix is not updated as only *a priori* novelty is of interest in this study. After scoring all the sketches, there were 16 novel solutions (sketches that have at least one novel mean) from the pre-sketching group and 9 novel solutions from the experimental group. While the protocol was developed to be as objective as possible, it was tested for inter-rater reliability to assess its robustness. A panel of four graduate student judges was used to score a subset of sketches. The distribution of analysis was done such that at each sketch was evaluated by at least two judges and one judge evaluated sketches shared with all other judges. Each judge analyzed the sketches individually and the agreement in the results from the analysis was tested using Joint Probability method of inter-rater reliability [33].

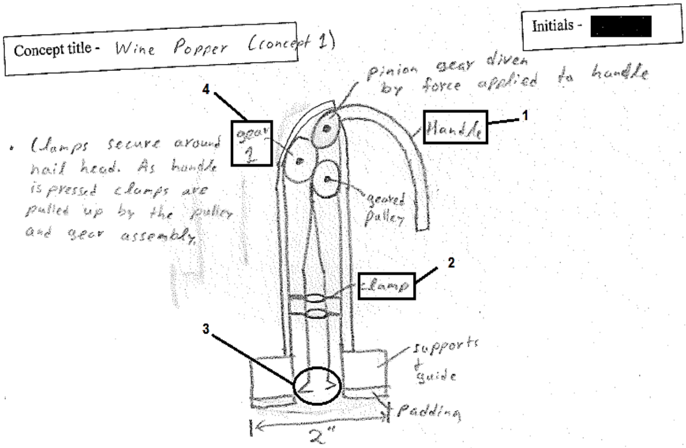

Fig. 2. Example sketch detailing a completely un-novel solution of student A

Rater A analyzed all the sketches (70 sketches from experimental group and 57 from control group). If the Joint Probability Agreement was found to be sufficient, this set of analysis would be used for the inferential statistics. Rater B analyzed the second half of the sketches from both groups. Raters C and D scored the first half of the sketches of both pre-sketch and no pre-sketch groups. The joint probability agreement between the raters for the experimental group is (AB=0.70; AC=0.86, AD =0.71; CD=0.71) and the control group is (AB=0.90; AC=0.74; AD=0.81; CD=0.85). All inter-rater scores were above the target of 0.7, so the protocol is assumed robust and the analyses of Rater A are used for further analysis.

An ANOVA test is done to determine whether the two groups are equivalent in their responses through the novelty scores. Four novelty permutations are assessed within each individual, as the student is the unit of study. The first score is the count of novel scores generated per designer (novel solution). Should a designer generate four sketches but only two determined to be novel, the score for this designer would be 0.5. The second score is the total number of novel solution fragments or means that were generated by an individual. The novel means might exist within a single sketch or may be distributed across multiple sketches without changing the score assigned to the designer. Third, the means density is the total number of novel means for a designer divided by the total number of solution fragment possibilities in the number of sketches generated. The final score is the novel solution density where the number of solution sketches that had a novel fragment is divided by the total number of sketches generated. By examining both the novel solution and the novel solution fragment perspective, the pre-sketching activity can be examined for influence at different levels of granularity. Moreover, by including the density for the number of sketches generated, these scores can be adjusted for those situations where a designer may generate many non-novel ideas against those where a designer may generate one or two highly novel solutions only.

The ANOVA test with single factor is performed (Table 2), with and alpha=0.15 common in designer experimentation [37]. The lowest p-value for the four metrics was found to be 0.21, suggesting that the two groups are not statistically dissimilar.

Table 2. ANOVA for Novelty without Outlier

	Novel Solution		Novel Means		Novel Density		Novel Solution Density	
	With	WO	With	WO	With	WO	With	WO
Column Pre-Sketch	16	16	16	16	16	16	16	16
Column No Pre-Sketch	15	14	15	14	15	14	15	14
Sum Pre-Sketch	16	16	24	24	1.05	1.05	4.03	4.02
Sum No Pre-Sketch	9	7	18	8	0.79	0.39	2.1	1.70
Average Pre-Sketch	1.00	1	1.50	1.5	0.07	0.06	0.25	0.25
Average No Pre-Sketch	0.60	0.50	1.20	0.57	0.05	0.027	0.14	0.12
Variance Pre-Sketch	0.67	0.66	2.00	2.00	0.004	0.004	0.07	0.07
Variance No Pre-Sketch	0.83	0.73	6.89	1.03	0.01	0.003	0.05	0.04
P-value	0.21	0.11	0.70	0.05	0.68	0.084	0.22	0.15

Upon closer investigation of the data, it is found that a single student generated ten novel means out of five sketches, approximately twice the amount of the next highest performer. This student was also recognized as a more creative student in the class based on a review of the student's performance in other portions of the class. Therefore, the ANOVA test was done again, this time without this outlier's scores. In the adjusted analysis, all p-values are less than or equal to 0.15. These results, combined with higher pre-sketching quantity, though not statistically significantly, suggest that a pre-sketching can provide value in an ideation activity by increasing the likelihood of generating novel solutions. That said, as a single outlier can have this amount of impact on the statistical significance, it is recommended that additional testing is conducted to expand the sample sizes to truly represent the population.

7 Conclusions/Future Work

This paper presents the findings of an experiment studying whether a sketching "warm-up" activity has a positive influence on novelty and does not negatively impact quantity. It was statistically found that novelty was positively impacted by the warm-up activity, if not considering the discovered outlier. Further, while the data suggests that quantity was also increased, though not statistically significant and thus a larger sample is needed to draw final conclusions.

More types of activities related to sketching can be tested prior to idea generation sessions to determine if the results obtained in this paper can be attributed a causal relationship. Higher replication counts are needed to perform statistical analyses of these results. In order to determine causal relationships two more studies can be done, one with a pre-sketching activity with an engineering related topic and one with a pre-activity that does not involve sketching i.e solving a design problem verbally. If results show that the activities yield to a greater number of concepts with an increase in novelty then one could determine that what causes these enhancements is the warm up activity before the idea generation session. At the very least, it is recommended that designers include a short "pre-sketching" warm-up exercise when they seek innovative solutions to problems.

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Design Approach for an Adaptable Highly Integrated Hydraulic Feed Axis

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Abstract. Currently, micro-machines are often based on principles of macro-machines. Results are unfavorable ratios between the build and the work space and also between the large moving masses and the work piece mass. To overcome these shortcomings, it is necessary to develop new approaches for work piece adaptable micro machine components as well as new kinematic chains especially geared towards the requirements of micromachining. For this reason, a work piece adaptable, highly integrated, piezohydraulic feed axis is developed. In this paper, the design of the hydraulic feed axis as well as a simulation and scaling tool are outlined. Furthermore, measurements regarding accuracy are presented.

Keywords: Micromachining, conceptual design, hydraulic.

1 Introduction

In product design, a significant decrease in part sizes but also an increase in the part's complexity and produced units can be noticed. This is due to three main factors: Energy and resource shortness, enabling of functions and demand of comfort and customization. Decreased part size leads to less resource consumption during manufacturing and lesser energy consumption during operation. Small parts and machines enable functions such as the usage in minimal invasive surgery. Customers claim smaller devices e.g. mobile phones due to comfort reasons, but on the other hand they also wish to have personalized devices to meet their specific requirements.

Therefore, production technology faces three main challenges: First, parts are becoming more complex while significantly reduced in part size. Second, the functional density of the devices is increasing. Third, the produced units are increasing while large numbers of varieties are required.

Small parts can be defined, as shown in Fig. 1, with part size in the cm and sub-mm range, structure sizes in the mm and sub-µm range as well as tolerance requirements in the µm and sub-µm range. Those parts can be exemplarily found in medical applications, consumables such as optics and mobile phones but also in automotive and industrial applications. This leads to high-volume production.

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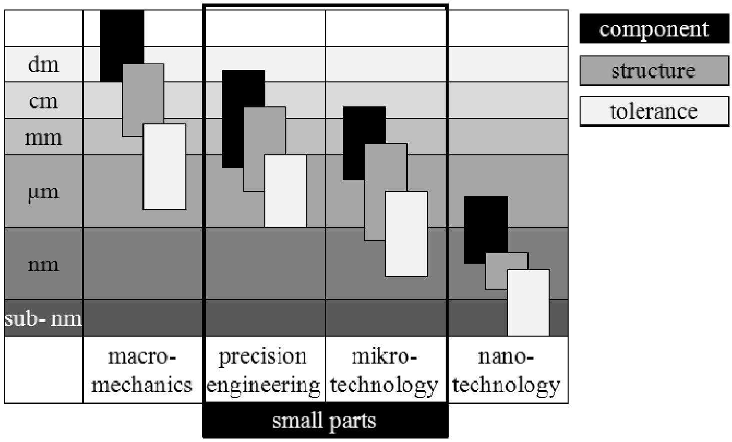

Fig. 1. Parts machined on small machine tools [1]

2 State of the Art

2.1 Current Machine Tools for Micromachining

Current machine tools for the production of parts in the specified range are often based on macro machine tool principles, components and kinematic chains [2]. Therefore, these machines feature a disproportionate build space in comparison to the work space (see Fig. 2).

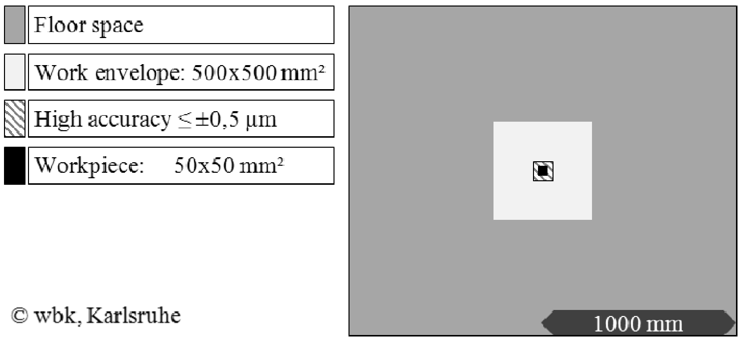

Fig. 2. Exemplary floor space and work envelope of a current micro machine tool

This disproportion further leads to ecological, economical and technical drawbacks. The production of a non-work piece adapted machine tool requires more material during production and higher energy consumption during operation due to larger moving masses. The powerful feed axis required for high dynamics emits heat which heats up the machine tool. This requires strong cooling systems. Economically, the high energy consumption and the lack of portability of current machines are unfavorable. Additionally, current machine tools are hard to reconfigure which will be required in the future due to high part varieties. Technically, current machine tools feature a large component size requiring clash conditions which reduce the achievable machine complexity.

Current work piece adapted machine tools are shown in [2]. It can be stated that the feed units of the machine tools are one influencing factor for the machine tool's size. Furthermore, reducing the size of the machine tool leads to reduced masses which in turn lead to higher eigenfrequencies that can be excited by e.g. a milling process. However, the production of small, complex parts requires high accuracy which can only be achieved by an increased damping within the feed axis. Therefore, the reduction of the feed axis dimension, the scaling of the feed axis as well as an increase of the damping in the guidance system is one approach to a work piece adapted machine tool.

2.2 Current Feed Axis for Micro Machine Tools

Currently, a wide variety of feed axes is used in machine tools. In micro-machining where high accuracy is required hydrostatic guides are often used due to reduced friction, wear and damping. As drives for propulsion, ball screw drives, hydrostatic thread drives and linear direct drives can be found. In Table 1 and Table 2, different feed drives and guidance systems are compared.

Table 1. Comparison of guidance systems [4]

Requirements		Force density	Functional integration	Damping	Stiffness	Running smoothness	Scalability	Sum:
Aerostatic		◕	◑	●	◔	●	●	◔
Magnet-guidance		◔	●	●	◑	●	●	◑
Sliding guide	Metal/ Metal	◕	◕	●	●	◔	◑	○
	Metal/ Plastic	◕	◕	●	◕	◔	◑	○
Linear bearing	Ball	◕	◕	◑	◕	◑	●	○
	Roll	◕	◕	◑	●	◑	●	◔
	Cam roller	◕	◕	◑	◑	◑	●	○
Hydrostatic		◕	●	●	●	●	●	●

Concluding Table 1 a hydrostatic guidance system features a high damping ratio, enabling high precision for manufacturing. Hydrostatic feed axis feature a lack of stiffness. Due to small strokes within small machine tools the stiffness is considered sufficient.

Table 2. Comparison of feed drives [4]

Requirements		Force density	Functional integration	Damping	Stiffness	Dynamics	Scalability	Sum:
Piezo		◑	◔	◑	◔	●	◔	○
Direct lin. actuator		◔	◔	●	◑	●	●	◑
Electro-mechanical feed axis	TGT	◑	◕	●	◔	◕	●	◑
	KGT	◑	●	◔	◕	●	●	◕
	PGT	◑	●	◔	◕	●	●	◕
Hybrid feed axis	Piezo/ Mech	◑	◔	◑	◑	●	●	◔
	Piezo-Hyd.	●	◔	●	◑	◑	◑	◔
Fluidic feed axis		●	●	●	◑	●	●	●

TGT: Acme screw drive

KGT: Ball screw

PGT: Planetary screw assembly

In conclusion it can be stated, that a combination of a hydraulic feed drive in combination with a hydrostatic guidance system proposes a compact and highly dynamic feed axis with high damping for ultra-precision application.

2.3 Current Simulation Approaches

Currently, simulation is widely used in machine tool design. It can be found in concept, design and realization [5]. While 3D-CAD design and kinematics optimization used during concept activities is reduced in complexity due to widely changing models and the need for fast prediction of the feasibility of the proposed concept, simulation models and tools are significantly increasing in complexity towards the end of the design process of a machine tool. At the Institute of Production Science in Karlsruhe, an approach for simulation of machine tools with minimal effort is proposed [6]. Within this integrated approach, the model's complexity is increasing for each step of the development process. While in early stages of the product development process the fast and easy testing of kinematic chains as well as the estimation of first design parameters is more important than the required accuracy, simple kinematic models are sufficient for this purpose. Along with the progress in the development process, the model's complexity also has to increase, requiring more time for simulation allowing more precise results.

As configuration tools in enterprises, scalable CAD models are often used for configuration of machine tool components. CAD systems often allow the parametric design of assemblies and parts. Therefore, internal and external parameters can be defined. Furthermore, parameters which cannot be varied can be defined as well as parameters which vary with fixed mathematical functions. For example, the feed of a feed axis consists of the traverse path as well as the width of components such as the carriage. It is on the basis of these specified parameters that the others can be calculated.

3 Approach

The configuration and scaling of the work piece adapted feed axis will take place at the end of the product development process. Hence, the further outlined approach is based on results, methods, simulation tools and techniques especially proposed for the final stages of the development process outlined in [6]. These techniques and tools are adapted and geared in particular towards an easy and targeted configuration and scaling of the highly integrated work piece adaptable hydraulic feed axis.

In comparison to [6], the approach for a work piece adapted feed axis consists of two main parts: First, the targeted configuration, simulation and adaption of the feed axis is enabled by a simulation and scaling tool. Furthermore, this tool permits an efficient pre-tuning of the controller as well as an estimation of the dynamic behavior before the actual feed axis is manufactured. Results of this tool are the controller parameters, the dynamic behavior as well as the drawings of the parts to be produced.

Since the basic design of the feed axis is the same for all variations, the feed axis varies in size, dynamic, stiffness as well as in force. In the following, the overall concept will be outlined.

3.1 Simulation and Scaling Tool

For an efficient and targeted configuration of the work piece adaptable hydraulic feed axis, a simulation and scaling tool has to be used (see Fig. 3). On one hand, it combines a Matlab Simulink and on the other hand a parametric Catia model.

Within this tool, the later described concept of a highly dynamic hydraulic feed axis is implemented in the Catia Model as well as in the Matlab Simulink model. At first, the requirements resulting from the work piece and the process, e.g. cutting force, dynamic, traverse path and stiffness, are inserted. With these parameters, the Matlab Simulink model calculates the design parameters, such as the sizes of the hydrostatic pockets of the guidance system, the piston diameters and the required tubing. Within the Matlab Simulink model the behavior of the feed axis is implemented analytical. The equations are obtained by using the pressure build-up equation. The hydraulic and mechanical parts are linked via the equilibrium of forces. For the piezo electric seat valves the mechanical and electrical equations are linked via the pressure build-up equation with the piston. In the first step not all piezo electric effects could be reproduced within the model possibly resulting in an inaccuracy of the model. In the next step these effects will be considered and the simulation model will be harmonized with the actual feed axis.

With these design parameters, the parametric Catia model is adjusted. The moving masses, the outer dimensions, the drawings as well as the resource consumption can be derived from this model. With the Catia model, FEM Simulations, e.g. with Abaqus can be started for obtaining the systems eigenfrequencies as well as the material's stresses. After transferring those parameters back to the Matlab Simulink model, the dynamic and control investigations can be executed. In the end, control parameters, system behavior and energy consumption can be calculated. On one hand, the Matlab Simulink model offers a set of control parameters but on the other hand, also enables an offline optimization of the parameters. With the results of the simulation and scaling tool, an optimized feed axis targeted to the work piece can be manufactured.

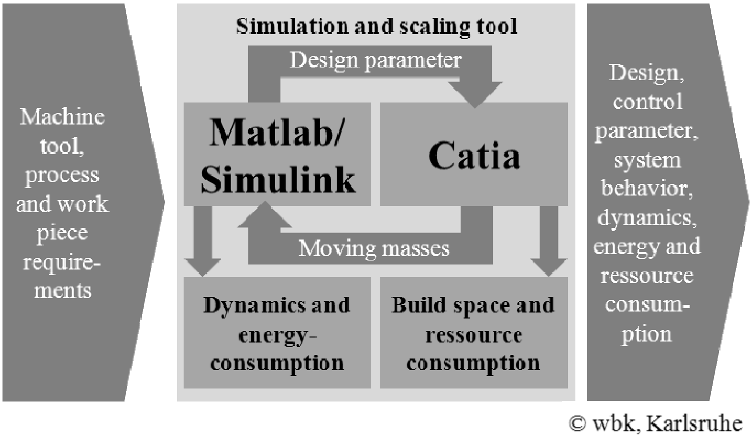

Fig. 3. Structure and usage of the simulation and scaling tool

Further research will focus on the design of an experimental approach for determining the significant influence parameters on the feed axis build space, the energy and resource consumption as well as the control parameters. Therefore, a systematic variation of the parameters will be executed and the significance of the parameters is evaluated. The aim of this approach is to further miniaturize the feed axis, but also to determine the limits of build space, energy and resource consumption as well as the control parameters.

Another focus will rest on enabling the simulation and scaling tool to increase the overall accuracy of the feed axis. This is envisioned by actively using simulation results for improving the control behavior and error compensation of the feed axis. Therefore, the model's complexity will be significantly reduced by concentrating on the significant parameters drawn from the design of experiment.

3.2 Overall Concept of the Feed Axis

The feed axis was developed and optimized using VDI Guideline 2221 [10]. The process is outlined in detail in [7]. The demand for high damping [7] leads to the use of a hydrostatic guidance system. Furthermore, hydraulics features a high force density enabling compact feed units. The multifunctional use of the hydraulic fluid for guidance, for propulsion as well as for temperature control enables high compactness. Since equal stiffness in both axial directions is required, the piston surface areas in both piston chambers are of the same size. The demand for high stiffness, in particular in standstill, further leads to equal pressure in both piston chambers during standstill. Since friction based effects have to be excluded, all seals are realized by gaps, leading to a continuous leak of oil. Therefore, oil must be continuously supplied in order to maintain the pressure. For this reason, the control valves are integrated into the return flow of the actuator. This control principle can be characterized as a two-metering edges control. Adjustable throttles have been integrated into both supply apertures to ensure that an opening of the valve does not lead to an uncontrolled flow of fluid into the piston chambers.

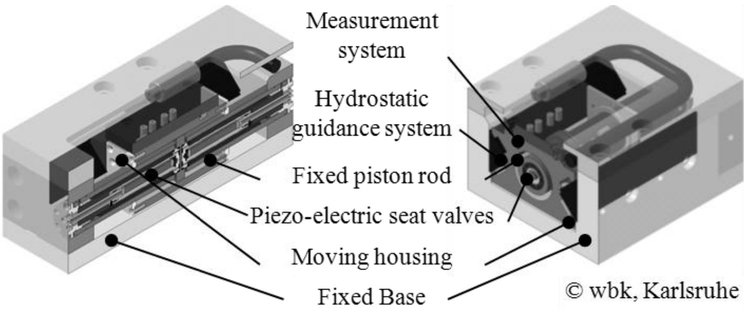

Fig. 4. Design concept of the hydraulic feed axis

Since moving masses have to be reduced, the developed concept features a stationary actuator housing and piston rod with the moving piston housing. The piston housing also comprises the hydrostatic guidance system and the carriage. The hydrostatic guidance system is almost friction free and features the highest possible damping of all guidance systems. In order to increase control dynamics, the fixed oil columns are reduced, realized by piezoelectric proportional seat valves that are directly integrated into the piston rod (Fig. 4). For more information see [7].

4 Results

In the following, the results of the characterization of the feed axis are shown. The feed axis is prototypically realized out of standard parts with standard proportional valves (HAWE, EMP-21-V) (see Fig. 5).

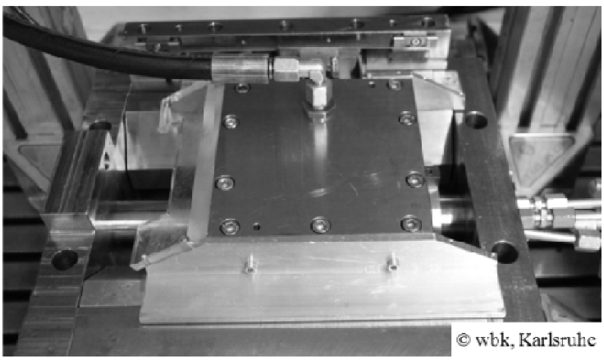

Fig. 5. Functional prototype, build out of standard parts [7]

The control principle is the same as specified above. This realization enables a first characterization of the feed axis behavior. Measurements have shown [7] that this type of axis features no friction based effects such as the stick-slip effect. For this reason, it was positioned slowly while measuring velocity and position. Furthermore, the stiffness of the feed axis was determined. It features a maximum stiffness of 250 N/µm at a hydrostatic pressure of 2 MPa. This is considered to be sufficient for micro machining.

In order to achieve a small positioning error, a control system was implemented. The controller is a PID controller with anti-windup [8] measures to control the integrator. Fig. 6 shows the response of the controlled system for a stepwise increase of the carriage set position. It can be stated, that the feed axis achieves stationary accuracy of less than 10µm. The agitated characteristics can be explained by possible stick-slip effects and nonlinearities within the standard valves. An increase in dynamics as well as an improvement in control characteristics is expected by using the highly dynamic, piezoelectric direct seat valves comprising an integrated hydrostatic guidance system.

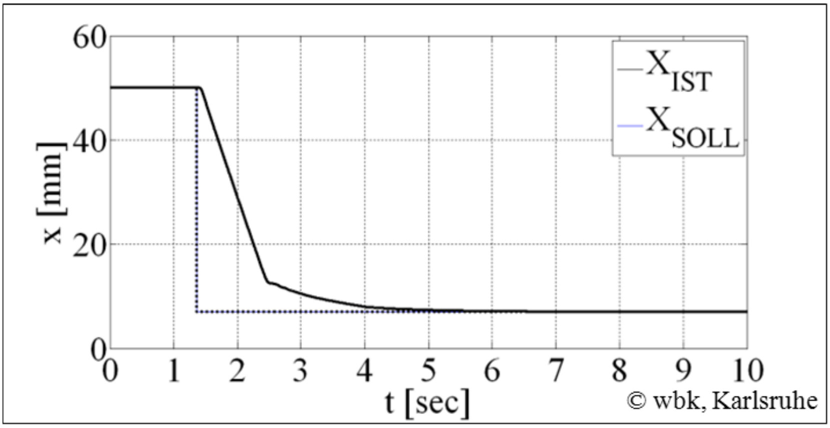

Fig. 6. Stepwise increase of the carriage's set position

An approach similar to the DIN ISO 230-2:2006 guideline [9] was applied to determine the positioning error. Therefore, eleven different positions were approached and the distance between actual and set position was determined (xi in Fig. 7). The measurement was conducted with a dSpace system using an integrated incremental glass scale featuring a resolution of 0.4µm. The sampling rate was set to 1000Hz. The measurement was conducted as specified in the guideline: The positions were approached from one side left to right. After the position at the outer left at the stroke boundary was approached, the scheme was applied from right to left. The whole cycle was conducted 5 times which equals a total of 110 measurements, five measurements at one position approached from right to left as well as from left to right were conducted. The position deviation was evaluated after the feed axis was in standstill for 5s. During measurement, the temperature was monitored. A temperature of 43°

Celsius was not exceeded. It can be stated, that the axis shows temperature stability after the heating up. All measurements were conducted after warming up to this temperature. As outlined in the guideline, the measurement is evaluated statistically allowing the determination of the positioning error based on statistics.

It can be noted, that the feed axis features a bi-directional positioning error of 8μm (see A), a bi-directional positioning repeatability of 7.2μm (see R) and a mean bi-directional positioning error of an axis of 2.48μm (see M, Fig. 7). For more details the guideline DIN ISO 230-2:2006 has to be considered. For micro machining 8 μm is not sufficient. The non-satisfying positioning error is due to the used seat valves which are not optimal for this purpose. The integration of the piezo electric seat valves promises improvements in positioning errors.

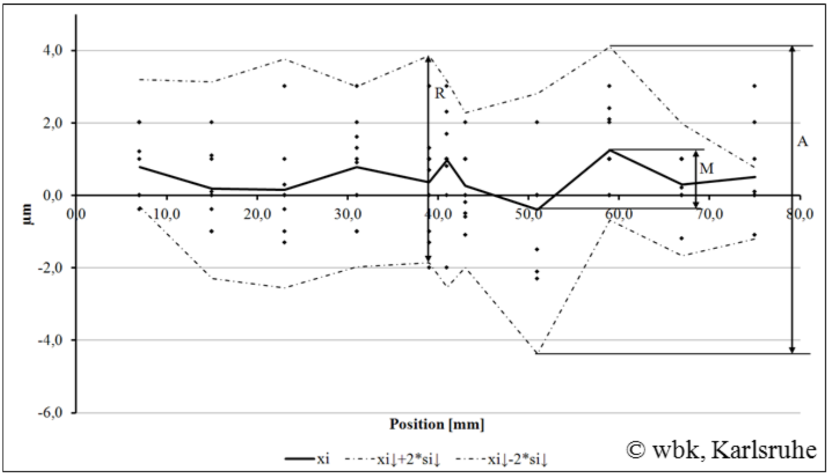

Fig. 7. Positioning error similar to DIN ISO 230-2:2006 [9]

Furthermore, an optimization of the feed axis build space was conducted. The new designed apparatus features a moving mass that decreased to one third and a build space that decreased to about one half of the shown functional prototype. This apparatus features the main parameters such as the prototype, e.g. piston diameter and traverse path. Since this design is far more compact than the shown prototype, stiffness as well as dynamics are supposed to be improved significantly.

5 Outlook

Further research will focus on an alignment of the simulation and scaling tool to the real prototype. Other major issues are the currently used seat valves. They will be replaced by the above mentioned piezoelectric seat valves. Due to the better controllability of the valves, an increase in control dynamics as well as in control accuracy is expected. Moreover, the designed concept will be manufactured and then characterized. Also, further optimization, in particular on resource and energy consumption, is required. In addition, it is planned to enable the simulation and scaling tool for online control adjustment to improve the overall system accuracy.

6 Conclusion

This paper presents a new concept for a hydraulic feed axis. As required, this feed axis does not feature any friction based effects such as the stick-slip effect and provides high damping due to the hydrostatic guidance system. In parallel, a simulation and scaling tool is presented, enabling a targeted design, optimization, manufacturing and commissioning of such a feed axis.

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Automated Configuration of a Machine Simulation Based on a Modular Approach

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Abstract. In this paper a module-based methodology for the automated configuration of machine simulation is presented. The aim is the fast generation of different simulation models for control tests and virtual commissioning which are based on a module database. This approach can be integrated into current engineering processes of machine builders. Depending on the degree of detail of the module, the simulation can be used in individual engineering steps. Therefore, it is not necessary to have completed engineering data. The methodology comprises several steps beginning with the systematic module identification based on the machine components and its functions; followed by the evaluation and assessment of the identified modules. Finally the modules are modeled and validated for the automatic or manual configuration of simulation models from a module database. The impact of the methodology is examined exemplarily on a production machine.

Keywords: Integration of Virtual Machine Engineering, Modularization, Management in Product Development, Virtual Commissioning.

1 Introduction

Complex requirements from customers, increasing cost pressure and short delivery times present major challenges for the manufacturing of machine tools and production machines. In order to meet these challenges machine builders employ extensible machine platforms or construction kits. Additionally, the employment of machine simulation for the control test and virtual commissioning responds to these challenges. With simulation early engineering steps can be reviewed. Concepts can be compared and early errors such as design errors can be detected. In subsequent steps the control software can be tested and pre-optimized before commissioning. The quality of the machines can be improved and single engineering steps are parallelized towards simultaneous engineering. Hence, the employment of machine simulation leads to a more efficient engineering process.

The major obstacle in the application of machine simulation into company's practice is the expense for the simulation modeling process. Different simulation models are created from mechanic, electric and control data for different tests in the life cycle

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of a machine [1, 2]. Another problem states the consistency of the data, as data is changed frequently and its level of detail changes during the engineering due to sequential process steps. Current approaches for the automated configuration of a machine simulation mainly base on multipurpose language which collects and transforms engineering data. It is complicated to put these approaches into the current engineering process. Not only the incomplete data, but also the lack of practical experience with those languages forms a problem.

A module-based approach facilitates the creation of different variants of machine simulation, even if the data is incomplete. The modules required for this purpose must have specific properties. Based on the respective machine concept with its components and functions, scalable and configurable modules can be combined easily and reused for other simulation projects.

2 State of the Art

Simulation models are used to validate and compare different machine concepts at an early stage in the engineering process. Furthermore the control programs can be tested and a virtual commissioning can be executed. Therefore, it is necessary to create a functional performance model of the machine. Additionally, often a 3D-model has to be created to support special tests e.g. collusion tests. The simulation models are based on the data of mechanical, electrical and control engineering fields.

Simulation models are often developed only for a single application and for a particular purpose. New requirements demand that the simulation models have to be reused for different purposes along the engineering and machine life-cycle [2]. Therefore, it is necessary to create different variants of simulation models easily [1]. The economics of a simulation project can be measured with current approaches. It depends, among other parameters, on the type of simulation creation and on the level of detail of the simulation model [3]. Simulation modeling can be carried out manually, semi-automatically or fully automated, whereby the manual modeling causes the largest cost and must be carried out by simulation experts. In contrast, the implementation of the automated creation of a simulation model is very complex.

Many approaches for the automatic creation of simulation models use standardized description language for the compilation and transformation of the required engineering and process data. For process plants, an approach for the automated creation of simulation models, which can be sufficiently accurate and complete to be used for control tests or virtual commissioning, is presented [4]. In order to transform the engineering information, the description language XML is applied and used for the functional model of the system. Another approach describes the automatic creation of simulation modules for production machines [5]. In comparison to the approaches for process plants, 3D-models of the production machine have to be created and linked to a functional model. Fundamentals of this approach are the actual structure of the machine and its complete circuit diagrams. These approaches show successfully the possibilities for an automated creation of a simulation model. However these approaches get complex in the implementation if for example the engineering data is incomplete or missing or because of unskilled personal.

Another way to increase the efficiency and economics in simulation projects is the reuse of existing models and sub-models [1]. In research projects, the requirements on engineering systems for the processing of reusable models are analyzed [6]. In the VDI guideline 3633 the complete and partial reuse of simulation models is recommended, but specifications of the modules properties are not discussed in detail [7]. First modular approaches demonstrate the use of simulation modules [8]. The simulation modules are based on mechatronic engineering data such as circuit diagrams, fluid plans and 3D-CAD data. A special benefit of simulation modules is the ability to integrate this approach into current engineering processes [8]. Those modules are used for the automatic or semi-automated creation of simulation models. The semi-automated modeling is done with a simulation kit. This construction kit contains basic function blocks which can be combined and completed for the simulation model of a machine.

Other approaches show the benefits of using mechatronic modules in the engineering process and propose a component-based approach for the creation of simulation models based on these mechatronic modules [9-11].

Existing modularization strategies such as design structure matrix or the modular function deployment are only conditionally suitable for the identification of simulation modules [12]. One reason is the limited degree of freedom in the determination of the modules. The machine concept and certain other conditions are already determined at the time of the module identification. In addition the technological capabilities of the simulation software and the integration of the control software can only be partially considered in existing modularization strategies.

3 Motivation

A recent study based on the survey "Implementation of the kinematic simulation in several engineering processes"[1] has been conducted in 2012 at the *Institute for Production Engineering* of the *University of Siegen*. Manufacturing companies of custom machine tools and special purpose machines have been interviewed about their engineering processes, their application and connection of CAx-systems and their special requirements for the kinematic simulation.

A striking result is the cognition that the engineering process is still dominated by the mechanical design construction and sequent process steps. Timely delayed, the mechanical construction is followed by the electrical design and the development of the control program. Instead of a mechatronic engineering process with comprehensive parallel work, a special kind of simultaneous engineering is applied where single steps follow each other delayed. The development and engineering of customized machine tools or special purpose machines are mainly based on reference plants and modular construction kits which can be complemented by new designs of subsystems (Fig. 1a).

[1] Number of evaluable responses n=14.

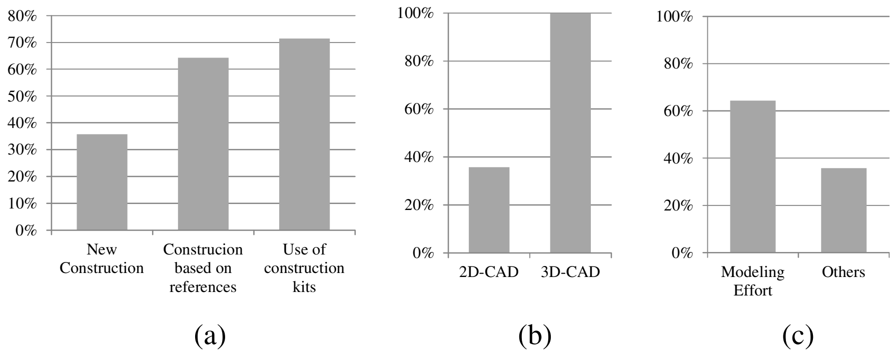

Fig. 1. Statistical analysis of the surveys' results

The companies surveyed implement different CAx-systems in the mechanical and electrical engineering fields. The selection of these systems is based on special demands, this is why no dominating system is detected. The use of 3D-CAD data is also important for the modeling of a kinematic simulation. Especially for the collision analysis of e.g. moved axis in the machine these data are necessary. All surveyed companies employed a 3D-CAD system, on top of that more than 30% of the companies are still using 2D-CAD systems for the engineering of sub systems (Fig.1 b). This can be explained by the use of 2D-drawings of reference plants, which can be easily changed but still are difficult in transforming into 3D-drawings. A fast and easy data exchange is necessary for an automated update of the simulation model, but the networking of the different CAx-systems with each other or with ERP or MES-systems is implemented only fragmentarily.

More than 66% of the surveyed companies already used the kinematic simulation for selected projects. The applied software is chosen according to the goals of the simulation of the company and also depends on the machine concept to be tested. In comparison to the study in 1997 where the integration of the simulation was a future trend [13], today the added value of the simulation is not mainly seen in the design review and concept tests, but in the virtual commissioning of the machines and in the early tests of the control programs. Nowadays simulation topics are maintained equally by the mechanical design and the control programming.

The main advantages of using simulation techniques are primarily the shortening and quality improvement of individual process steps. The largest barrier for the application of simulation (stated by 65% of the companies), far in front of the cost aspects, is the effort to model the simulation (Fig.1 c). This is consistent with a survey from 2005 where 61% demand reusable models to decrease the modeling costs [14]. A methodology for identifying such reusable simulation modules will be presented in the following chapter.

4 Modular Approach for the Configuration of a Simulation Model

The presented methodological approach includes the identification and the assessment of reusable simulation modules. The aim is to use these modules for an easy manual, or automated configuration of specific simulation models based on a data basis. The approach depicted in Fig.2 is divided into five steps.

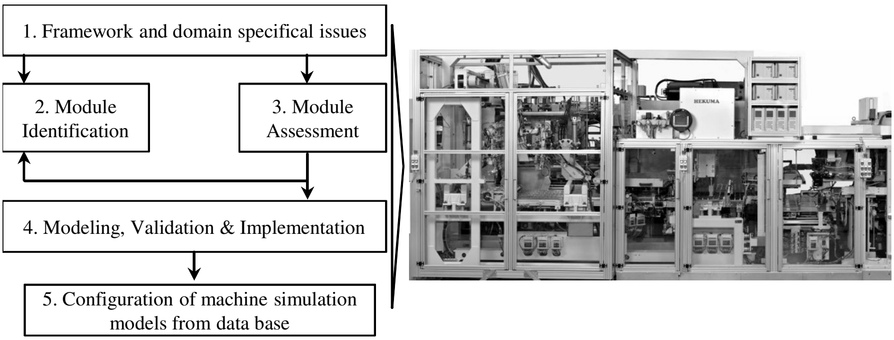

Fig. 2. Overview of the modular approach and an example of a machine concept

First, each step of the approach is explained in general and thereafter deepened in detailed aspects on the practical machine example of the *Hekuma GmbH* company. Their fully automated machines are for the manufacturing of plastic products and comprise the functions plastic powder injection, transport of the work pieces, assembly of parts, quality control and packaging of finished products. For controlling different PLC-systems are employed.

4.1 Framework and Domain Specifically Issues

The first step forms the basis for the subsequent domain-specific identification and assessment of the modules and takes special reference to the company's particular situation. In this step the basic indication factors have to be determined and matched. This should be done for every simulation project by an interdisciplinary team of company's experts.

These factors depend on the different goals for the implementation of simulation, the control system to test and the machine concept. The factors have to be defined and prioritized in advance. In this example the specific objectives are: the early control tests of sub-modules of the machine as well as of the entire system, collision detection between the moving axes and a comparison of different conceptual options which determine the optimal cycle time. The early testing of the individual modules based on detailed engineering data is not possible in this example. As at the time of testing, these data are not all available or they are changed permanently during the engineering process. Here the test on the basis of reusable and amendable simulation is of advantage.

The defined and prioritized objectives of the simulation influence the choice of the simulation software. Further influences come from the applied control-system and the use of engineering data e.g. 3D-CAD data. Rarely in simulation projects completely new developed machines are tested. It is more common that new machines are developed and tested based on existing machine concepts. Therefore, the present machine concept has also to be considered for the identification of reusable modules. In the given example, the machine concept is based on an expandable construction kit. The customized machine is then only a combination of different components of the construction kit and for specific requirements components are changed or newly constructed.

4.2 Module Identification

The second step is the actual identification of the simulation modules. For the known machine concepts, existing machines are compared along their material flow in order to identify similar or recurring components. The functions and geometries of these components form the simulation modules. An initial rule for the identification process is that the modules should be large and functionally comprehensive. Such modules can be quickly and easily used for the creation of new simulation models. A positive side effect is the simplified data management. On the other hand, too large modules are complicated to scale and to alter; this is why they are difficult to handle. The optimal size for the application of modules is obtained by an iterative approach which comprises the steps module identification and their subsequent assessment.

In the application example, the recurring modules are the plastic molding machine, robot systems, transport axes and quality control systems. For the simulation project not all functions of these modules are relevant. Therefore, the modules are divided in their functions and required 3D-geometries. The aim is to focus on simulation-related functions and geometries, and consequently reducing the complexity of the modules early in the approach.

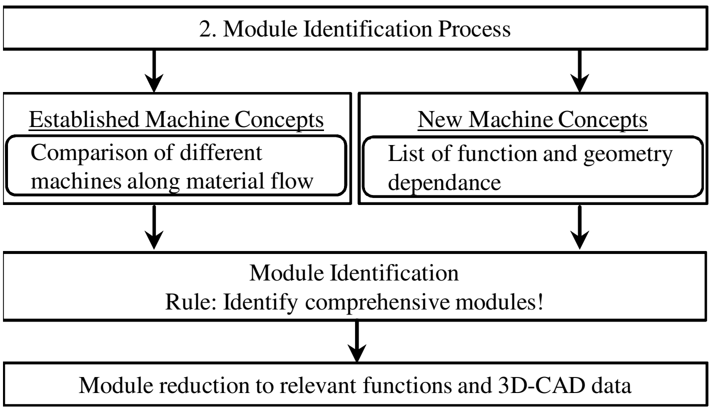

Fig. 3. Module identification process

In the case of new machine concepts, the individual machine functions have to be determined first. Therefore, the simulation-related functions and geometries are listed and then evaluated according to their dependence. This can be done with different modularization strategies e.g. the design structure matrix. Functions with a strong dependency form a simulation module. The initial rule to identify comprehensive functional modules is the same as mentioned above. In Figure 3 the process of the module identification is shown.

4.3 Module Assessment

The identified modules have to be assessed in order to determine their suitability for the domain-specific simulation task. For the assessment, the modular indication matrix and its module drivers are employed [12]. Especially the following module drivers can be adapted for the assessment of specific simulation aspects:

- Carry over: Module is based on an existing module.
- Technical specification: Module is changeable for customers' needs.
- Common unit: Module can be used for different machine concepts.
- Separate testing: Separate testing and validation of single modules.

The adapted module drivers consider the established objectives and framework of the simulation project for the assessment of the modules. The associated weightings have to be determined by the mentioned team of experts. It is important to keep the weighting for different modules equal to enable the comparison of modules with similar functionality and also for the assessment of different variants of modules.

The result of the assessment is based on the total score of the module. The higher the score the better is the suitability for the simulation project and for its reuse. However, there are elimination criteria that force to a re-identification process. If a single high weighted factor is rated low or zero, the module has to be changed. An example of the assessment of a specific module is shown in table 1. This module gets a total score of 43 out of 50 points.

Table 1. Assessment matrix of a simulation module

Assessment Factor	**Score (0-5)**	**Weighting (1-3)**	**Sum**
Separate testing	0	3	0
Implementation in simulation system	5	1	5
Scalability	3	2	6
…	…	…	…
Total Score			43

Considering only the total score, the assessment is positive and the module passes to the following steps. As in this example the high weighted factor "separate testing" is rated with zero, it states the elimination criteria for this module. The module has to be changed and be rated again.

After the assessment of a module, another iteration loop for the identification follows. A negative assessment leads to changes in the module as long as all requirements are fulfilled; whereas after a positive assessment modules can be modeled and implemented in a database. The change of the module can be done by combining or splitting the module or by adding or removing functions. The number of iterations for each module depends on both, the assessment and the characteristics of the individual module.

4.4 Modeling, Validation and Implementation

After a positive assessment, the modules can be modeled and implemented in a database for further application and for the creation of simulation models. Due to the different number of identification and assessment loops, the modules have different sizes and different comprehensive functions.

The modeling focusses on relevant functions of a module. For example the modeling of the module plastic molding machine can be reduced significantly. Related functions such as opening and closing of the mold have been mapped while internal functions have not been modeled. The effort of modeling also depends on whether the individual functions or variables are modeled scalable. An example for a scalable variable is the speed of the mold motion. On the one hand the scalable modeling means greater expenditure of time, on the other hand it allows a simpler alterability of the module. Further module properties are depicted in Fig. 4.

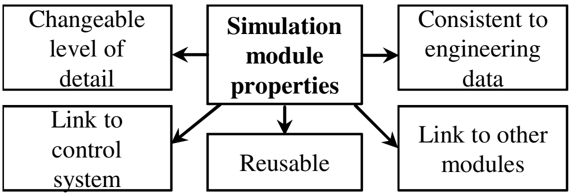

Fig. 4. Module properties

The modeled and pre-validated modules can be used for both manual and automated creation of simulation models. In this example, the database system of the simulation software is used for storing the created modules. In addition, it is also possible to use an external databases which are connected to the simulation software.

5 Discussion

The quality of the identified modules is mainly pre-defined by detailed constrictions of the company-specific initial situation in the first process step. The identification- and assessment process can be conducted the better the specification and the aims are stated. In this status a suitable simulation system is chosen. The consideration of an interdisciplinary team eases the integration of simulation and its modules in the engineering process. On the one hand each participant can state his specific requirements and on the other hand he should know about the potentials and restrictions in the simulation project.

The presented approach aims to identify the reusable simulations modules for the creation of specific simulation models. The stored and pre-validated modules in the database are combined to machine simulation models, whereby the combination may take place manually or automatically. The reuse of the simulation modules can be realized in various ways:

- direct reuse and recombination of modules;
- scaling and resetting of the variables of the modules;
- model fitting of the modules;

The recombination of the modules enables the reuse of modules without the additional effort. With existing and scalable simulation modules, similar components can be simulated faster. An example might be the simulation module of a robot system which can be adapted to the specification of various robots and robot systems. By the fast scalable and resettable modules, a simulation in the early stage is also possible without engineering-data. The effort of rescaling existing modules is proportional to the degree of adjustment and can vary in individual cases. Depending on the effort, it might be reasonable to re-model the module or even to renew the identification and assessment phase. The constantly growing database eases the simulation modeling.

The modeling and validation of simulation models ask for profound knowledge of simulation systems. Hence, these are executed by trained specialists. In comparison the modeling of the simulation model on pre-modeled and pre-validated modules require less expertise and can be performed by an operator of the simulation task. This fact promotes the integration of the simulation in the existing engineering process.

6 Conclusion and Further Work

The presented modular approach enables and eases the generation of variants of machine simulation. The separation of the module-modeling and the creation of the simulation model from a database contribute to model-driven development. Consequently the application of models in the engineering process is supported. The presented approach can also be employed on fragmented engineering-data because of the adaptability of the single modules. This is also the reason why the simulation model of a machine can be adopted and refined during the engineering.

The scalability and resetting of the modules are striking factors for the reusability. The presented example shows that same modules can be identified and modeled with different degrees of scalability. The aim is not to have the maximum degree of scalability, but to find the balance between scalability and the modeling effort. A similar problem results in the automated simulation configuration. Here, the implementation often requires additional software and the maintenance of the data base is also complicated. It has do be discussed if and how a marginal limit can be set to the automated configuration of simulation models.

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System Design of PLC-Controlled Specialized Production Machines

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Abstract. PLC-controlled specialized production machines are usually employed to automate customer-specific production processes. Sequential engineering processes are frequently used for designing these machines. To reduce the time and effort, parallelization of the different disciplines as well as increasing the reuse of already designed modules has to be considered. Both of these activities originate in the system design phase. Therefore, the sequential design process is analyzed to define the information required for starting detailed engineering in parallel. Additional requirements in the system design phase are derived from the characteristics of the system design phase itself and the special situation when designing specialized production machines. A method how these requirements can be fulfilled is shown based on these requirements.

Keywords: PLC, System Design, Systems Engineering, Specialized Machines, simulation, modularization.

1 Introduction

Shorter product lifecycles result in the challenge of achieving short times-to-market for new products. Further, the individualization of products is increasing and machines are needed to manufacture these products. Based on the individualization of the products, the manufacturing technologies employed have to be adapted. This turns into challenges for machine builders to deliver customer-specific machines in a shorter time. When using a sequential engineering process, the different discipline-specific phases cannot be shortened furthermore. However, to still reduce time, the various phases could be parallelized.[11]. Another approach that some machine-builders are using is a modular-machine design, which separates the development process into a module development process and an order-dependent development process. [3] In this case, the machine is individually adapted to the manufactured product by combining different modules. For this reason, a minimum number of built modules is necessary. But some products require high customer-specific production technology, which cannot be achieved by just combining different modules. Therefore, specialized production machines are built. Based on the very customer-specific production technology and the fact that the product is highly dependent on the production process, only one or two of these types of machines are built.

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2 Current Engineering Process for Specialized Production Machines

Specialized production machines consist of purchased components such as motors, sensors and mechanical parts, designed by the machine builders themselves. To automate the machine, programmable logical controllers (PLCs) are used. The current design process starts by defining the customer's requirements regarding the machine. Here, the most important requirement is the specified cycle time for executing the manufacturing process. Based on this, mechanical engineers start by drafting possible solutions to fulfill these requirements. They are usually sketched by hand and implicitly contain information about the actions required, rough geometrical descriptions of parts, the first definition of assemblies, kinematic dependencies and module states during operation. This definition of a principle solution has a significant impact on the detailed engineering in other disciplines [2]. The next phase of the mechanical design process is characterized by detailing different geometrical parts in a mechanical CAD system (MCAD), where assembly groups are first defined. This detailed engineering goes hand-in-hand with defining the kinematics, the drive concept, the moved masses and the kinematic states within the process. The actuators to be ordered are calculated from these definitions and the required motion time between the kinematic states. The last mechanical engineering phase involves the detailed engineering of the different parts and assemblies. Specifying the sensors and actuators to the electrical department marks the transition from the mechanical engineering to the electrical engineering department. Here, the electrical engineers create what is known as a functional structure in an electrical CAD system (ECAD) and add the sensors and actuators specified by the mechanical engineering department. In this phase, each sensor and actuator can be directly mapped to symbols in the circuit diagram. Further, the engineers must know the sequence of operation for the sensors and actuators, e.g. if two pneumatic cylinders should extend at the same time; however this can only be controlled if there is a common valve for both cylinders. Based on this information, the electrical engineers draw circuit diagrams. Once all of the signal interfaces of the devices being used and the mechanical results (mechanical design, kinematic information etc.) have been transferred, the automation department starts to define the various machine states. These states are generally kinematic states, e.g. "cylinder is extended" and the associated transitions, e.g. "cylinder extends". Further, the transition conditions between the states are defined using the signal interfaces of the sensors being specified by the mechanical and electrical engineering departments. Detailed engineering adds additional states and transition conditions along with safety functions such as interlocking conditions. The machine is finally assembled and commissioned. As mentioned previously, the decision regarding the principle solution has a significant impact on all of the disciplines involved. To obtain the best "mechatronics" solution, all disciplines should be involved in the system design phase [8]. Based on the individual customer requirements and the situation, the mechanical engineers frequently do not know whether a module has already been developed that can be used in this project assemblies, once developed, are infrequently reused [10]. The decision regarding the ability to reuse modules is also made directly by defining the principle solution. To reduce time within such a process, it should be possible to reuse modules as well as engineer new modules in parallel. To achieve both of these objectives, a method for designing the concept is needed before the various disciplines start detailed engineering in parallel.

3 Engineering and Design Approaches for System Design

Engineering specialized production machines is characterized by developing a mechatronic system, where the mechanical engineering is the leading discipline. In this case, the machine itself can be seen as the product of a machine builder. [13] suggests a development method for mechatronic systems, which is divided into three main phases. It starts with a concept or system design where all of the disciplines are involved, followed by a phase where the detailed mechanical, electrical/electronics and software engineering is executed in parallel. The final phase is the overall system integration. Using this macro process as a basis, this paper focuses on the concept or system design phase with the requirements that have been derived: Parallelizing disciplines, facilitating the reuse of mechatronic assemblies of the machine and considering the cycle time specified by the customer. Further, [13] explains a general method more specifically for the system design. Based on the requirements, the crucial problems are abstracted, a functional structure is drawn up and solutions for these functions are searched for. The main solutions are then evaluated and an interdisciplinary concept of a general mechatronic system is defined. This basic procedure is also used by [9] and [14] for system design, but with the focus on the mechanical engineering. Regarding the functional structure there, it is defined as functions connected to each other through energy, information or material flow. Based on this, principle solutions are identified for the different functions, combined and then a decision about the principle solution is made. [1] adapts this macro process to the development of PLC-controlled machines, by adding transition conditions between functions to model logical dependencies of the sequence between them. These dependencies and the rules for identifying sensors and actuators as a result of the information and energy flow, enable the automation department to start detailed engineering work. [1] also considers modularization of the machine, but not to reuse the various modules in a mechatronic way. Instead, it defines work packages for detailed internal engineering work running in parallel. Further, defining sensors and actuators based on the functional description is too abstract to allow symbols in a circuit diagram to be mapped to them. This represents a gap, and the electrical engineering department is not able to start with detailed engineering. [6] also mentions that selecting a principle solution based on functional descriptions is not sufficient to start detailed engineering. Therefore, what are known as aspect models can be used, such as sketches for the mechanical system and attached to the principle solution. [6] also introduces assigning a principle solution directly to a single function. [5] extends this approach by automatically searching for the implementation by defining a verb-noun-verb combination and taxonomies for them, related to stored principle solutions in a database. The machine building approaches mentioned in the introduction also use the word function. [17] however indicates that the term function in this context is understood and used differently than in the approaches previously discussed. The term function is strongly related to the implementation of a function, such as a conveyor. Certainly, a conveyor is just an abstract description of a component that can be ordered. The abstraction level (the term function in these approaches) can be compared with them, which corresponds to the name of a principle solution. This level is called the logical level in the following.

Similar approaches can be found in [7-8] and [16], where the focus is on reusing modules and generating engineering data based on libraries.

4 Requirements Placed on System Design

If the situation of the intended development process is considered, starting with the requirements and the need of an interdisciplinary system design phase, ending in detailed engineering processes for specific disciplines running in parallel, then an abstraction of the requirement definition is required, which in turn facilitates opening the solution search field. The engineering workflows within the different disciplines are described in Chapter 2. Based on the information that these workflows need to start with, it can be seen that a really detailed component-oriented view has to be available to start detailed engineering in parallel. Additionally, the general requirements on the system design phase can be derived from the situation described in the previous sections. An interdisciplinary description is required to allow all of the disciplines to participate. The cycle time is a key requirement for such machines, and also has to be given consideration. Figure 1 is derived from all of these requirements placed on the system design phase.

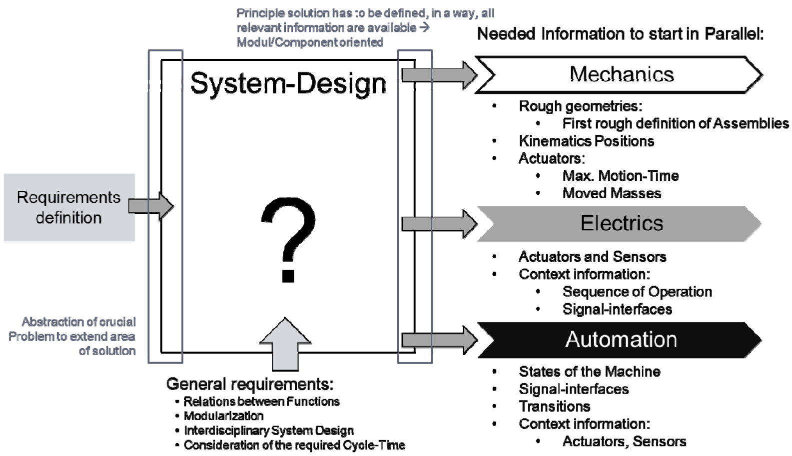

Fig. 1. System design requirements for PLC-controlled machines

5 System Design for PLC-Controlled Specialized Machines

[17] mentions that system engineering consists of three activities, the requirement analysis, the definition of the functional architecture and the link to the design architecture. Transferring these activities to Fig. 1, defining the requirements for the machine equates to the first activity in system engineering. The design architecture can be understood as the modularization and the abstract definition of components, which takes place at the logical level. This leads to two main stages within the system design

phase: Defining the functional architecture and the design architecture at the logical level. The specific steps within these two levels and the transition between them are described in the following.

5.1 Functional Description

The functional description bridges the gap between the requirements and the design architecture. It is an interdisciplinary description and can be used for analyzing the intended project and specifying the interfaces. [17] These characteristics enable the engineers to narrow down the general requirements on the machine to create the design architecture. The first step of defining the functional description is an abstraction of the crucial problem. For example, if the new machine is for "picking a box from a conveyor and placing it on a machine", the crucial problem would be "providing the product". Here, an abstraction of the term "box" was done by replacing it with the word "product", which is associated with opening a wide area of principle solutions, such as mentioned in [15]. The same applies to the word "placing". Further, the "picking functionality" is ignored, because the main functionality is "providing product". As a consequence, the "picking product" function can be included into a functional hierarchy, below the "providing product" function. This hierarchical description can be achieved by asking the question: "How is the function done?" Based on the requirement specification, additional functions can be included such as "stocking products". This leads to a functional hierarchy such as shown in Fig. 2.

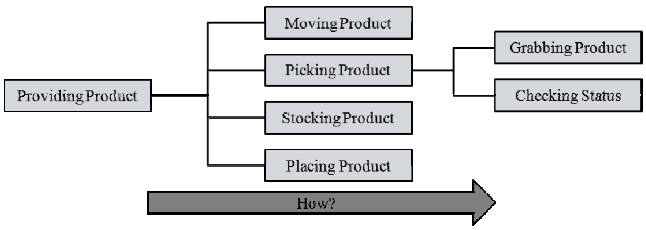

Fig. 2. Drawing up the functional hierarchy

The typical engineering methods, such as [1], [6] and [9], interlink the different functions with relationships for three main flow types: energy, material and information. Some links are quite obvious, such as a material flow between "stocking product" and "placing product". When considering a simple example, it can be seen that adding such a relationship between the different functions narrows down the quantity of possible principle solutions. Figure 3 shows a principle solution for a system that is based on a gripper. In this case, the relationship between "checking status" and "grabbing product" is realized dependent on the position of the "checking function". As can be seen, if the "checking status" function is performed directly at the position, the gripper can grab the product, the relation of material flow is not required. Conversely, if "checking status" is performed before this gripping position, then a material flow relationship has to be added. Depending on the relationship is drawn, decides whether alternative 1 is a potential solution – or not. As a consequence, a top-down-approach from defining the functional structure and then evaluating possible principle solutions is not useful, and an iterative procedure must be employed.

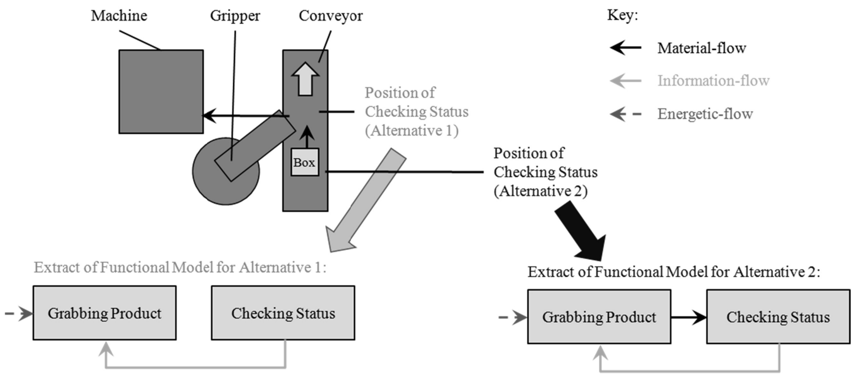

Fig. 3. Dependencies between functions and principle solution (design architecture)

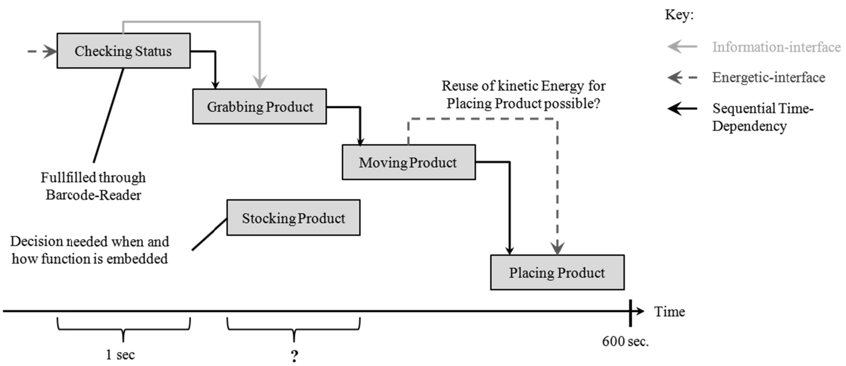

Fig. 4. Gantt chart for breaking down cycle time into functions

Based on the particular manufacturing process, it is quite easy to define time dependencies between functions without knowing the flow types, e.g. “checking status” has to be done before “grabbing product”. Further, the diagrams above do not take into consideration planning the cycle time. In this case, the most important information concerns which functionalities have to be done in a sequential way or which can be done in parallel. This information is provided in the form of Gantt charts. If a solution, e.g. a barcode-reader for fulfilling the “checking status” function, is known and the duration can be assigned, e.g. based on experiences or tests, it is possible to break down the required cycle time into functionalities as shown in Fig. 4. As a result of what has been identified about the dependencies between the functional architecture and the design architecture, the Gantt chart cannot be entirely defined using a top-down approach. This means that the Gantt chart has to be created iteratively, which forces the engineers to think about the cycle time and implementations, which can achieve the process step required in the given time slot. This also helps engineers to see, e.g. if different functions can be implemented in parallel or if energy from a previous function can be used (indicated by the blue dashed line in Fig. 4). Regarding alternative 2 in Fig. 3, assigning the duration to the "material-flow" between the functions "checking status" and "grabbing product" is suitable. However, defining the time behavior using Gantt charts requires that this relationship is modeled as a separate function so that the duration can be assigned and visualized. As a consequence, the three-types of flows are interpreted discreetly with respect to time, but indicate the interfaces required for the functions, e.g. energy input or output.

5.2 Transition to the Logical Level

A search is made for principle solutions based on the functional description. This could be done manually by using creativity methods [9] or by employing automatic searches within databases [5][17]. [17] uses hierarchical semantic definitions of the wording. Identifying different solutions for functions can be visualized in a morphological box [9]. If automated searches are used, this box can be predefined using a software system. However, it should also be possible to add new principle solutions based on the creativity of the engineers. When taking a closer look at morphological boxes, it is possible to find principle solutions fulfilling different functionalities, e.g. a "conveyor" for "moving product" or "stocking product". Based on this situation, decisions have to be made if different functionalities can be integrated into a single principle solution – or if it is useful to reuse the same principle solution for different functions. Integrating different functions leads to a n:1 relationship between functions and principle solutions. If a function is realized using a separate solution, then this represents a direct 1:1 relationship. Regarding modularization, the functional modeling and the relationships to principle solutions have to be done in such a way that no n:m relationship appears between functions and principle solutions. Otherwise, the system borders of the module cannot be identified clearly, which makes it difficult to reuse mechatronic modules. After selecting the principle solutions, the functional architecture has to be detailed and validated regarding the cycle time and the other constraints.

5.3 Logical Level

To communicate with other departments involved in the detailed engineering, it is useful to structure the principle solutions. Regarding the method of [8], the material flow is one of the first definitions within a modularized engineering approach. Therefore, this can be taken as criteria for structuring the principle solutions into a hierarchy. When compared to Fig. 3, the conveyor could be the child of an "Infeed-Module". Creating such a structure is very similar to the functional structure, which electrical engineers use when starting detailed engineering work in an ECAD tool. As previously mentioned, finding a principle solution is not sufficient to start detailed engineering. As far as Fig. 1 is concerned, such a principle solution has to be described in a way so that all of the information required is shown on the right. As far as the information required is concerned, three main types of information can be defined: 1. geometries and kinematics, 2. actuators and sensors with signal-interfaces, 3. sequences of operations. The information about the first category is usually provided by an MCAD tool. By assigning information about classified sensors and actuators, which could be mapped to a symbol in a circuit diagram, it appears that this structure can be directly used as starting point for the electrical engineering in ECAD. The signal definitions at the PLC hardware represent the interface between the automation and electrical engineering disciplines. Therefore, in addition to the states and transition conditions, signals should also be described within the operating sequence. To provide information about the effect of setting or reading a signal, the connection between signals and the actuators should be available as context information. Another requirement on the sequence of operation involves the machine cycle time. The maximum time for executing the different movements is obtained by breaking down the required cycle time to a function and defining relationships using 1:1, n:1 and 1:n to the principle solutions. In conjunction with information about the geometrical positions, the start and end of motion and the moved masses, the actuators can be precisely calculated to achieve the required cycle time. This in turn requires a time-based description for the sequence of operation, to break down the cycle times into the motion of the different principle solutions and to directly influence the selection of the actuators. A lot of description languages are available for defining sequences. As can be seen from Fig. 4, Gantt charts have a time-based description and the operations entered into them can be interpreted as states. The black arrows indicate transitions. Signals and transition conditions can be visualized, if it is possible to add signals and conditions to these arrows. [4] describes additional languages. Within pulse diagrams, the connection between sensors/actuators and signals is obvious, based on the resources available. The transition conditions have to be added to the arrows, drawn for signals. PERT charts do not have a time axis like Gantt charts or pulse diagrams, but assign starting and end times to states. Logic networks, sequential function charts and state charts do not have information about time and no information about the signals connected to sensors or actuators. All other information that is required is directly visualized within these description languages. It can be seen that pulse diagrams represent the best fit for describing the sequence of operation of principle solutions, which has to be extended by adding conditions to the signal arrows. Regarding the requirements derived for the description of the principle solution for PLC-controlled, specialized production machines, a combination of a geometrical/kinematic MCAD model, the logical structure with sensors and actuators that have been classified and a pulse diagram contains all of the relevant information required to start engineering a machine in parallel.

6 Implementation

To consider the requirement of [8] the phase of system design has to be supported by simulation. Therefor Mechatronics Concept Designer can be used to combine the geometrical and kinematics model of NX with a simulation model to visualize the sequence of motion for a specific module of the machine. This geometrical model is the same as the one used in the mechanical discipline. So this can be directly used for detailing. To execute the simulation, actuators for defining the motion of the kinematics, based on constraints for positions and speed are added. To detect, if a Geometrical-Part reaches a Position, sensors can be added, too. [12] To provide a tool for the interdisciplinary system design phase, fulfilling the requirements shown in the chapters above, this model should be controlled by a pulse-diagram. The description of those can be done in Sequence Designer, which provides the possibility to generate directly PLC-code. Connecting both tools, the actions of Sequence Designer lead to the motion of the kinematics, executed through actuators. Therefor the exact geometrical position is mapped to the given state of Sequence Designer. But a pulse-diagram does not give the information about: how a position is reached. This is solved through defining relation between the states and the actuator, which is responsible for reaching this state. Signals for the transition between the actions are available in Mechatronics Concept Designer by sensors. Mapping them to the given signals in Sequence Designer, the transition between the different actions is defined. To do this enrichment and the mapping an application was developed. Using this, it is possible to provide a simulation tool within the system-design phase, which owns enough information, to start detailing within the automation and mechanics discipline. If there would be the possibility of extending the information about sensors and actuators in Mechatronics Concept Designer by adding a detailed classification of the sensors and actuators, also the electrical department would be able to start detailing.

7 Summary

To reduce time and the associated costs when designing specialized production machines, it is not possible to split the engineering process as proposed by [3]. To reduce time, it must be possible to reuse modules that have already been designed, and the various disciplines have to be parallelized. This could be done based on the macro process of [13]. Therefore, the current sequential process was analyzed to define the information required for starting all of the disciplines involved in parallel. Additional requirements for the system design phase are derived from the general characteristics of this phase. The design process of PLC-controlled specialized machines was predominantly adapted in 4 steps: 1. Functional breakdown of the requirements, 2. Adding dependencies between functions with the types of: time-dependency (Gantt chart), material, information and energy, 3. Searching and selecting the principle solutions for functions, taking into consideration integration and reuse, 4. Drawing-up a logical structure, including linking discipline-specific descriptions as geometrical/kinematic for mechanics, sensors and actuators that have been classified for the electrical system and pulse diagrams for the automation. Based on this approach, the cycle time can be continuously planned down to the motion of a single axis. Further, all of the information required for starting detailed engineering in the various disciplines is available. To support this phase an application was developed to connect the tools Mechatronics Concept Designer and Sequence Designer.

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A New Method for Human Reliability Analysis in New Product Development

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Abstract. Human reliability is an essential quality of the complex and highly dynamic domain of new product development (NPD), because a low level of human error positively influences quality, cost and safety of a product. However, there is lack of empirical research in this area, especially regarding methodological approaches. In this paper, based on the abstraction hierarchy and the multi-facet human error taxonomy of Rasmussen as well as on the requirements of systematic engineering design by Pahl et al., a theory for human reliability in NPD is described. Based on this theory, a framework for a large-scale laboratory experiment (n=111) with three NPD-compliant design tasks was developed, which focused on the effects of limited available time on human reliability. The experiment provided a broad range of empirical results, which were quantitatively analyzed, and serves as the base for follow-up NPD experiments.

Keywords: human reliability, human error, new product development, research methodology, systematic engineering design, time, empirical analysis.

1 Introduction

Successful new product development (NPD) is essential to gain competitive advantages in global markets [1]. In systematic engineering design, NPD is described as a dynamic, highly iterative process with numerous interdependencies between problem, process and product. This stems from the demands of a systematic requirements analysis, which stipulate that a product has to satisfy numerous requirements on the functional, working, constructional and systematic interrelationship levels [2][3]. In NPD, a high level of human reliability is essential, because a faulty product not only puts material and spatial constraints at risk (constructional level), but also endangers the overarching physical effect (working level), which in turn endangers the product function (functional level) and in the worst case destroys the overarching product system (systems level). About 80% of all product-related errors and about 60% of all product recalls due to customer dissatisfaction are rooted in a flawed product development process (e.g. unsystematic, myopic approaches) [2]. A high level of human reliability in NPD contributes to a higher quality, lower cost and greater safety of the

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product, and leads to a higher level of customer satisfaction, lower market price, punctual arrival on time, and most importantly, it ensures that the product in development reaches its intended function [2].

However, regarding human error in NPD, there is lack of empirical research, especially regarding methodological approaches adhering to the standards of systematic engineering design. Previously, Schütze et al. [4] and Dylla [5] experimentally analyzed product development processes, but only used a relatively small number of participants and/or limited themselves to simple tasks. In this paper, a theoretical framework for NPD analysis is presented, which is based on the abstraction hierarchy and the multi-facet human error taxonomy by Rasmussen [6], [7], and is adapted for the domain of NPD. The essential performance shaping factors are further categorized by adapting the structure model of individual human action by Busse and Lampe [8]. Using this approach, human reliability factors can be categorized into person-, process- and product-oriented variables. Based on this framework, a large-scale laboratory study (n=111) in new product development under temporal constraints was conducted, and results concerning engineering design quality and human reliability are presented here.

2 Human Error

Rasmussen (1982) describes human errors as “very difficult to define satisfactorily”, because “frequently they are identified after the fact“. Therefore he proposes viewing errors in a greater context as “man-machine or man-task misfits”. Rasmussen distinguishes three levels of human error [6]:

- Knowledge-based errors in unique and unfamiliar situations, in which detailed multi-level planning is required.
- Rule-based errors in familiar situations, in which stored rules are used to regulate actions. Errors here are typically connected to recognition of wrong rules.
- Skill-based errors in automated, stored patterns of behavior, which typically relate to a false time, space or force coordination.

Concerning the most complex category of knowledge-based errors, Rasmussen establishes a five-level abstraction hierarchy [7]:

- functional purpose, which clarifies system objectives
- abstract function, which deals with abstract, causal input-output structures of mass, energy and information flows
- generalized functions, which cover concrete technical functions
- physical functions, which name electrical, mechanical or chemical processes
- physical forms, which deal with the physical form and location

According to Rasmussen, this approach is useful for the design and evaluation of complex technical systems: by mapping high-level purposes and low-level physical implementations onto each other, the satisfaction of functional, physical and material requirements can be facilitated. Rasmussen also describes a multi-facet taxonomy of human error [6]:

- causes of human malfunction (e.g. external events, excessive task demand, intrinsic human variability, disturbances)
- performance shaping factors (e.g. mental load, affective factors)
- mechanisms of human malfunction (e.g. information processing/comprehension mistakes, false inference, false discrimination)
- situational factors (e.g. task characteristics, work time characteristics)
- internal human malfunctions (e.g. faulty detection, identification, action)
- personnel tasks (e.g. equipment design, procedure design, fabrication)
- external mode of malfunction (e.g. non-performance of a necessary task or commitment of an erroneous or extraneous task, i.e. errors of omission, errors of execution, errors of intention)

The variables of this taxonomy are only partly observable: whereas external malfunctions, situational factors and performance shaping factors can be measured, the other parts are internal. Additional factors listed by Vicente are the quality of the human-machine-interface, situational familiarity and situational anticipation [9][10]. Shappell and Wiegmann [11], who developed the Human Factor Analysis and Classification System (HFACS) based on the approach by Reason [12], describe human error as "factors in a mishap when mental or physical activities of the operator fail to achieve their intended outcome" and list problem misjudgement, lack of available time ("tough schedules"), poor spatial perception, inexperience, and external distractions. Similarly, Hacker describes human error as "unsatisfactory human execution of a tangible work task", and stresses the lack of available time and limited human information processing ability as important contributing factors [13]. Bartsch describes human error as "the ability of the person in the work system to bring a suitable qualification and the corresponding physical and mental performance preconditions into a specific work process… whereby technical, economic, humanitarian and ecological criteria and a failure acceptance range are respected", and lists a broad range of predominantly physical human error shaping factors (e.g. health, qualification, strain, stress, visual-spatial memory) [14]. Several of these authors list the limited amount of time as an important factor. However, time constraints are often underestimated. Deadline shortening puts product quality at high risk and lead to an exponential growth of complexity [4]. However, in NPD, the terms "human reliability" and "human error" are not well defined, which makes categorization of human reliability factors difficult.

3 Human Error in NPD

In systematic engineering design, the product must conform to the requirements as decided on between the customer and the development team. Fulfillment is deemed as quality, and failure to meet these standards can be subdivided into errors of omission as well as errors of execution. All quality requirements as well as their respective acceptance limits on the functional, working and constructional interrelationship levels can be categorized using the levels of systematic engineering design [2][3]:

- The functional interrelationship level expresses the intended relation between input and output (i.e. the product function), and result is the functional structure. The designed product must conform to function-specific requirements, generic requirements and logical requirements. Requirements on this level are very abstract. Common errors are failure to understand the main function; naming a physical law or a product component instead of a function; incorrect subdivision of main and auxiliary functions; incorrect subdivision of functions; illogical solutions etc.
- On the working interrelationship level, relevant laws of physics as well as geometrical and material constraints are considered, and result is the working structure. The appropriate physical effect must be modeled with appropriate formula, geometrical and material constraints. Working requirements have a medium abstraction level. Common errors are choosing the wrong physical effect; naming a function or a product component instead of a physical law; picking the wrong formula; setting the initial and boundary conditions wrongly etc.
- The constructional interrelationship level highlights components, joints and assembly points, according to the requirements of assembly, transport etc., and result is the construction structure. Requirements on this level are concrete, i.e. the abstraction level is minimal. Each component, each connection and the assembly itself have to be correct. Common errors include naming a function or a physical law instead of a concrete component, value or dimension; wrong dimensioning or order of assembly; creating spatially impossible components and/or connections etc.
- System interrelationships deal with the role of the product as a part of an overarching system, especially regarding external input-output-relations. Because this paper only deals with small-scale NPD, the systems interrelationship is not included in further sections.

Pahl et al. elaborate that establishing functional relationships can be challenging, because the high level of abstraction is difficult to interpret [2]. In general, there are similarities between the abstraction hierarchy of Rasmussen, which focuses on internal human mental models, and the levels of systematic engineering design by Pahl et al., which emphasize technical qualities (see Table 1). Additionally, both approaches emphasize the importance of high abstraction levels, and take into account that humans prefer to work on the lower levels. Whereas Rasmussen's approach consists of mutually dependent internal and external modes of malfunction, and defines three possible external error modes (errors of omission, errors of intention, errors of execution). Pahl et al. focus on the subset of external, observable errors: "errors of intention" are not applicable, but become observable in the two remaining categories "errors of omission" and "errors of execution".

Table 1. Levels of abstraction compared to levels of systematic engineering design

Abstraction hierarchy (Rasmussen)	Systematic engineering design (Pahl et al.)	Common concepts
Purpose	Functional Interrelationship level	Main function
Abstract function		Functional structure
General functions	Working interrelationship level	Working structure, physical effects
Physical functions		
Physical forms	Constructional Interrelationship level	Construction structure, assembled product

In the error models described previously, a broad range of possible human error shaping factors is listed, but there is a lack of categorization. According to the structure model of individual action by Busse and Lampe, human action can be modeled as a circular interaction between subject and object, in which every element is connected to the other two [8].

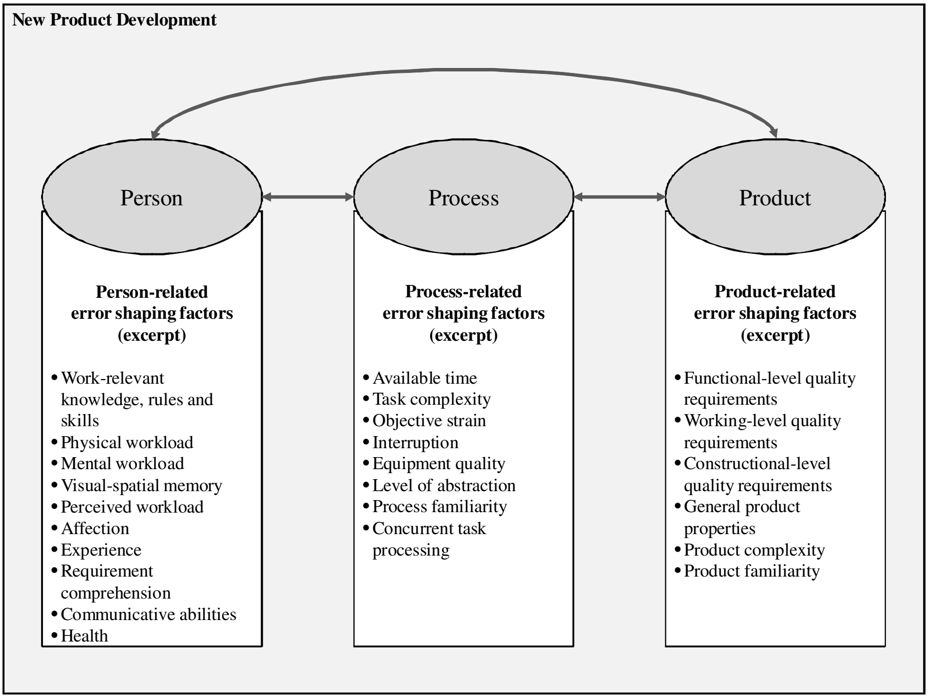

Fig. 1. Structure model for new product development

The circular relation expresses the mutual interaction between the psyche of the subject and the properties of an object, which are influenced by both activity- and non-activity-related aspects. Based on this model, error shaping factors in the previous literature review can be classified whether they are person-oriented, process-oriented or product-oriented. A NPD adaptation is depicted in Fig.1. Intuitively, several possible relations become evident, e.g. between “perceived workload” and “objective strain”. These error shaping factors could be additionally subdivided into NPD-related and non-NPD-related, but the boundaries are often not clearly definable.

4 Framework for NPD Analysis

Using the model listed above, a theoretical framework for the analysis of human error of NPD in laboratory settings was developed. Firstly, it is essential to identify the product in development, because each product has a different purpose. Based on this, it is vitally important to list the necessary requirements on the functional, working and constructional interrelationship levels of systematic engineering design. Secondly, errors in fulfilling these requirements are categorised and counted as either “error of omission” or “error of execution”. Thirdly, in a laboratory experiment setting, it is essential to start with tasks relating the functional interrelationship level, proceed with tasks in the working interrelationship level, and end with tasks dealing with the constructional interrelationship level.

Furthermore, it is essential to determine what error shaping factor the laboratory experiment should specifically focus on. There are a multitude of possible variables, as the NPD structure model in Fig.1 illustrates. The effects of limited available time on quality of the result (on the functional, working and constructional levels) are highlighted by several authors [2][6][15]16] and were therefore focused on. Lack of time poses a serious risk for product quality, cost and safety, as well as for the perceived workload on the respective product developers. Previous research on work under time pressure mostly focuses on simple tasks like speed typing. Speed typing is far less creative and dynamic than NPD, but already in this simple task, a non-linear relationship between available time and human error probability (HEP) was found [15]. In a follow-up experiment, a similar non-linear relationship between available time and perceived workload on the other hand was formulated [16]: if time constraints become too restrictive, HEP and perceived workload rapidly increase.

5 Laboratory Experiment

Based on the theoretical framework described above, a laboratory study was conducted, in which participants had to perform a multi-part NPD task under time constraints. The experiment was carried out in the laboratories of the Institute of Industrial Engineering and Ergonomics at RWTH Aachen University. A between subjects design was chosen, and each person participated exactly once in this experiment, i.e. no repeated measure was carried out. The product in question was a set of gear wheels with treadles, and prior to the experiment, a requirement list for every level of systematic engineering was compiled. Based on these lists, a multi-part NPD setting was developed, which deals with the functional, working and constructional levels of systematic engineering design:

- In task F, the participants hierarchically established the functional relations.
- In task W, the working relations were described: improvements based on a set of given deficiencies had to be developed and sketched in a principle solution.
- In task C, the participants hierarchically sketched the constructional interrelations.

To provide a degree of freedom, the participants could conduct F and C simultaneously. In this experiment, the main independent variable was the amount of available time. Several dependent variables were examined. Firstly, for every task, the quality of the design was evaluated based on the fulfilment of the respective functional-, working- and constructional-level requirement lists. Secondly, the perceived workload level according to the NASA-TLX technique was evaluated. Finally, extraneous variables such as personal data, level of education, work experience and ability of three-dimensional visualisation were collected. The sample of participants consisted of 111 junior engineers, all of them students in higher semester engineering classes at RWTH Aachen University, were divided into four groups (group 1: 27 participants; group 2: 25 participants; group 3: 28 participants; group 4: 31 participants), each with a different time to complete the three tasks (see Table 2):

Table 2. Available time per group

Task	Group 1	Group 2	Group 3	Group 4
F+C	5 min	8 min	10 min	12 min
W	10 min	12 min	16 min	20 min

The participants were mostly male (91%), had a mean age of 22.76 (SD=1.36), and generally evaluated themselves as "medium or highly experienced" in both technical drawing (80%), but only "little or not experienced" in the design of actual products (54%). The experiment itself was divided into three phases: Pretests, data acquisition and semi-structured interview. In the pretest phase, the participants filled in questionnaires in which personal data (age, gender etc.), level of education and work experience (technical drawings, manual labour etc.) were anonymously collected. After that, the participants carried out a preliminary IST 2000 R test [18] to measure their ability of three-dimensional visualisation, after which the main experiment was performed: In the data acquisition phase, the participants performed the tasks described above. Also, the perceived workload according to the NASA-TLX assessment technique was documented [19]. This multi-dimensional rating procedure derives workload using six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration. At the end, a 10-minute semi structured interview was conducted. Based on the sample of the 111 participants, a detailed analysis of the above mentioned hypotheses was carried out. For the analysis of the empirical data, the software Statistical Software for Social Sciences (SPSS, version 19) was used. At first, it was checked whether the empirical data met the conditions for a standard analysis of variance (ANOVA). A simple histogram analysis of the empirical data revealed that within the four groups, the dependent variables follow a normal distribution. The homogeneity of variance was checked with a Levene's test. If the data passed this examination, an ANOVA was carried out with a Tukey post hoc analysis, and the chosen level of significance for each analysis was $\alpha=0.05$.

6 Results

The data analysis (see Table 3) shows that in each task, an almost linear relation between the success rate, the human error rates (both errors of omission and errors of execution) and the amount of available time is observable. According to the results of the corresponding ANOVA analysis, the available time significantly influences the quality of the design ($p<0.001$). The Tukey post hoc analysis revealed that both a significant differentiation of paired groups and ranking of the groups are possible.

Interestingly, a descriptive analysis reveals that the frustration levels are highest in Group 4 (cumulated mean of the three tasks=109.8, SD=43.1), which had the most time available, and also the order of Group 1 (cumulated mean=102.9, SD=32.7), Group 2 (cumulated mean=105.0, SD=40.9) and Group 3 (cumulated mean=91.1, SD=31.5) was unexpected. This paradoxical result can be partly explained by the analysis of the semi-structured interviews. Participants of Group 4 said that they were regularly finished before the available time was up. In the remaining time, they consciously reflected what errors they committed, without having enough time left to correct everything, which led to frustration.

Table 3. Human error probabilities

Task	Error category	Group 1	Group 2	Group 3	Group 4
F	Omission	56.33%	47.20%	33.81%	29.25%
	Execution	18.90%	11.84%	6.38%	0.56%
	Success	24.77%	40.96%	59.81%	70.19%
W	Omission	48.89%	41.20%	28.21%	16.45%
	Execution	31.22%	20.83%	21.40%	5.56%
	Success	19.89%	37.97%	50.39%	77.99%
C	Omission	27.60%	24.00%	18.57%	8.39%
	Execution	36.21%	19.20%	16.26%	6.07%
	Success	36.19%	56.80%	65.17%	85.54%

Additionally, for all groups, the rate for errors of omission is highest for the task F, in the middle for task W, and lowest in task C. For example, in Group 3, the rates were respectively 33.81%, 28.21% and 18.57%: the higher the level of abstraction, the higher the "task entry barrier" seems to become. However, once this threshold is surpassed, the solution seems easy: there was a very low rate for errors of execution in task F. On the other hand, for task C (constructional level), the rate for omission errors was continuously lower than for other tasks. This indicates that the "task entry barrier" was lower. However, the rate for execution errors was continuously high, which indicates that formulating concrete solutions seems challenging. For the working level, it is difficult to formulate exact results. For Groups 2 and 3, the rate for execution errors in task W was higher than in tasks F and C; however, for Groups 1 and 4, this figure was higher than the respective execution error rate in task F, but lower than in task C. Moreover, Group 3 actually made more execution errors in task W than Group 2, although they had more time.

7 Summary and Conclusion

In this paper, a new theoretical and methodological framework for human error analysis in new product development (NPD) was presented. Based on the abstraction hierarchy by Rasmussen, the three levels of systematic engineering design by Pahl et al., and the structure model of individual action by Busse and Lampe, a research framework for NPD was established, which allows the categorization of human error shaping factors, and the expression of their mutual relation. Based on these thoughts, a laboratory experiment (n=111) was conducted, in which the effect of limited available time was analyzed. Empirical analysis confirmed the impact of this human error shaping factor on the quality of the result, and several non-intuitive relations between abstraction levels, and both category and rate of human errors were observed, which require deeper analysis. Further studies should concentrate on a detailed analysis of the specific execution errors on each level, and observe the influence of additional factors, such as disturbances or incomplete information, and integrate resulting findings. In the long term, the experimental findings will lead to an enhancement of actor-oriented work process simulation models by considering bounded human reliability and its influence on complex NPD projects [19].

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Design for Usability by Ubiquitous Product Documentation

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Abstract. The use of current complex products is rarely intuitive and self-explanatory. The approach presented in the paper in hand therefore considers support of product users by facilitating ubiquitous and providing easy access to product information for different use case scenarios through the use of new information channels. The approach includes a design method for the integration of accessible technical documentation into product development. A special emphasis of the proposed product documentation is made on special quick guides with instructions for the installations and frequently occurring use case scenarios, as well as references to more detailed information. To provide a first validation of the approach, a case study is introduced towards the end of the paper.

Keywords: marking technologies, mobile computing, product documentation, product life cycle usability, QR-Code, RFID.

1 Introduction

The use of current complex products is rarely intuitive and self-explanatory. Many products in everyday life and the industrial environment are hardly or even not at all usable due to the lack of information regarding the handling of the product and the range of functions. Even the availability of standard documentation may not ensure the proper use of complex products. The technical documentation of complex products often comprises several hundred pages, which can pose considerable effort to the users. Both the lack of information and too much information can lead to an inappropriate use of certain kinds of products. This may even result in damage to users, the environment, or the products itself. Particularly affected are products the user is unfamiliar with or that are infrequently used.

The paper in hand introduces a design method for the reduction of usability problems that is suitable in particular for complex products. The proposed method should be integrated into the product development process. To enhance the usability of a product, the method suggests the testing of products in different maturity phases in interplay with its documentation. The distribution of the developed documentation is enabled by the new generation of smart devices and can enable every product life cycle party to access the right information in the right place at the right time, after the

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point of sale. To render nearly any kind of device or product versatilely applicable, the presented approach exploits cloud computing and the Internet of Things based on internet-capable mobile devices and marking technologies. The developed method and its derived solutions shall lead to a shorter introduction time when handling products. A special emphasis of the proposed product documentation is made on special role- and device-specific quick guides with instructions for the installations and frequently occurring use case scenarios, as well as references to more detailed information.

The proposed quick guide is intended as a supplement to the common product documentation and may contain a reference to it. This short documentation is user-centered and therefore be provided in a multicultural and multilingual version, which can be used as a sales argument for the producer. Examples for products which are in the focus of the presented approach are highly complicated devices, rental equipment, portable devices, corporate devices that are used jointly, many resold devices without technical documentation, devices with a potential risk to human health and the environment, devices with high operating costs (energy and resources), and industrial machines without display.

The presented approach is suitable for all kinds of products. The paper in hand emphasizes the documentation process of quick guides for technical capital goods. The approach should be integrated into the development process of new products, but is also suitable for products, that are already in serial production. To provide a first validation of the approach, two case studies with serial products, a pump and a concrete chainsaw, which have been carried out in cooperation with the German department of civil defense “Bundesanstalt Technisches Hilfswerk” (THW), are introduced in chapter 4.

2 Related Work

2.1 Use of Product Identification Technologies with Mobile Devices

The number of mobile devices such as smartphones and tablet PCs has been increasing significantly over the last years. These devices facilitate mobile computing, mobile communications, and mobile internet use, which offer new ways of human–computer interaction. Many of these devices have embedded cameras, which can be used to read visual product identification technologies like barcodes, e.g. the QR-code. Some later generations of mobile devices even have reader modules for electromagnetic identification technologies like Near Field Communication (NFC) or Radio Frequency Identification (RFID). Product identification technologies offer an opportunity for automated identification of marked physical product items without manual errors like assignment or typing errors, and allow to store a unique URL or ID on the mark and onto a particular product item. These URLs or IDs can be read by mobile devices to access and alter related data sets of a product item in databases via the internet.

2.2 Design Approaches

In addition to traditional approaches for product development as described in norms like VDI 2221 [1], in the last decade, new approaches have been developed. One of the main reasons for the need of new approaches is the emergence of new requirements for the development processes. Apart from mechanical engineering, other disciplines like electrical engineering and informatics had to be integrated into the development process. An example for this kind of approach is the V model de-scribed in VDI 2206 [2]. This model has been further extended by aspects like the development of adaptronic systems in the so-called W model [3]. The concept of the V model corresponds to the design methodology of VDI 2221 but does not contain as many detailed process steps. The approach starts with the definition of requirements. The next step is the execution of system design for the different disciplines. These are mechanical engineering, electrical engineering, and informatics. The next process step is domain-specific design and the integration of the different design disciplines into an overall solution. These steps are repeated until the serial production phase is reached [2].

Another group of approaches are the Design for X methods, which support the designer with integrating multiple properties of the different aspects into the product. This poses a huge challenge to the designer as desired product properties influence each other. As an example, low energy usage can influence the total cost of the product [4]. Examples for these methods are design for usability, design for costs, and design for sustainability. The design for usability approach already considers the user of products during the development process. This can be achieved in various ways. There are methods for user-centered design, behavior-based design, practice-oriented design, co-creation in terms of using user-generated content, and co-design in terms of including co-creation within the design process where users and designers work together [5]. The user-centered design approach is also described in ISO 9241-210:2010 [6].

Other approaches like design for sustainability have been gaining significance, due to the steady increase of energy-using equipment with the consequence of a significant impact on the environment, as well as based on public regulations [5].

The integration of usability aspects for capital goods into product development will lead to cost-efficient, sustainable, and proper use of serial products.

2.3 Product Documentation

According to VDI 4500 [7], technical product documentation can be divided into two areas: internal technical documentation and external technical documentation. Internal product documentation concentrates on the internal processes of a company e.g. in development, production, or quality assurance. External documentation concentrates on areas like marketing, the use phase, maintenance, and the disposal of products. Such content is technical information intended for distribution, users and consumers. It is vital for an external documentation that the quality and comprehensibility is sufficient with regard to an easy understanding for the user. These factors determine whether the target group can use functions of the product in a proper way. Results of the documentation process are e.g. accompanying documents, operating manuals, instruction manuals, and technical descriptions. In these instances, contents can be basic security instructions and manuals for preparation, assembly, commissioning, operation, and maintenance. Additionally, there are instructions for the end-of-life considerations of the product [8].

Apart from the usual distribution ways with printed manuals, there are new ways of distributing documentations. Examples for these kinds of manuals are documents with integrated, three dimensional design data, virtual reality, or even augmented reality for the integration of real environments with design data.

3 Our Approach

3.1 Overview

The presented approach should be integrated into the V model-based development process of new products which is described in VDI 2206 [2]. The approach is also suitable for products that are already in serial production. To offer a way to create an ubiquitous accessible, role- and device-specific, structured product documentation as a supplement to common versions, the paper in hand presents a special documentation process derived from VDI 4500 [8]. Fig. 1 provides an overview over the integration of the proposed documentation process into the development phases of new products.

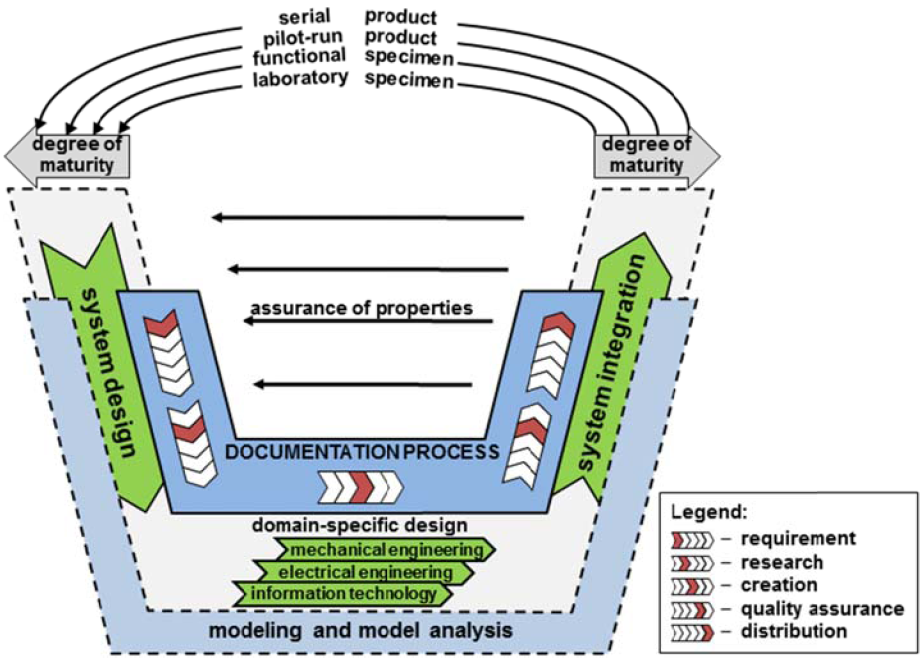

Fig. 1. Approach for ubiquitous product documentation based on VDI 2206

The proposed documentation process consists of six basic phases: planning, requirement analyses, research, creation, quality assurance, and distribution.

The planning phase of the documentation process starts with the beginning of the development phase. The purpose of the activities in the planning phase is the development of a concept that ensures harmonized interaction between activities, assets or resources, and the involved roles.

The requirement phase of the documentation process ranges from the beginning of the development to the completion of the pilot series. The requirement analyses are based on all external documentation, which is intended for the customer. To provide the documentation in the form of a user-centered quick guide, the requirement analysis is focused on use cases and major use scenarios, which are developed in the product planning phase of the development process. Most of these use scenarios are specified for the different roles that interact with the product like users, professional users, and maintenance technicians.

The research phase ranges from the first creation of technical data to the completion of the pilot series. The main task in the research phase is to gather norms, standards, and internal technical documentation (e.g. exploded drawing or virtual three dimensional models) and analyze these documents with regard to their relevance for the documentation process. Due to the fact that the proposed quick guide is designed to be a supplement to the conventional documentation, the focus in this phase of the proposed approach lies on internal technical documentation, which is generated in the different development phases.

The creation phase and quality assurance of the documentation process are integrated into the development of the pilot and serial production. The creation phase and quality assurance are depicted in the chapter 3.2 and 3.3. The distribution of the quick guide, which is described in chapter 3.4, takes place simultaneous to serial production.

3.2 Creation Phase of the Documentation Process

The creation phase of the documentation process starts with the development of the pilot production as the pilot products should have the same properties and appearance and is continued in the serial production process. The proposed quick guide is intended as a supplement to the common product documentation and should include a reference to the common documentation. Unlike common documentations, the proposed quick guides shall be centered on the user and not on the technical specification of a product. The focus of the quick guides lies on a short presentation of a step by step walk through the use cases and major use case scenarios, which can be performed by the different user roles like users, professional users, and maintenance technicians. Depending on the user role, the quick guide has to be comprehensible without any prior knowledge of the product or its functions.

To make the guides easy to understand and to facilitate a quick usage without handling errors, the operational instructions should be graphically presented e.g. via a sequence of photos with a short additional description. The graphic representation of the product shows the exact product and not similar versions with different appearances.

Operational steps shall be understood from their graphical representation without reading additional text. A major focus of the quick guides must also lie on safety.

Thus, all operational steps that entail risks for the user or the product have to be highlighted by caution marks in the quick guide. To ensure safe operation, the caution marks have to be conspicuous and clearly distinguishable from normal additional text.

To address a broad range of users, the short documentation should be available in a multicultural and multilingual version, and should be accessible from different devices. In order to be sufficiently displayable on different devices, the quick guides must be formatted only in widely used format types like html or pdf.

3.3 Quality Assurance of the Documentation Process

According to the approach described in Fig. 1, the fifth step of the documentation process is effected in the pilot production and the serial production phase. In these phases, the quality of the conversion of the requirements according to the completeness of the internal documents, the context of usage, and the involved roles are validated. Moreover, the use case scenarios that have been developed and described in the product planning phase of the development process are examined and, if necessary, optimized. The contents of these use case scenarios include e.g. the description of installations and frequently occurring situations, as well as references to more detailed information. In order to support this step in terms of user-centered design, the quality of the document is checked again through tests that involve different user groups. In this phase, the quick guide, which is described in chapter 3.4, is developed, and then tested in step four of the documentation process. The details of these quality tests are lead back to the requirement step. The new information can then be used for the next loop in the V model, and serves as feedback to the designers.

The output of the quality assurance process step is a quality assured product documentation, in this case a quick guide. This quick guide is ready for integration into the distribution process which is described in the following chapter.

3.4 Distribution of the Quick Guide via the Internet of Things

The proposed short documentation can easily be made available via the Internet of Things, based on internet-capable mobile devices and marking technologies. The use of mobile devices like e.g. tablet computers or smart phones with embedded cameras or embedded NFC readers facilitates access to the quick guides of product items that are associated with identification marks such as barcodes or NFC tags. Fig 2 shows a schematic architecture for the distribution system of the quick guides. The left side of Fig 2 shows how a product item is prepared for later use of the quick guide, while the right-hand side of Fig 2 illustrates the access to the quick guide.

To facilitate the later use of the proposed short documentation, the product items are labeled with identification marks like 1D barcodes, 2D barcodes, or NFC tags. These identification marks store references or URL to a folder with different versions of the respective short documentation for different devices, user roles, and languages.

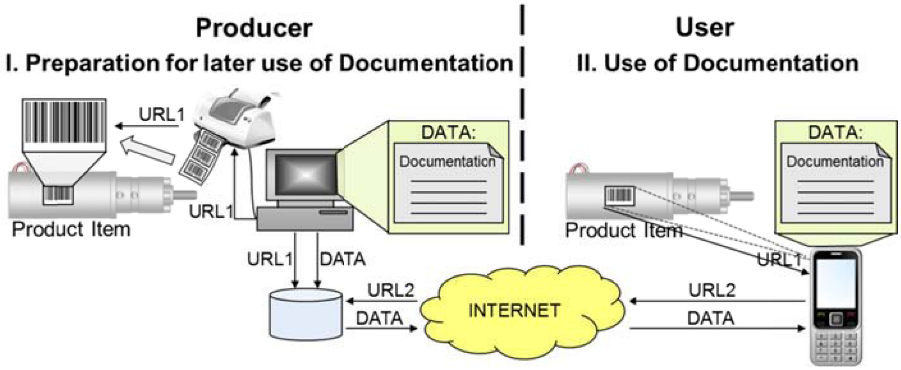

Fig. 2. Schematic of the distribution system for the quick guide

After the producer has prepared the product items, users can access a version of the quick guide suitable to them. To access a suitable version of the documentation, the users have two basic possibilities:

The users can either use a general reader application like a widely available QR-code reader application, to access the folder, which is referenced by the URL (cf. Fig 2: URL1) to choose a suitable version of the short documentation.

A considerably more direct and comfortable way to access the short documentation is provided if the producer offers a special reader application that transforms the URL from the mark (cf. Fig 2: URL1) into another URL (cf. Fig 2: URL2), which directly generates a suitable version of the quick guide.

The producer can store the quick guide in her or his product data management (PDM) systems [9] for internal purposes and for access of business customers for technical industrial goods, which are produced in small numbers. For products that are produced in large quantities, the producer can better use dedicated webserver or cloud computing solutions.

4 Validation

As a first validation of the proposed approach, two case studies have been carried out with products that are already (in the phase) of serial production. Both case studies have been carried out with technical capital goods. In the first case study, a pump with a capacity of 5000 liters per minute has been used (cf. Fig 3, right-hand side). The second study deals with the use of a concrete chainsaw and a supplying hydraulic aggregate (cf. Fig 3, left side). The two studies have been carried out in cooperation with the German department of civil defense "Bundesanstalt Technisches Hilfswerk" (THW). To provide a quick guide in an easily accessible way, QR codes with stored URLs are attached on the product items. These URLs have been used with smart-phones to access documents formatted as pdf via the internet. Several teams with different levels of knowledge about the usage of the related technical capital goods have taken part in the case studies.

Fig. 3. Case studies using the approach with capital goods

The majority of the participants in the case studies already had a smartphone with an installed QR code reader application.

The first significant result of the two case studies is the decrease in the number of operating errors through the use of the proposed quick guides.

Another result of the cases studies is that even inexperienced users that are supported by the quick guides were capable of handling the complicated devices without significant errors. A fundamental result of both case studies is that inexperienced users with the quick guides scored nearly the same rate of operation errors as experienced users supported by the guides. The paradox of this ratio of operation errors lies in the fact that the experienced users often act intuitively and thus ignore steps that are performed only rarely. Inexperienced users strictly perform every operational step of the quick guide to the best of their knowledge. The studies further show that experienced users with the quick guide have no considerable time advantage.

The studies` results show that there are many similarities between the two use cases with regard to the handling of the products supported by the quick guide via smartphone. Nevertheless, the studies show only few differences about the advantages of the quick guides. This can be based on the different dimensions of the considered products. The handling of the pump shows that, with the help of the quick guide, both experienced and inexperienced users have a strong focus on security aspects such as the use of protective clothing, provision of a fire extinguisher, and the use of ear protection. This leads to a secure handling for complex products like the considered pump. The handling of the concrete chain saw supplied by a hydraulic aggregate shows that, with the support of the quick guide, fewer errors were made that could have led to system damage.

In conclusion, the use case studies show that, in a normal training situation, the developed approach can lead to a secure handling of the products with a minimum risk of damaging the products themselves. This result applies to both the experienced as well as the inexperienced user groups.

Nevertheless, it is most likely that in stressful situations like disaster operations, the experienced user groups will achieve better results.

5 Outlook and Future Work

A possible extension of the presented approach can deal with the use of further contents and devices. Examples for especially useful kinds of content are virtual reality, animations or videos, which shows a sequence of steps of a use scenario. Examples for devices with potential for swift execution of the approach are tablet computers with large displays and high resolutions, and glasses with heads-up displays, or embedded monitors. The use of such glasses offers further possibilities like the two-handed product use. Additional potential lies in the use of augmented reality concepts.

More benefits that can be achieved with the presented distribution system lie in the fields of logistics, anti-counterfeiting [10], and the strengthening of Customer Relationship Management (CRM). The distribution system can also be used to offer a new, fail-proof way of ordering spare parts and follow-up models of products, which can be referenced in the quick guides.

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Simulation in Human-Centered Design – Past, Present and Tomorrow

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Abstract. Due to the ever rising significance of the products' usability the consideration of the user in the product development process becomes more and more important to stay competitive. This paper firstly outlines the historical evolution of how user-product relationships have been investigated and considered in product design in the past. A literature research has been conducted to acquire information about the state of the art in the multidisciplinary field of human-centered design as well as to derive which challenges towards a virtual assessment of human-related product properties exist. Finally the most recent research activities aiming to solve the identified issues as well as future prospects in simulating human-product interactions are presented.

Keywords: human-centered design, ergonomics, simulation, virtual product development, digital human modeling, biomechanics, hybrid mock-up.

1 Human-Product Relationship in Design

Until the early 1960s the dominating view on product design was affected basically by technical and economic aspects. Designing a product used to be defined as the process of finding a technical perfect, economic reasonable and aesthetic satisfactory solution for a given problem [1]. Although the last criterion is in some way human-related, user-product relationships were not explicitly in the focus of design theory.

The American industrial designer HENRY DREYFUSS is regarded a pioneer in the field of human-centered design as he was one of the first to explicitly incorporate the user into design theory: *it must be borne in mind that the object being worked on is going to be ridden in, sat upon, looked at, talked into, activated, operated, or in some way used by people […] If the point of contact between the product and people becomes a point of friction, then the designer has failed* [2]. His work introduced a new scientific view on design and had been an important foundation for the emerging fields of ergonomics, anthropometry and human factors. Along with an increasing complexity of technical systems (computer science and aeronautical engineering), an awareness for the whole system, formed by the product and its user, grew among designers. In the following decades several models have been developed that describe the complex relationships between user and product from a multidisciplinary point of view involving engineering, anthropometry, psychology, sociology and industrial design. The model schema depicted in Figure 1 contains all the basic elements

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necessary to describe the relationships between the product and its user: it is assumed that the product is described by a set of extensive properties which are influenced by decisions made during the design process. The user as a human being on the other side is described by demographic and psychographic characteristics according to [3]. The interaction between user and product is modeled as a process of perception and response. Based on perception and recognition the user is able to assess the properties of the product and choose his behavior. Most important the behavior includes all activities necessary to operate the product.

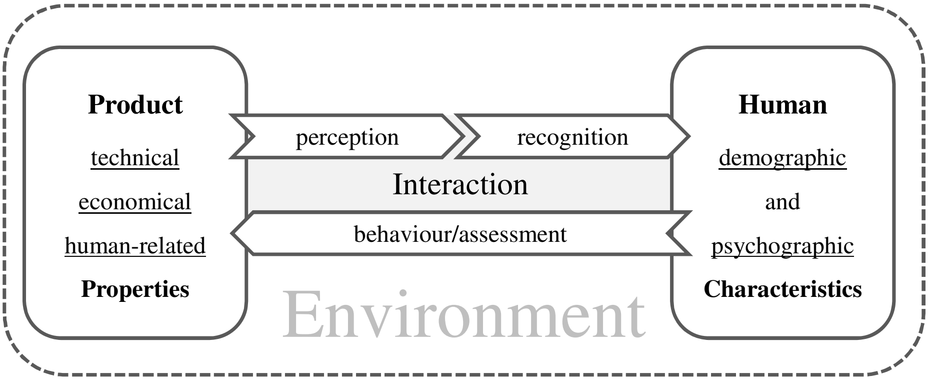

Fig. 1. Model of human-product relationships based on [3]

The objective of human-centered design activities is to create a product whose properties match the characteristics of the user and the environment in the best possible way. Therefore it is crucial for the designer to have as much information as possible on the prospective user and the way the interaction with the product takes place.

This paper examines the application of simulations used to analyze and predict aspects of the interaction between user and product in order to assess design concepts with respect to human-related properties. Based on a literature survey early examples are given where mock-ups have been used to optimize human-machine interactions. Furthermore, examples that illustrate the state of the art are used to reveal which challenges towards a virtual assessment of human-related product properties exist. In addition the authors' recent research activities to address the identified issues are presented. The paper closes with the explanation of future steps to be taken to enhance the simulation of human-product interactions.

2 Simulation in Human-Centered Design

2.1 Approaches towards Simulation of Human-Product Interactions

According to VDI 3633 [4] the term simulation defines a procedure to emulate a real or fictive system including its dynamic processes by means of a model in order to conduct experiments which lead to insights that can be transferred back to the real system. A literature survey has shown that examined approaches towards simulating human-product interactions can be classified as shown in Figure 2.

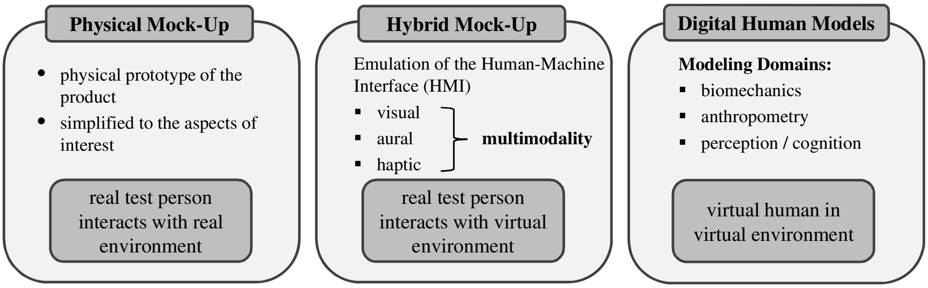

Fig. 2. Approaches towards the simulation of human-product interactions

The most basic idea of a simulation is the physical mock-up. The interaction is examined empirically by presenting a simplified prototype of the product to real test persons. The major drawback of this approach is the expense of time and cost that the making of physical prototypes entails. This can partly be overcome by a hybrid mock-up, a simulation system containing both, physical and virtual components. The idea is to emulate the human-machine interface of the product in a multimodal way so that a real test person is enabled to interact with a virtual prototype. For this purpose elements of the product which require haptic interaction are represented in hardware whereas the visual appearance, aural feedback as well as the physical behavior of the product is reproduced by computer simulations and immersive projection systems. Instead of trying to put the product into reality the philosophy of digital human models is to put the user into virtuality in order to examine the interaction with a virtual model of the product. In product design the human aspects of interest and therefore relevant modeling domains are mainly biomechanics, anthropometry and perception/cognition.

In the following sections examples of the application of simulations in user-centered design are presented based on a literature survey.

2.2 Physical Mock-Ups

The Link-Trainer (Figure 3) has been developed in the 1930s to accelerate the education of pilots including instrument flying. The system uses electric and pneumatic actuators and controllers to mimic the physical behavior of an airplane during flight. Even though the intention of the Link-Trainer is not directly related to product design, it is an early example of a sophisticated physical mock-up used to examine human-machine interactions. [5]

Despite the extensive use of computer simulations in product design physical mock-ups are still being used especially when focusing on aesthetic or ergonomic aspects of a new product. An example is the continuing use of clay models in the automotive industry.

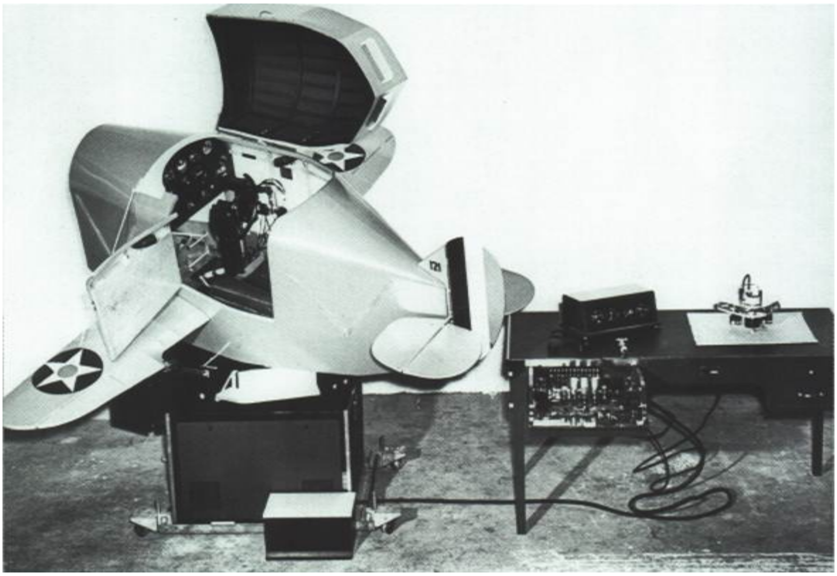

Fig. 3. The Link-Trainer as an historic example of a mechanical simulation system [5]

2.3 Hybrid Mock-Ups and Immersive Environments

The core technology of a hybrid mock-up is virtual reality. The objective is to emulate the behavior of a virtual prototype in a way that it is accepted as real by the user. The effect that the user is no longer able to distinguish between virtuality and reality is called immersion. In product design this can be used to examine the interaction of test persons with virtual product prototypes without having to produce fully functional physical mock-ups.

In [6] a commercially available haptic device (force feedback device) controlled by a dynamic simulation was used to mimic the feel of a manual gearshift typically built into passenger cars. In order to validate the degree of realism a usability test has been conducted with several test persons. The test persons had to assess the forces necessary to operate the virtual gearbox in comparison to a physical gearbox whose mechanical design served as a blueprint for the simulation. Such a system could possibly be applied as a supporting tool during the design of gearboxes in order to find out about what the mechanical behavior of the gearshift should look like according to the customers.

Another interactive simulation system for mechanical products has been presented recently in [7]. The system comprises a stereoscopic projection system, a universal haptic device and a real-time simulator. In a case study the usability of a crank driven car jack is analyzed. The setup can be seen in Figure 4. It is assumed that the usability and user experience is influenced by the interplay of motion and forces imposed on the user during operation. In the present use case the haptic device emulates the crank of the car jack. As soon as the user moves the crank he will not only see the mechanism move but also perceive the mechanical load acting back on the crank. It is important to notice that the system behavior is computed in real-time in dependence of some design variables. This means that the test person can change some characteristics like e.g. the gear ratio and instantaneously perceives the altered product behavior. In this way the users can be incorporated intuitively into design activities.

Fig. 4. Hybrid Mock-Up of a car jack [7]

2.4 Digital Human Models

Digital human models aim at the virtual representation of the human appearance and behavior. These usually cover just partial areas of the huge variety of human properties and abilities. Most models are specifically made for delimited use cases such as anthropometric, biomechanical, anatomical or cognitive analyses. [8]

The three most commonly used man models in industry are *Jack* (Siemens PLM), *Human Builder* (Dassault Systèmes) and *RAMSIS* (Human Solutions) which are shown in Figure 5. [9]

Jack for example is mainly applied for the evaluation of the interior design of vehicles. In contrast *Human Builder*, initially named *Safework*, was made for workplace design but nowadays additionally offers tools for anthropometric and comfort analyses. In this regard, comfort analyses evaluate static poses regarding their joint angle constellations. *RAMSIS*, the most popular man model, additionally consolidates extensive methods for the simulation of the comfort inside vehicle systems such as mirror, seat and belt analyses. [8]

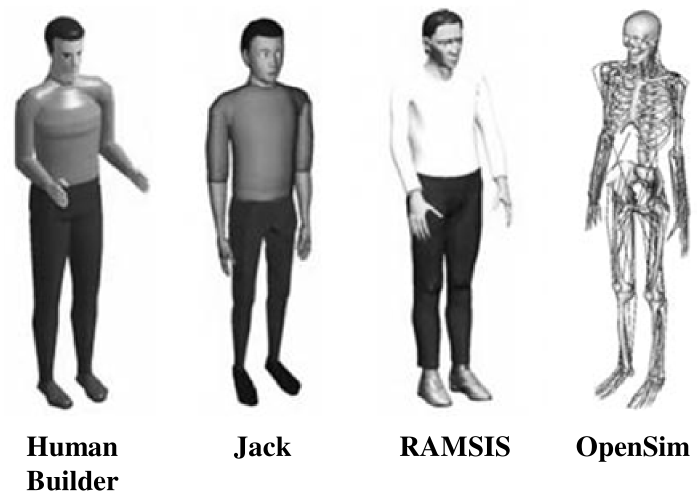

Fig. 5. Important Digital Human Models based on [9]

Jack, *Human Builder* as well as *RAMSIS*, as examples for anthropometric digital human models, are available inside predominant CAD systems and are therefore capable of examining interactions between users and products. They consist of a skeleton and a skin model and are mostly scaled using anthropometric databases before ergonomic analyses are conducted. Anthropometric models are powerful tools for visualizing reach spheres as well as the field of vision. On the other hand the main weakness of pure anthropometric models is that these manikins usually provide just static and comfort analyses and hence cannot take the physical dynamic effects of body movements into account.

To consider these effects as well as to analyze muscle and joint loads, biomechanical digital human models are being developed. These models still lack wide application in industry, not least due to unresolved issues concerning the consideration of user-product interactions. Consequently, their biggest field of application is still in research. Biomechanical models, also known as musculoskeletal models, commonly contain a skeleton, modeled as multi-body system, as well as muscles acting as actuators. The underlying simulation systems are capable of conducting dynamic simulations, whereas muscle forces and activations can be determined. These can be regarded as the cause of a given motion behavior.

RASMUSSEN et al. proposed musculoskeletal modeling as an ergonomic design method as well and therefore developed the so called *AnyBody Modeling System*. To confirm their hypothesis, they optimized the design of a hand saw handle and analyzed the forces acting on a human sitting on a chair. [10]

An example for a freely available biomechanical simulation environment is *OpenSim* (Stanford University) which can be seen in Figure 5. [11]

MOES and HORVATH are following a completely different approach. They are using finite element models of the human body, for example for the optimization of seat shapes. [12]

3 Need for Research and Recent Activities

The examples presented in the previous sections provide a good outline on the existing possibilities to simulate the interaction between users and products. When compared to physical and hybrid mock-ups, digital human models have considerable pros with respect to flexibility of application, time and costs. Since the simulation takes place entirely “in silicio”, no expensive prototypes or specialized hardware devices are necessary. Therefore digital human models are ideal for a continuous application throughout the whole product development process starting from early conceptual phases. Because it can be expected that results become available in a comparable short period of time unavoidable design iterations are accelerated. However digital human modeling is a challenging field of research. Even simple human-product interactions like the opening of a car door, involve highly complex cognitive and sensorimotor processes which up till today can’t be described using deterministic mathematical models. State of the art simulation systems therefore are based mostly on phenomenological approaches. Biomechanical analyses e.g. like those presented in [10] use recorded and therefore empirical motion data in combination with inverse dynamics and numerical optimization to determine muscle activation patterns. The standard process of gathering those motions is usually associated with costly marker-based motion capture techniques. Aiming towards a purely virtual simulation procedure this approach has to be considered problematic since the motion which determines the interaction with the product is observed rather than predicted. Therefore further effort has to be put on the improvement of motion prediction procedures. One possible approach is to combine forward dynamics computations with numerical optimization methods. The major drawback of this approach is the extremely high computational load. A simulation of half a human gait cycle [11] required more than 10,000 CPU hours on a machine featuring 32 cores.

The authors’ research activities therefore focus on fast, simplified simulation approaches that enable product designers to access the power of biomechanical simulations. In [13] the integration of such biomechanical simulations into engineering environments is proposed. The underlying framework is depicted in Figure 6. For a successful biomechanical analysis the applied digital human model has to match the corresponding real person performing a specific task. To achieve this goal a tool for the fast acquisition of body measures has been implemented using the inexpensive markerless depth imaging device Microsoft Kinect. The gathered data enables the calculation of scaling factors for each body segment and eventually enables the scaling of the used OpenSim model. The mentioned tool additionally allows the markerless capture of body movements which are being used to extract the underlying motion styles which in turn are used as reference in the synthetic generation of realistic motions. The mentioned simplified approach comprises advantages of inverse and forward dynamics simulations. The interaction between the simplified kinematical dummy and the virtual product model (e.g. CAD geometry) is defined by some geometric motion objectives. These serve as boundary conditions for the inverse kinematics simulation, which can be solved in real-time. The functioning of the inverse kinematics solver is described more detailed in [13]. The result of the inverse kinematics step is a motion sequence. This motion has to be calculated taking the motion style of reference motions into account to achieve the natural motion behavior of real humans. Additionally the external loads acting on the human body while conducting the calculated motion sequence are to be obtained by some CAE simulations. The calculated motion data as well as the external loads are then transferred to the scaled biomechanical digital human model to execute the biomechanical simulation where the desired dynamic quantities and eventually muscle activation patterns can be computed. In [13] the mentioned motion generation approach is demonstrated by a steering motion, whereas the driver's hand follows the circular trajectory of the steering wheel and the torso is fixed to the car's seat.

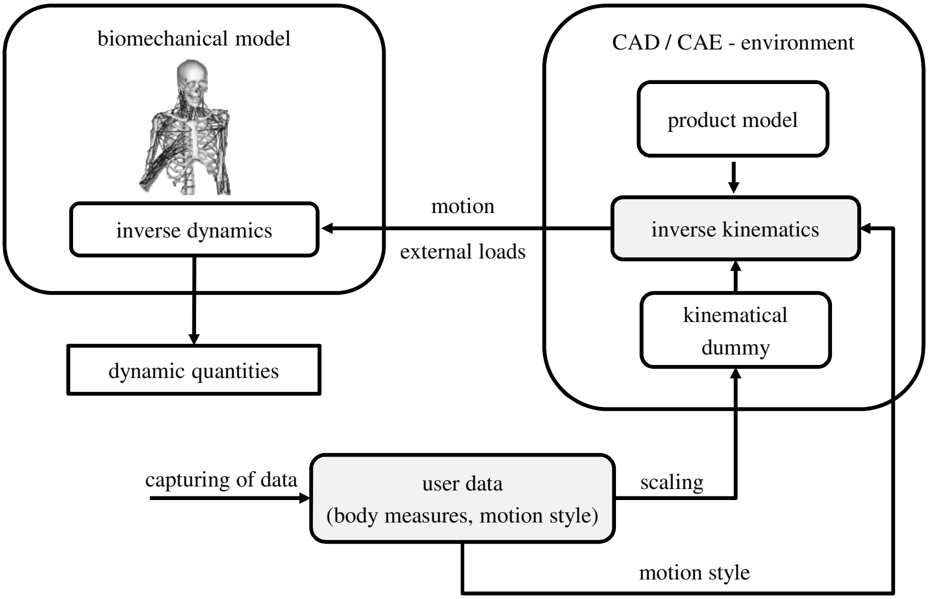

Fig. 6. Simulation Framework [13]

4 Future Prospects

Biomechanical digital human models appear to be the most promising ones for future applications in the field of product development due to the possibility of considering dynamic effects of the musculoskeletal system. The main reasons to integrate biomechanical man models into CAD/CAE environments are to increase their acceptance and consequently their application among product designers as well as to improve the simplicity of their use to enhance their efficiency. The configuration of user-product interactions should therefore be easy to model. Thus, the motion generation should work without the need for captured motions. A promising attempt to accomplish these objectives is already done by using an approach based on inverse dynamics as stated above. The mentioned methods still have to be refined to be able to fully describe the interactions between the human body and a product or environment, especially the synthetic generation of natural motions taking into account external loads. This would eliminate the necessity for motion capture techniques. Furthermore tools have to be developed to enable product designers to compare and optimize product variants without deep knowledge in biomechanics and human factors engineering. Additionally the development of individualized biomechanical digital human models should be promoted, which can then be utilized for the evaluation and optimization of products regarding individual users or user groups. These models should then be able to take into account for example differences in maximum isometric forces and range of motion extending the currently existing scaling functionalities. [13], [14]

5 Summary

In this paper a general motivation for simulation in human-centered design has been given. Due to the virtuality of digital human models as well as that no physical product prototypes are necessary for their application they can be used even in the early stages of product development. In general they are flexible to use, but still face some issues to be addressed in future research. Biomechanical models currently seem to be most promising for sophisticated applications in the field of product development. The decisive advantage over other model types is their possibility of taking dynamic effects of the musculoskeletal system into account. Moreover, these emerging virtual methods are to be incorporated into contemporary CAD/CAE environments to further increase their acceptance among product designers. Nevertheless, there are still reasons which justify the existence of hybrid and physical mock-ups, especially when emotional product properties are to be evaluated like for example the shifting sensation in virtual gearshift simulations or the haptic perception of consumer products.

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Distance Collaboration Support Environment

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Abstract. This paper explains a new distance collaboration support environment for use in product development processes. This environment makes it possible to organize a meeting with up to eight stakeholders in two locations, where there is minimal distraction by the distance. Not only audio and video are shared, but also physical products placed on a table and hand movements are visible for each participant. This allows for pointing with a finger at objects which are only present at one location. All these technological possibilities are integrated in one physical setting to minimize start-up times and to ensure that all remote locations are comparable. Consequently, so participants know exactly what participants at the remote location see.

Keywords: virtual reality, multi-stakeholder, distance collaboration, virtual presence.

1 Introduction

Working in a group setting implies communication and collaboration with other stakeholders to share thoughts and opinions on certain aspects within the development process. The most commonly used method to actualize the need for communication and collaboration is in the form of a meeting. These meetings are often facilitated by communication equipment to enhance the possibilities and methods for collaborating. This varies from a simple audio connection by telephone, to a live video supported workspace. Even though the availability and possibilities of the equipment is constantly increasing, a noticeable difference remains between local collaboration and collaboration over a distance.

2 Collaboration in Product Development

In current product development cycles, the need for fast decision making, incorporating external expertise and collaborating with other (remote) stakeholders is crucial. In order to utilize the expertise of all different stakeholders to its fullest extent, the way of mutual interaction should be as little disrupting and distracting as possible. This presupposes an effective connection between different stakeholders during the various phases of a project. Traditionally, this results in consequential travelling efforts. In

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reducing the inefficiencies involved in travel and doing justice to the relevance of collaboration amongst (global) stakeholders, the need for adequate remote collaboration tools is increasing.

Tradition entails that the most common way of interaction in a project is by means of a meeting. They are often organized with a specific goal in mind, based on the available participants and the current state of the product development. This implies that different meetings require different set-ups, working methods and tools.

3 Remote and Local Meetings

A clear distinction, which is independent of the goal and aim of the meeting, can be made between meetings taking place at one location (sharing the same environment) and meetings that involve stakeholders at multiple locations (i.e. not physically in the same environment). The way in which a meeting is organized and held is often based on the location of the participants, the available budget or time and the goal of the meeting. The purpose of the meeting has direct consequences for the required types of communication; the challenge is to define on beforehand what communication and interaction possibilities are necessary and useful.

Currently, research efforts are directed towards nullifying the differences between ‘local’ and ‘remote’ meetings. As such, the intent is to address ‘remote’ meetings as if they were ‘local’. Technical means are employed to get across the disadvantages of not being in the same environment.

Yet, there still is a substantial difference between local and remote meetings; in general, a local meeting (with participants sitting in the same environment, experiencing the same equipment, around the same table) is experienced to be more efficient and natural.

In the future, there might be different means to structure, configure and deploy meetings that involve multiple locations. For short and mid-term solutions, focus should, however, be on diminishing the dissimilarities between local and remote meetings by improving the technical means and working methods that facilitate the remote meetings.

4 Distance Collaboration

4.1 Disadvantages of Current Approaches

Currently, remote meetings often only use video and audio communication equipment to enable visual and aural communication. With these video conferencing systems, a combination of camera and microphone on each location is used for recording, while playback is done on monitors or televisions. The availability of tools to facilitate this form of communication is increasing continuously, where the quality of the video and audio increases. Interestingly enough, above a certain threshold, the quality of the video and audio signal not necessary increase the quality of the meeting.

Communication tools often allow for the integration of additional functionality like screen sharing, virtual whiteboarding and file sharing. Such additional functionalities enable participants to extend collaboration beyond merely audio and video, thus addressing for example sharing of information, documents and even haptic feedback. The need for such possibilities stems from the wish to present and discuss digital and physical content belonging to the project, rather than only having a spoken discussion.

Nevertheless, no video conferencing tool covers the entire spectrum of possible collaboration methods. Moreover, as mentioned, they do not provide the same experience as sitting together at a table. The reason for this is that in local meetings, much more aspects than just seeing someone's face and hearing his voice are relevant; also objects and information on the table or body language provide us (even subconsciously) with information.

Most videoconferencing systems show a video of the participants as if looking through a window, while in actual local meetings the participants are not cooped in a rectangular frame. During remote meetings, people often are distracted by background activities of both the local and the remote locations. This also implies an interesting requirement since people get a distant feeling if differences in weather or time are visible during a meeting.

Moreover, it is usually not clear what every participant can see and observe. This results in a lack of feedback from the other participants, causing them to doubt if others actually heard and understood what has just been said. Participants often complain that a lack of feedback from other participants, either aural or visual, caused much repetition and explicit confirmation request [1]. Frequent repetition of statements, and frequent meta-interactions "did you hear what I just said" obviously hamper the content and progress of the meeting. As such, the organization and execution of the meeting often becomes one of the most important topics of the meeting. Therefore, in many meeting it is infeasible to separate the means and ends of it.

Not only the lack of feedback from other participants due to indistinct and distracting technology can cause a feeling of distance, the awareness of the communication system itself is likely to create a feeling of distance as well [2]. This awareness can, for example, arise if the users experience the system as an explicit interface between them, or when dynamics in the meeting (e.g. with respect to the number of participants) imposes a physical re-arrangement of equipment.

A meeting with the use of video conferencing equipment is often experienced as less personal, because participants felt as if the speaker was addressing them as a group, and not as individuals [3]. This mainly occurs because eye contact isn't possible, and when the sound direction is independent from the source of the sound. The risk of misinterpretation of communication is always present due to misreading body language. This can have technical causes, e.g. by lag or hiccups in the connection; more often than not the cause is non-technical, as traditional video and audio equipment is simply incapable of transmitting the signals related to body language. This can also be caused by receiving an incomplete image of the remote participants, because a face can express a lot of emotion but it does not reveal nervousness visible by shaky hands [2], [4].

Furthermore, reviewing and discussing shared objects is problematic, because it is not possible to physically point at (shared) objects, which makes it difficult to discuss specific parts of the objects. This issue especially occurs when reviewing digital data with more than two persons, or when explaining a specific point on a physical object which is available on only one location. In these cases the need for seeing the arms and hands of the participants is a first prerequisite. Where a person's eyes can quickly change focus from a presenter's face, his pose and the object of discussion, this is well-nigh impossible to achieve with video conferencing equipment.

4.2 Requirement Specification for Support Environment

Based on the previous paragraph, supporting distance collaboration can be done by confining the environment of the meeting, to enable the participants to know what to expect. In a support environment the participants should not be seen as remote locations 'connected by wire', but a virtual environment should be created where all stakeholder seem to participate in. This confined environment, like a table, can be present in all remote location and other stakeholders can virtually 'join' all tables. The environment should virtually project all stakeholders on each other's real-world setups; having the same setup enables this.

In this environment it is essential to not only see the face and facial expression in real time, but also physical activity of all persons at the local and the remote table. The perspective of this visual feedback of the remote location should closely resemble the perspective of the local table. Furthermore the ability to share physical items to the meeting will increase the clarity of discussed objects. In addition to visual feedback, it is also of great importance to hear the voices of all participants, where any participant must be able to locate the origin of the sound. To achieve this, the audio playback location should closely resemble the source of the sound. To further enhance the cooperation the environment should offer a digital work space that is shared by all persons at the local and remote table [5], [6]. This offers the opportunity to see in real time what other persons are working on in project documents, from everybody's own perspective.

5 Distance Collaboration Support

An integrated solution for distance collaboration can dispel the disadvantages of current communication means and methods. A dedicated distance collaboration environment to facilitate meetings is composed to create a physical setting in which remote meetings are experienced and executed as similar to local meetings as possible. In the case study described here, the meeting is based on collaboration between two locations with up to 8 participants. This is not doing justice to the more generic requirements as stated in section 4 yet it enables to investigate the essence of adequate collaboration between two locations. Consequently, users should be able to have a meeting with people at the other physical location with minimal distraction by the distance. Activities during these meetings consist of for example the planning of activities, reviewing data, concept development and decisions making. More communication technologies and possibilities are added to create a common ground to work on, and to transfer current possibilities and use practices of local meetings to remote meetings.

As a rudimentary initial solution, an oval shaped table with eight seats has been selected (figure 1). Four of these seats are physical present at the location of the participant, and four of them are the virtual copies of the seats at the other locations.

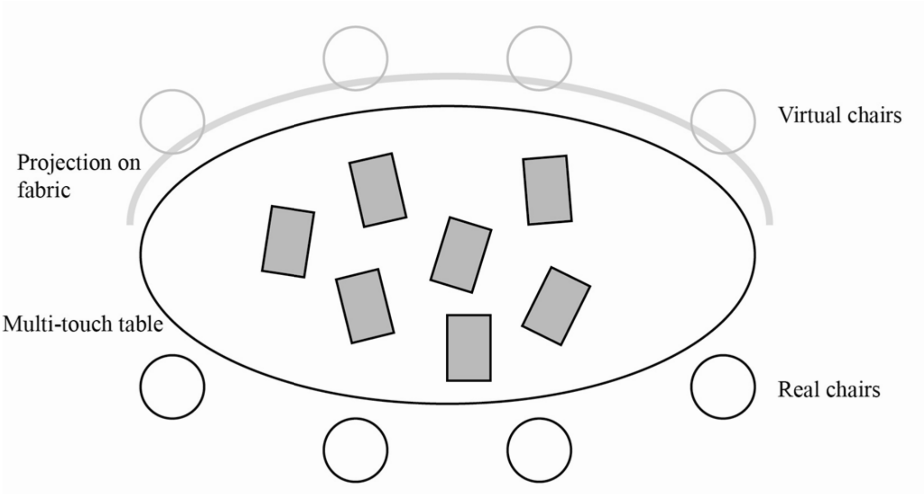

Fig. 1. Schematic overview of the table

5.1 Audio and Video

To establish an environment that allows for the virtual presence of the other (up to four) participants as realistically as possible, the participants are viewed using a camera located at approximately eye level. The image of the virtual participants is processed to remove all the background, leaving only the character. This image is projected on a half-transparent fabric which is suspended on one side of the table (figure 2). The projected image of the participants has the same physical dimensions as the captured image, to achieve a real-size view of the remote location. This results in a projection where only the participants are visible, and the viewer sees the participants in his own local environment. This avoids distraction by the background of the remote location. Also the feeling of looking at a screen is minimized because there are no clear boundaries of the projection. Because of the fixed configuration, it is possible to see who is looking at who, and to have eye contact (figure 3).

Furthermore, the voice of each participant is individually recorded and played on a speaker that approximates the direction of the source. This makes it easier to discern what sound comes from which participant, even without having to look at the screen to see which mouth is moving or to know the voice of every participant. It is clear that this solution will reduce the necessity for exact synchronization of video and audio that is paramount in traditional video conferencing. As such, an obvious source of distraction is removed.

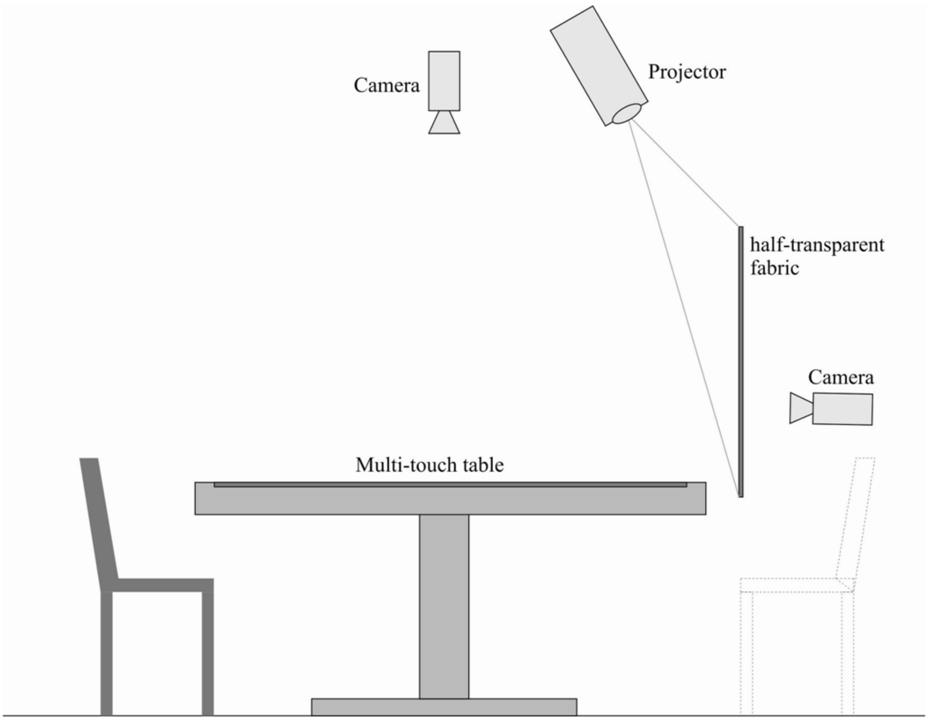

Fig. 2. Overview of the configuration

5.2 Table

To add to the realism of the meeting, the envisaged environment facilitates more than only an audio and video connection. The tabletop of the oval shaped table contains a large multi-touch screen, which shows the same content at both locations. Both locations have the ability to manipulate content on the surface by touching it. While using the touch screen, the arm and hand of the user are captured using a camera placed above the screen, and projected on the tabletop at the remote location. This makes it possible to point at a virtual object projected on the tabletop, while the participants at the remote location see your arm and hand moving over the screen. This also allows the users to place physical objects on the tabletop, varying from paper documents to 3d objects, and point at them with a finger or adding comments to it using the touch-screen (figure 4, 5). The possibility to work on shared documents, images or drawings, in a real-time editing functionality is an important feature in the collaboration process, and highlights the direct interaction of the multiple participants on a shared data collection.

Fig. 3. First test with the configuration

Fig. 4. Sketch of the tabletop

Fig. 5. Photo of the tabletop during the test session

5.3 Advantages of an Integrated Setting

All these technological possibilities are integrated in one physical setting to minimize start-up times and to ensure that all remote locations are comparable. Consequently, participants know exactly what participants at the remote location see. Moreover, assessment of body language is better possible, because the viewable area of the remote participant is the same as if he would be sitting at the table at the local location. Even hand gestures on the table can be recognized because they are captured and projected at the remote location. The recognition of these hands also allow for version history whereby every action of individual users is captured. This information can be processed further to review the design rationale of the stakeholders, or to analyze the process of decision making.

6 Discussion

Existing videoconferencing systems have some limitations which could hamper the collaboration process. One of the main drawbacks of those systems is the feeling of looking through a window, as seen by e.g. the HP Halo, Cisco Telepresence, Polycom TPX, MultiView by University of California and FP7 3DPresence [7][8]. Furthermore most of the current systems do not visualize the arms and hands of the user if they are placed on the table, although the im.point by Fraunhofer and Cisco Telepresence show a virtual shared desktop. Another big drawback is the distraction caused by showing the background of the remote participants and the lack of an interactive tabletop.

The proposed collaborative environment offers new and expanded opportunities to facilitate collaboration. It combines various techniques in a dedicated environment. Of course there are also some limitations in this setup. There is a risk that a virtual participant will look at an object in his environment that is not available in the local environment of other participants, and is out of scope for any camera. This can be disruptive for other participants because it is not visible where the distraction comes from. In addition, the main objection is that this arrangement is suitable for only two locations. This means that the envisaged environment is not suitable yet to replace existing video-conferencing systems which offer group discussion with more than two locations. It is also of great importance to ensure that all interaction possibilities be-tween both locations are synchronized. Any deviation of any of the feedback possibilities will disrupt the process.

7 Concluding Remarks

The use of a dedicated distance collaboration support environment shows many advantages seen in terms of ease of use and mutual understanding between stakeholders. The main advantage is that the sense of distance is minimized, because compared with current video conference systems more information is shared with both locations. But mainly because the shared information is presented in a more ubiquitous and unified setting, the stakeholders are less distracted by the used technologies. Due to the use of low cost and off the shelf available technologies the presented configuration can easily be duplicated to more locations and allows for faster espousal.

7.1 Future Developments

Based on the findings of this first version of our proposed collaboration environment some directions and challenges for future developments can be determined. First of the table should allow for collaboration between more than two locations. In an ideal setting every seat should have the option to be a virtual or local seat. This makes the setup more flexible, and reduces any noticeable difference between local and remote participants.

Furthermore the integration of a version control and history system is considered. This allows changes to be assigned to specific individuals or stages within the process. This information can be used to examine which effects can be assigned to which choice, but may also provide insight into how the participants deal with the method in order to bring improvements.

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Technology Framework for Product Design

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Abstract. The management of product design relevant information in the context of technologies is getting more and more relevant in industries and research. In this paper a framework is introduced to support the management of technology in extension to existing PLM concepts. Moreover, the Technology Object (TO) as one main building block of this framework is presented. With the TO it is possible to represent information which is relevant on technology level – instead of on product level. Furthermore, dimensions of information are introduced that help to describe each TO; such as requirements towards this technology or performance capabilities which a technology is able to fulfill towards the respective environment. This paper focusses on concepts and methods in context of the introduced Technology Framework.

Keywords: Product Design Information, Product Lifecycle Management, Technology Management, Technology Framework, Technology Object.

1 Introduction

Global companies working in the manufacturing industry represent a major part of the economic power in many parts of the world. The engineering processes and design capabilities are the core competences and the heart of those companies. Capturing and managing the product design information is a key success factor.

Looking into the most innovative and successful companies it becomes obvious that only capturing product data is not enough, when aiming at constant innovation and growth. 35% of interviewed companies stated as relevant to include the most cutting-edge technology in their products [1]. This paper will discuss the need of introducing a new layer of product related information to be able to manage technologies – instead of just products. The introduced framework is aiming to better support a holistic view on technologies to benefit cross products and product lines. This paper focusses on the elaboration of concepts and methods to manage relevant information. It is not aiming to provide IT solutions or tools, which will be subsequent supporting tasks. Moreover, the framework enables designers and engineers to enrich design data with cross-product-lifecycle information (e.g. manufacturing, sales or recycling).

To establish such a framework, the following research questions have to be answered.

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Research Questions

- Which information is required to (better) support the management of technologies and innovation?
- How can this information be captured, formalized and incorporated into a technology framework?
- Which building blocks of the framework exist and need further research activities?
- How would existing PLM systems need to be enhanced to implement such a technology framework?

The outline of this paper is as follows. First, it will analyze the state of the art elements that frame the topic of this paper - starting with Product Lifecycle Management and Technology Management. Fig. 1 positions these two concepts in the field of the project and management processes in engineering design. Second, after identifying deficits and deriving needs for action, we will introduce the framework and describe main building-blocks and focus on the Technology Object as one key element. Finally, the views of research and industry are discussed, and in the conclusion and outlook further research steps are elaborated. We understand this paper as a building block in a series of contributions in this research area [2], [3]. It will set the frame and focus on identifying the needs, and it will propose research and solution approaches.

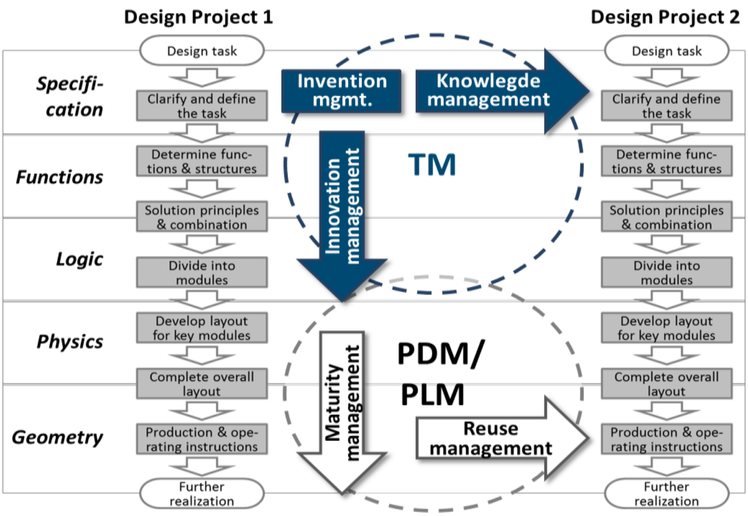


Fig. 1. Positioning of Technology Management (TM) in relation to Product Data/Lifecycle Management (PDM/PLM) and design project processes (example: VDI 2221)

2 State of the Art – Industry and Research

2.1 Product Lifecycle Management

Product Lifecycle Management (PLM) is a strategic management concept for managing products along their lifecycle. Multiple definitions of PLM do exist in literature.

Eigner includes in his definition several elements to support a broader view on the topic: management functions, material sourcing, customer needs management, product data management, manufacturing engineering management and engineering collaboration [4]. Product Data Management (PDM) is often seen as the parent of PLM. This is not correct. PLM, as seen above, is a concept and not an IT system. As a consequence, PDM in contrast to PLM can be bought as a system; moreover, PDM can be a component for the realization of a PLM concept. Other typical components within a PLM concept or solution include Computer Aided Design (CAD) tools or Team Data Management (TDM) systems. [5]

Especially in discrete manufacturing industry PLM is well-known and already seen as a key enabler for efficient product information management [6]. Narrow views on PLM often focus just on the IT dimension as a supportive tool for established business processes and methods, then mainly in the form of Product Data Management (PDM) systems. In a broader understanding however, PLM features four dimensions of: organization, processes, methods and IT; all of them being interlinked and not to be addressed independently [3]. Mainly used in the design phases of the product lifecycle PLM often doesn't play an important role in the later phases. These phases often are more penetrated by solutions of Enterprise Resource Planning (ERP) [5].

The PLM concept can be described in multiple ways [4]. From an economic point of view the so called Product Lifecycle Curve is used in many articles. This curve reflects the typical approach of sales figures along the product lifecycle phases per product.

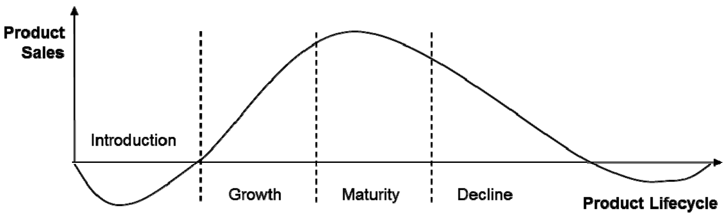


Fig. 2. Product Lifecycle Curve (following [12])

Beside the more or less well-established PLM/PDM approaches in industry several existing information modeling frameworks exist. The following sub-chapter helps to frame a common understanding of modeling in the context of this paper.

2.2 Design Information and Knowledge Modeling

Research View

The research work of this paper can be positioned in the context of related work on the example of two concepts which set boundaries in terms of modeling of design information and knowledge. One well-known research work is the Characteristics-Properties Modeling [10] of Weber. In his work, Weber focusses on design knowledge in terms of characteristics and properties on product level. Moreover, different types of relationships are described that drive the behavior and the order of existence of the different elements of the model. Another well-established research work from Dankwort is the concept of Engineering Objects in design context [11]. The Engineering Object is described by properties which are linked to the environment the object is used in, such as context and person.

Both research areas which focus on the product level are well-established approaches in the modeling of engineering information, data and knowledge. For this reason this paper will utilize the results and way of working of those approaches and will try to leverage experiences and principles of modeling to the technology level.

Industry/IT View

In industry, design information modeling is often left in the responsibility of the IT systems (i.e. PLM and/or ERP systems) applied. IT system suppliers provide information models underlying the data models of their systems. They generally follow a pure product centric view, braking product programs down to the level of single components with the respective data. With their database foundation, they may also be able to handle technology oriented objects; they do however not provide any concepts or methods dedicated to that. [13]

2.3 Technology Management

Technology management describes all activities and methods which are required to make a certain technology usable for industries. A technology describes the fulfillment of a requirement by a technique. Both terms are used in literature and business context not distinctly. In this context the term technology will be used also as a representation of a technique.

Technology S-Curve

The Technology S-Curve is a model within the discipline "Management of Technology" which describes the technology performance along the R&D effort spent on the respective technology, see figure 4.

This model is used in industry to support strategic business decisions, especially regarding innovation investment decisions. This model can be used as a retro perspective view on a specific technology or used as a forecast method by reference to a defined point in time (t0). The Technology S-Curve used as a retro-perspective view allows recapturing information on the performance of a certain technology. Based on this guidelines and boundaries can be derived and transferred to new or other technologies. A proactive steering of the investigated technology itself is not possible. To utilize the S-Curve in terms of a forecast a challenge is to get reliable data for both axis to depicture the curve and by this the expected performance of the technology. Beside these spotlights on the Technology S-Curve this model is discussed with its pros and cons in literature, showing the boundaries and limitations of this approach.

Technology Management Process

The Technology Management Process describes the activities within technology management. In industry and research literature several variants of the process are presented. Figure 3 reflects the high level view on this process.

The first phase of technology screening covers all activities which are related to the identification of new technologies. In this context new technologies can belong on the one hand to already existing technologies which are transferrable from other industries, products or markets. On the other hand new technologies can represent results from research and development activities - for technologies which did not exist before.

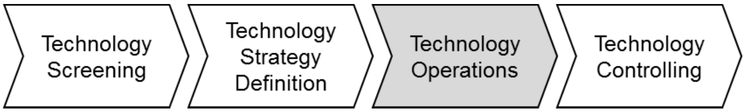


Fig. 3. Technology Management Process

After the pure identification of technologies these are analyzed and brought into an order of priority according to the individual needs of an institution or a company. Activities related to this phase are bundled in the technology strategy definition. The technology strategy is derived and linked to the business strategy in the industrial context. At the same time the technology strategy has an influence on the business strategy. For example new identified technologies can have huge impact on existing technologies where a company earns its money with.

The technology operations phase reflects activities in the day-to-day usage of a technology in products and operational processes of a company. The Technology Framework introduced in this paper can be positioned in this phase of the technology management process.

In the phase of technology controlling all technologies are managed and tracked. Methods like the S-curve model can be used to support these activities.

3 Technology Framework – Situation

3.1 Multiple Product Context

As described, currently the focus in management of design information is the single product or product families and their related information. There is no doubt that this information is a key element for companies in the discrete manufacturing. But looking into innovative and successful companies the potential of capturing information on a more abstract level – cross products and product families – promises a huge impact.

Looking for example on the European Aerospace Industry where knowledge in the area of carbon technologies are existing and companies are preparing to apply these technologies in other industries like the automotive industry. Another example is the consumer goods industry where a technology (cyclone to spun dust out of the air by centrifugal force in sawmill) originating from the agriculture industry was successfully adapted and became one of the most popular household machines in UK and the USA [8]. A way to reflect multiple products in the context of a single technology lifecycle is depictured in figure 4. [7].

This curve can be used to reflect on the one hand the usage of a single technology cross multiple product releases or product variant. This is used for example for so called “face-lifts” in the automotive industry where a specific car release (e.g. the Mercedes-Benz A Class) is introduced to the market.

On the other hand this approach can be used to indicate the usage of a single technology cross products or product lines which are not derived or dependent on each other. As described above the cyclone technology has been used cross products – sawmills and vacuum cleaners.

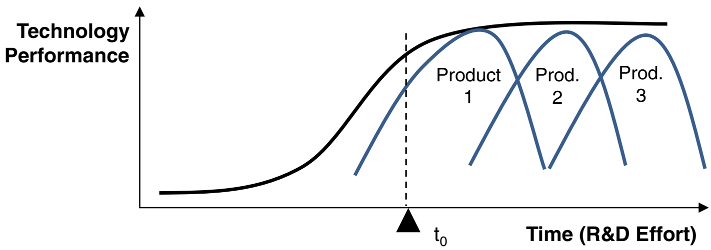


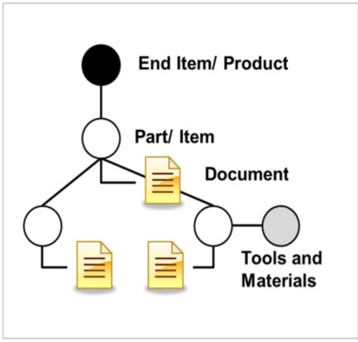
Fig. 4. Technology S-Curve with multiple products (following [7])

3.2 Information Management

The new Technology Framework – introduced in this paper - is an evolution of the traditional design information approaches Product Data Management (PDM) and Product Lifecycle Management (PLM). The Technology Framework (TF) describes an approach to bundle product data, process & production information across products and product families on technology level. Moreover, the TF is evolved and influenced by other modeling approaches and reflects ideas that are currently neither well established in research nor implemented in design departments and companies. A main building block of the TF approach is the holistic information modeling approach [3] – independent of currently existing IT tool boundaries (e.g. PLM systems vs. ERP systems) and based on information of related technologies. Currently in research and industry the focus is on product level and not on technology level.

Figure 5 shows a typical information model of PLM concepts, reflecting the product from top-down via an end item with a structure of physical parts or items below. Moreover, product related documents are attached along the hierarchy. PLM information models often allow including also manufacturing information – such as tools and materials.

The intent of this framework is to enlarge this product centric approach and enable a holistic view on engineering technologies without product boundaries to enable innovative product design and create engineering value. Contemporary Product Data/Lifecycle Management is thereby taken a step further to better support knowledge, technology and thereby innovation management. The framework intends to create a so called “Technology Layer” which enables engineers to store and manage product design information. Figure 6 indicates the Technology Layer as a new layer above the well-established Product Layer – managed by PLM.



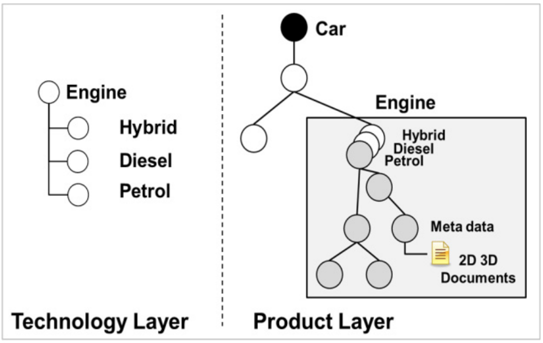


Fig. 5. Typical PDM/PLM Information Model

Fig. 6. Technology Layer vs. Product Layer

The intent of the Technology Framework is to provide the ability to model technologies independent of real physical parts that are reflected in an engineering product structure by PLM. As an example a product is reflected in a product structure and contains one specific item that represents the engine (in this example). In the product structure various types of engines are reflected as variants. On the technology layer an instrument is needed to be able to reflect these variants independent of the product where they are currently used in. This starting point is one main driver for the work on the technology framework presented in this paper.

4 Technology Framework – Building Blocks

4.1 Building Blocks

The Technology Framework is an approach to support product design information. The framework consists of four main building blocks, see figure 7.

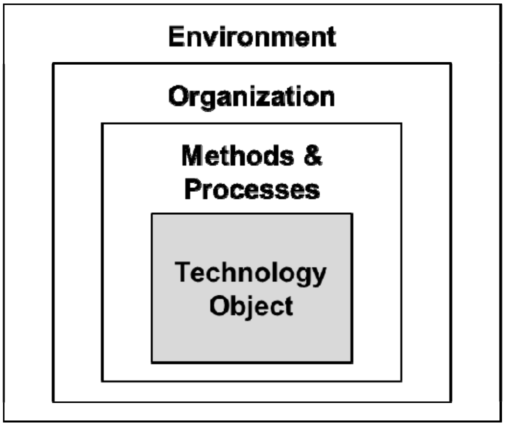


Fig. 7. Technology Framework

- The **Technology Object** as a core building block of the framework reflects key product design information on the technology layer. This paper will focus on this building block since this is the base for developing and deriving other building blocks of the framework.
- The building block **Methods & Processes** utilizes the defined elements of the technology object and defines the way of using the objects by engineers and end-users. Moreover, behavior and rules per object and in structures of objects will be described.
- The **Organization** building block addresses topics and requirements that are related to the business organization where the technology framework will be used. The focus here will be on a single entity (e.g. a company or institution) – in contrast to the next building block.
- The building block **Environment** covers the interacting area within a network of entities (e.g. companies, supply chains and interaction with customer and market).

4.2 Technology Object

Within the Technology Framework the Technology Object (TO) is described. The TO is used to reflect the lowest granularity of the framework; it can be described by four dimensions, see figure 8.

Technology Specification
The specification of the technology allows the engineer to describe all characteristics regarding the technology and the required behavior of the technology or part of technology. Specifications should allow capturing varieties of information, such as technical or economic requirements. Industrial examples are patents, guidelines or public warranties – such as allowed car emission values.

Products – Where Used
This dimension indicates where this technology is used. By this one or several products are associated with the technology and allow cross referencing with product design data. This element in the framework supports to reflect the information displayed in the technology S-curve above.

Performance of the Technology
The performance of the technology is the dimension to describe the outcome and the impact of a technology on the environment. The environment can be other technologies or the usage scenario the technology is designed for and working in. An example for performance characteristics of the technology "car engine" can be maximum turning moment or maximum emission heat.

Interlink – Connecting Technologies
The interlink dimension allows to reference from one technology to one or more technologies. For technologies on the same level of granularity this can be used to define substitutes or similar approaches. Moreover, variants (configuration options) of technologies can be reflected. For example: technology "engine" can have variants of "diesel" or "petrol".

For technologies on different levels of granularity this dimension enables the engineer to reflect technology structures. An example of a technology structure could be that the "cyclone technology" [9] and the "ball technology" are located under the technology end item "vacuum cleaner". By this the engineer is able to reflect interdependencies and create structures between technologies of different levels of granularity.

The introduced four dimensions of a Technology Object allow defining an object and the context this object is operating in. With this paper the basic boundaries are described and first research approaches are defined.

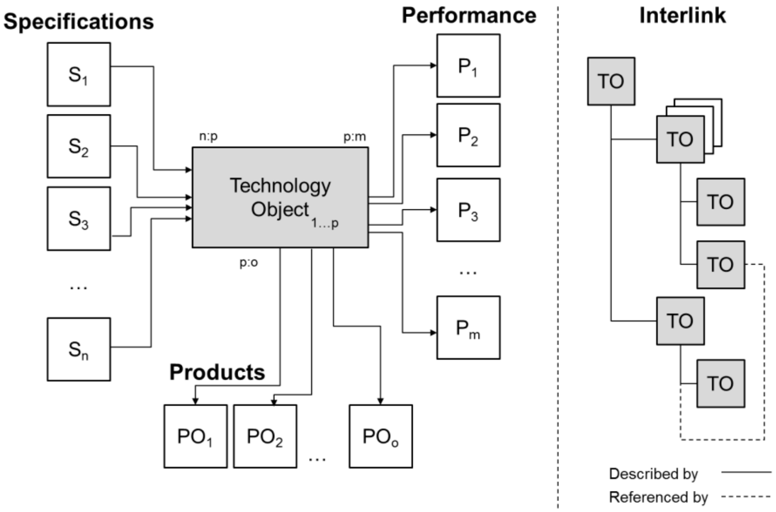


Fig. 8. Dimensions of Technology Object

5 Discussion and Further Work

In chapter 2 with the state of the art a gap between the PLM concept and the approach to manage technologies was elaborated. With PLM usually the engineers focus on the product level. Within the Management of Technology technologies are reflected on a high level without direct relations between technologies and sub-technologies. Based on this situation, the Technology Framework was introduced in chapter 3. To recap and derive a conclusion on the research work presented in this paper the defined research questions are discussed in the following.

- **Which information is required to (better) support the management of technologies and innovation?**
  The framework introduced four main building blocks to reflect the required information for a technology.
- **How can this information be captured, formalized and incorporated into a technology framework?**

With this paper a first element of the framework was introduced – the technology object.

- **Which building blocks of the framework exist and need further research activities?**
  Starting with the technology object, methods how to use the object and on the behavior of the object need to be elaborated within the next research activities.
- **How would existing PLM systems need to be enhanced to implement such a technology framework?**
  At the early phase of research activities, it is not possible to clearly state this. But the methods of PLM seem to have a good potential to be leveraged in the next step of research on the framework.

To summarize, this paper described the current situation of PLM and TM in research and industry and worked out the need to reflect and manage technology related design information as such and on top of the pure product information, as done today. Moreover, existing PLM concepts and methods were discussed to utilize them in the area of TM. The Technology Framework was introduced and main buildings block were defined. As a first and core main building block the Technology Object was presented. Furthermore, dimensions of this object were introduced which helped to describe the object itself.

In order to shape the future work, a first step in the definition of the Technology Object was done with this paper on a conceptual level, but further research work is needed to drill down the dimensions, to define instances of each dimension and to describe their relations (linkages). After this step, the linkage between objects on the same level in hierarchies and cross-levels needs further elaboration, to be able to build step by step the entire Technology Framework, and hence to allow effective technology information management for product development and design.

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Digital Representations of Intelligent Products: Product Avatar 2.0

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Abstract. Customer expectations towards products are constantly increasing. They are not limited to product quality alone but also include the accompanying services and information provided. Intelligent Products allow the retrieval and communication of large amounts of information from all stages of the product lifecycle. Customers have become used to user-centric presentation and customizable information presentation from their experience with the Web 2.0 and Social Networks. Implementing Product Avatars as parts of Social Networking Services (SNS) as digital representations of physical products allows the presentation of individually customized information in a familiar environment for different stakeholders. This can raise the acceptance and the lower the adoption threshold for Product Avatars by increasing their availability and usability on both stationary and mobile devices.

Keywords: PLM, Product Avatar, Social Networks, Web 2.0, Digital Representation, Information, Leisure Boat.

1 Introduction

In today's globalized world, customers increasingly expect physical products and related information of the highest quality. Current developments such as a higher sensibility towards sustainability have moved the whole product lifecycle into focus along with the need to actively manage and share product lifecycle information. Simultaneously, an increasing amount of products are embedded with computing and communication capabilities and are able to interact with each other and with human stakeholders, such as users or producers [1].

At the same time, Web 2.0, the "social web", is rapidly changing the way information is generated, shared and consumed. These activities have become collaborative and user-centric [2]. Studies indicate a quarter of the time spent online by German Internet users is with SNS such as Facebook [3]. SNS claim to be designed to support users in every aspect of their lives [4] are characterised by evolutionary, user-centric innovation and development of functionality and usability.

Another trend is the convergence of the physical and virtual worlds, with products using Web 2.0 services such as Twitter to interact with stakeholders [5]. One approach to manage communication between Intelligent Products and users is the

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Product Avatar [6]. Since its initial introduction as a technical concept, it has evolved into the concept of a customisable "digital representation" of product-related information. It enables stakeholders to benefit from value-added services based on product lifecycle information generated by Intelligent Products [7].

Developments in SNS can contribute notably to the field of Product Avatars. Users are familiar with the functionality, design and interaction paradigms of SNS. E.g., "pushing" information to both the computers and mobile devices is meanwhile widely accepted. Product Avatars could be implemented on SNS in a similar way to human users' profiles, which can also be considered "digital representation" or "avatars". This way, users would instinctively know how to use the Product Avatar to create, find or share product-related information. This facilitates a new level of interaction in the daily lives of users and creates opportunities for new and innovative services.

Following, the Product Avatar concept in SNS is introduced, focussing on Web 2.0, SNS, Product Lifecycle Management (PLM) and the Product Avatar itself. The concept is presented on the basis of a real life example: a leisure boat. Stakeholder requirements are derived and generalized where possible. Subsequently different SNS are investigated w.r.t. their applicability as platforms for Product Avatars.

2 Product Avatars in Social Networking Services

In this section, Intelligent Products are discussed as a prerequisite for acquiring and communicating product information throughout the entire lifecycle. After introducing Product Avatars and SNS, the concept of Product Avatars in SNS is presented.

2.1 Intelligent Products

Intelligent Products are physical items, which may be transported, processed or used and which comprise the ability to act in an intelligent manner. McFarlane et al. [8] define the Intelligent Product as *"...a physical and information based representation of an item [...] which possesses a unique identification, is capable of communicating effectively with its environment, can retain or store data about itself, deploys a language to display its features, production requirements, etc., and is capable of participating in or making decisions relevant to its own destiny."*

The degree of intelligence an intelligent product may exhibit varies from simple data processing to complex pro-active behaviour. This is the focus of the definitions in [8] and [9]. Three dimensions of characterization of Intelligent Products are suggested by [10]: Level of Intelligence, Location of Intelligence and Aggregation Level of Intelligence. The first dimension describes whether the Intelligent Product exhibits information handling, problem notification or decision making capabilities. The second shows whether the intelligence is built into the object, or whether it is located in the network. Finally, the aggregation level describes whether the item itself is intelligent or whether intelligence is aggregated at container level. Intelligent Products have been shown to be applicable to various scenarios and business models. For instance, Kärkkäinen et al. describe the application of the concept to supply network information management problems [9]. Other examples are the application of the

Intelligent Products to supply chain [11], manufacturing control [8], and production, distribution, and warehouse management logistics [12]. A comprehensive overview of fields of application for Intelligent Products can be found in survey paper by Meyer et al [10].

Thus, an Intelligent Product is more than just the physical product – it also includes the enabling information infrastructure. Up to now, Intelligent Products are not "socially intelligent" [13] in that they could create their own infrastructure to communicate with human users over or store information in. However, Intelligent Products could make use of available advanced information infrastructures designed by socially intelligent users, consequently enhancing the quality of information and accessibility for humans who interact with them.

2.2 Digital Representation through Product Avatar

The concept of the Product Avatar describes a distributed, de-centralized and fragmented approach to the management of relevant, item-level information throughout a product's lifecycle [6]. At its core lies the idea that each product should have a digital counterpart by which it is represented towards the different stakeholders involved in its lifecycle. In the case of Intelligent Products, this may also mean the implementation of digital representations towards other Intelligent Products. Consequently, the Avatar concept deals with establishing suitable interfaces towards different types of stakeholder. For Intelligent Products, the interfaces required might be, for example services, agents or a common messaging interfaces such as QMI. For human stakeholders, such as the owner, producer or designer, these interfaces may take the shape, e.g., of dedicated desktop applications, web pages or mobile "apps" tailored to the specific information and interaction needs. This contribution deals with the latter.

Examples of embryonic Product Avatars are already emerging on the market. For example, each new Smart Fortwo electric drive (Smart ED) car has its own web page, which shows e.g. maximum range capable with current battery charge [14]. The current charge status or the SmartCharging charge configuration can be controlled and managed via a web portal from a home computer or with any modern smartphone. In the future, several other features will be controlled remotely through a smart drive application for the iPhone [15].

2.3 Social Networking Services

There is currently no widely accepted definition of Web 2.0 [16-17]. Generally speaking, it provides Web technologies which allow users to connect socially, including services such as blogs, wikis and video/photo portals [18]. Web 2.0 can be described by three characteristics: community, platform/tools and online collaboration [19].

A widely accepted definition of social networking sites is "*web-based services that allow individuals to (1) construct a public or semi-public profile within a bounded system, (2) articulate a list of other users with whom they share a connection, and (3) view and traverse their list of connections and those made by others within the system.*" [20] Currently, Facebook, YouTube and similar sites are almost synonymous with these services. They are growing quickly and have established themselves in a very short time as the de facto standard for online interaction. With Web 2.0, the foundation has been laid [21] upon which new SNS can be built, spread and expanded among the users new services developed [18].

2.4 Product Avatars of Intelligent Products in Social Networking Services

A first step in setting up a Product Avatar is to decide how and where the representation of the Intelligent Product should be made available and for which stakeholders. Different stakeholder may prefer specific channels based on their individual requirements. For consumers, using a channel they are familiar with and can easily access is preferable. SNS like Facebook boast large user bases familiar with their functionalities, design and interaction paradigms: the service is an accepted communication tool. Their users are used to not just consume but to interact with the "avatars" of other users - the step towards interacting with a product through its Product Avatar a small one compared to introducing a completely new communication channel. A further benefit is the ready-made accessibility from arbitrary devices both stationary and mobile. To leverage these benefits, the Product Avatar needs to be designed in accordance with the chosen social networking service's design and interaction paradigms.

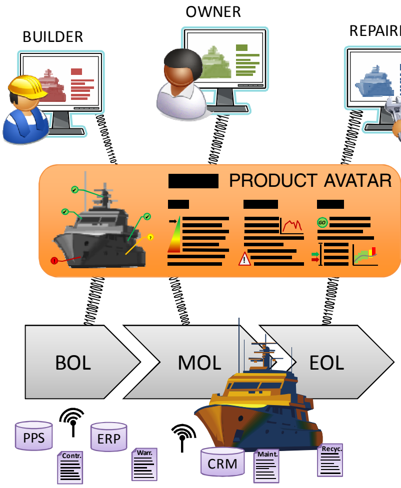

Fig. 1. Digital Representation of a Product through a Product Avatar

3 Exemplary Application: A Product Avatar of a Leisure Boat

This section describes an exemplary application of the Product Avatar for an intelligent leisure boat throughout its lifecycle. First, the rationale for and functionality of the intelligent leisure boat are presented. Its required functionality is defined. Suitable SNS are identified for its implementation. The section concludes with the presentation of a mock-up of the Product Avatar.

3.1 Rationale for Intelligent Leisure Boats

Up until today, leisure boat builders have focussed solely on the improvement of their products' quality to remain competitive in the marketplace. However, with the recent, drastic downturn in the boat market they are increasingly being forced to realise the need to additionally emphasize both the after-sales market and their customers' demands for products that are easy in upkeep, environmentally friendly and which offer them added-value services to enhance their boating experience. In order to fulfil these requirements, boat builders need to take concepts such as item-level and closed-loop PLM, Intelligent Products and Intelligent Maintenance into consideration. Leisure boats are complex, high-value consumer products which are often produced in small series, designed or made to order and often unique. Maintenance plays a key role in safety and ownership costs, the products can be in use for a considerable time, and sustainability and green issues are potential key advantages on the marketplace. Integral to the potential application of intelligent products taken here is a holistic view of the entire leisure boat value network: it includes all stakeholders in the boat lifecycle, such as the designers, ship yards, charterers, component suppliers, customers, owners, marinas, and boat hotels.

The functionality required by an intelligent leisure boat encompasses all phases of the lifecycle. For the beginning-of-life phase (BOL) this includes the enhancement of the design process using information from on-board sensors. In the middle-of-life (MOL) phase, concepts of Intelligent Maintenance such as a boat degradation model in combination with on-board sensors can improve the boats' safety, reliability and quality. Services for the improvement of the boating experience integrating Web 2.0 functionality are relevant to the younger generation of boaters. End-of-life (EOL) services address the boat builders' and owners' needs to for better refurbishing, reuse and upgrading of pre-owned craft. Information gathered in the previous lifecycle phases can be applied to these processes to increase their cost and time efficiency and consequently the sustainability of the overall product.

3.2 Required Functionality of an Intelligent Leisure Boats' Product Avatar

The potentials of intelligent leisure boats have been discussed in [22]. A result of that discussion is the identification of required functionality for intelligent boats by lifecycle phase, involved stakeholder and data source. Table 1 presents the types of functionality required by the corresponding Product Avatar in a social network, derived from the functionality by lifecycle phase and stakeholder for the intelligent leisure boats identified in [22].

3.3 Selection of Suitable Social Networking Services

The following section presents a selection of social networks based on a study carried out by the authors. Its objective was to identify the most suitable social networks currently available to host Product Avatars for leisure boats. The selection includes Facebook, as the biggest Social Networking Service with the most monthly active

Table 1. Required Functionality an Intelligent Leisure Boats' Product Avatar by Lifecycle Phase and Stakeholder [22]

Required Functionality	**BOL**	**MOL**	**EOL**	**Boat owner**	**Designer**	**Manufacturer**	**Suppliers**	**Service provider**	**Recycler**
Intelligent service recommendations		■		■				■	
Intelligent upgrade recommendations		■		■				■	
Predictive maintenance information		■		■				■	
Improved customer relationships		■	■	■		■			
Winter storage monitoring		■		■		■			
Theft monitoring information		■		■		■			
Full boat traceability	■	■	■	■	■	■	■	■	■
• Service history	■	■	■	■			■		
Process optimisation	■		■			■			■
Design optimisation	■			■	■		■		
Sustainable boats/components			■	■		■	■		■
Virtual manual		■		■		■	■	■	
Collaborative services		■		■		■	■	■	
Social services		■		■		■	■	■	

users [22], and its main competitors: so.cl, run by Microsoft, and Google+, run by Google. Additionally, two smaller SNS, Diaspora and Friendica, were added as they represent another, desirable aspect of SNS. They allow the users to create and host their own profiles and thus, keep their own information and data secure.

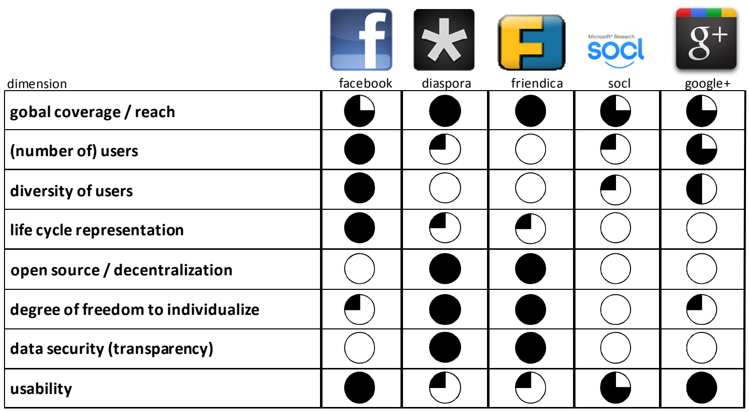

Fig. 2. Comparing selected Social Network Services

In Fig. 2, the five selected Social Networks are compared according to eight differentiable and descriptive dimensions. The set of dimensions is based on recent expert interviews, literature review and previews experience in the field. Each network was rated qualitatively and the score is indicated by a more or less filled circle. A fully filled circle means the social networking service totally fulfils the dimension's requirements whilst an empty circle means requirements are not at all met.

The final selection and a possible ranking depend strongly on the perspective of the stakeholders, the individual environment and the product itself. If their individual requirements are not yet derived, the selection cannot be utilized satisfactory. An example of such requirements is the following: a company decides their data cannot be uploaded on another server as it is confidential and has to be protected at all times. Therefore, the dimension "data security" becomes automatically a "kill requirement" influencing the selection critically.

3.4 Product Avatar within a Social Network

In this chapter a first mock-up of a possible Social Networking Service Product Avatar of a leisure boat is presented. The design and functionality is Avatar based on Facebook is illustrated in Fig. 3. Facebook was chosen as it is today the most popular Social networking Service and has the highest reach on the relevant consumer focus group. As mentioned before, it is also possible to use different channels for Product Avatars of the same product depending on the diverse stakeholders needs. This mock-up is solely based on the requirements of the consumers' perspective.

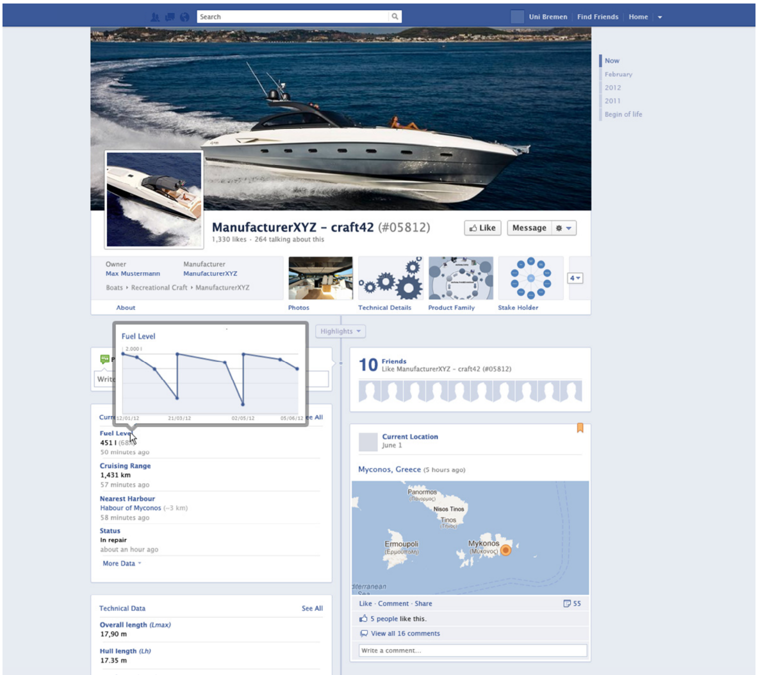

Fig. 3. Mock-up of a Product Avatar for an Intelligent Boat on a Social Networking Platform

The information provided by the Product Avatar of the leisure boat includes current and former location (boat traceability), theft monitoring, speed, fuel level etc (see Table 1). It can be shared with friends to arrange meeting points or just to inform about the ongoing trip.

A possible scenario could be the following. The boat employs certain sensors to analyze the water quality and independently matches the generated data with ideal fishing grounds for the preferred prey. The Product Avatar automatically interacts with other connected avatars ("friends") to find the perfect fishing spot in the area which is then presented to the user. Instant feedback of the user in case of a catch could be communicated to the connected avatars. After successfully catching a large Tuna the user wants to get back to the nearest harbour. The marina, incl. gas station etc., will be informed and receive relevant information so they can plan their tasks (and supplies) after the boat arrives. The local wine dealer can receive information about the catch and suggest a corresponding wine for dinner (if that information is released by user). In case the fish is big enough, the user can invite friends in certain proximity (identifiable by their connected Product Avatars) and celebrate the event.

4 Conclusion and Outlook

The goal of the paper was to present a concept of digital representation of intelligent products through the social networking service channel in order to develop new services based on product lifecycle data to an interested audience. Based on previous work on with a more technical [6] and conceptional [7] background, this paper focuses on the applicability and requirements towards implementation. Furthermore, the analysis of the available and applicable SNS and thus the opportunities and threads for professional (e.g. producers) and private (e.g. customers) stakeholders represent interesting insights for further developments. This was highlighted through a practical example of a Product Avatar for a leisure boat. The types of information to be represented by the Product Avatar on the social network service were derived from the requirements towards intelligent leisure boats identified in prior work. The presentation of a mock-up of a boat avatar concluded the paper.

The authors believe that the application of digital representation within widely accepted SNS through a Product Avatar presents vast business opportunities for different stakeholders along the whole Product Lifecycle. The next steps include the development and implementation of a Product Avatar (or multiple Product Avatars to represent different stakeholders' requirements for that matter) in a pilot case. Furthermore, the evaluation of this pilot case implementation will be executed with real users to measure the real life impact. Parallel, application of a Product Avatar in other domains, e.g. manufacturing processes (BOL) or recycling (EOL) will be analyzed.

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Product Evolution and Optimization Based on Gentelligent Components and Product Life Cycle Data

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Abstract. To implement a Product Evolution in the product development process, intelligent systems are necessary. Gentelligent components combine the intelligent system with genetic approaches. In that way, the life cycle information has to be prepared and to provide for Design Evolution. Design Evolution is an optimization strategy which implements evolutionary mechanisms to further develop gentelligent components within the scope of adaptive design. A gentelligent wheel suspension illustrates its practical application. By this way, it is shown how Product Evolution and usage data interact.

Keywords: life cycle data, evolutionary optimization strategy, design evolution.

1 Motivation

Nowadays, the focus of product development shifts towards intelligent systems. So mechatronic systems which could arrange self-optimization on their own [1] or intelligent sensors which could react to special situations are developed. Steadly enhancing energy awareness creates a need for such developments [2]. With these requirements, the complexity of the product development process increases. A lot of approaches are taken in using evolutionary mechanisms for the development process [3-4]. Also the communication between intelligently determined life cycle information and the product development process is a challenge which has to be solved for different interfaces [5].

This feasibility study project investigates the process of Product Evolution including an optimization strategy based on gentelligent life cycle information [6]. This project is part of collaborate research center 653 (crc) “Gentelligent Components in Their Lifecycle” [7]. CRC 653 develops gentelligent components which are capable of sensation. So these components could give some information about their loads during the product life cycle. First of all, this feasibility study will check the influence usage data from highly dynamically loaded mechanical systems has on the development process. Thus, the gentelligent, inherent load data is used for optimization during the product development process in order to achieve an adaptive design for real-life operational demands.

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2 Concept of Product Evolution

The concept of Product Evolution shown in Fig. 1 implies the life cycle of mechanical systems. It covers the product creation process, gentelligent components in the field and also the data feedback.

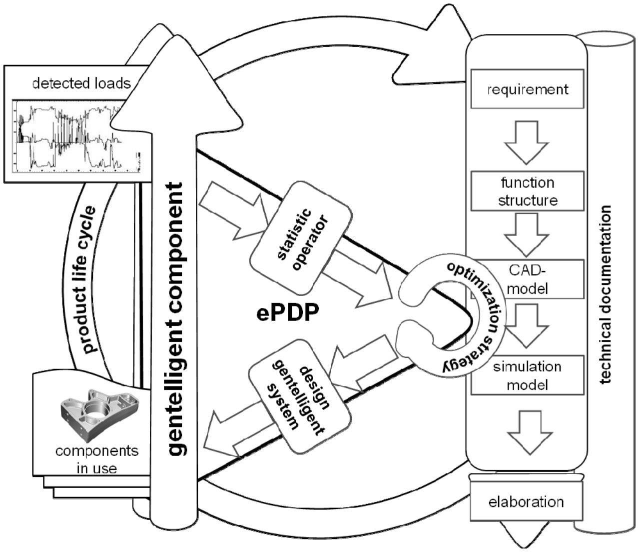

Fig. 1. Concept of Product Evolution

In this concept of Product Evolution, three operating points were detected.

- The first step is to design the gentelligent component. It expects the new technology to be designed in the product development process such that it delivers helpful data during the usage phase.
- In the second working package, the large number of load datasets has to be processed by a statistical operator. There some Cluster Analyses are studied.
- The third point is integration in the product development process. An optimization strategy which uses the information from the statistical operator by utilizing evolutionary mechanisms has to be implemented. Therefore the application of the genetic algorithm was investigated. So the optimization creates Product Evolution for an adaptive design of gentelligent life cycle information.

3 Data Generation

This chapter uses a gentelligent wheel suspension from a racecar provided by the HorsePower Team of Leibniz University of Hanover to illustrate the application, challenges and approaches of Product Evolution and Optimization based on gentelligent life cycle information.

The wheel suspension features kinematic functions of springing and steering movements of the car. It also has a major impact on the driving comfort [8]. In a racecar's wheel suspension it is possible to equip components with the gentelligent technology. One possibility is a wheel carrier of magnetic magnesium. This allows collecting load data information during the product life cycle [9]. Another possibility is to produce the wishbone or the driving shaft from metastable austenitic steel [10]. Figure 2 shows the wheel suspension with the suggested gentelligent components.

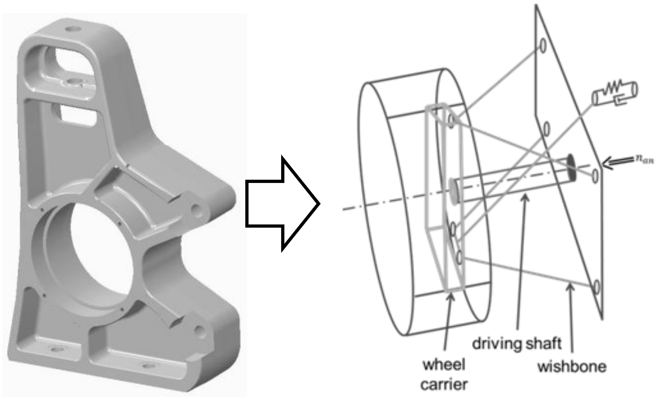

Fig. 2. Wheel suspension with gentelligent components

Implementing gentelligent technology in such a highly dynamically loaded system generates a few challenges. First of all, the gentelligent data from the component has to be transformed owing to restrictions of adaptive design. The fasteners of a component are strictly invariant because changes lead to different load cases and a different dynamic response. The fasteners are called hard points or joints. Three key challenges ensue:

1. Where is gentelligent technology positioned at the component?
2. How do we find the significant load cases for Design Evolution?
3. In which way is it possible to implement Design Evolution in the product development process considering the rules and constraints of adaptive design?

Design Evolution requires the gentelligent life cycle data to be prepared first. This is done in a statistical operator based on the cluster analyses methodology. Before explaining these methods, the way of generating the life cycle data is discussed.

Creation of Gentelligent Usage Data. At a first step, the project studies the usage data from highly dynamically loaded systems. Since no real field data was available, it fell back on the virtual method. So a multi-body simulation model from the racecar was created. This is shown in figure 3.

The figure includes a force curve generated from data of a simulated driving maneuver. With these virtual methods usage data of potential gentelligent components could be generated. At the next step, the statistical operator applies statistical methods to these large datasets in order to prepare them for Design Evolution.

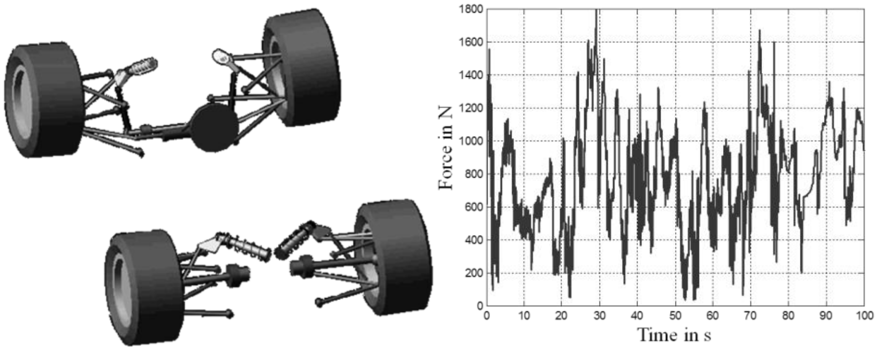

Fig. 3. Multi-body simulation model with a force profile

4 Statistical Methods

The scope of this study included the subtask of considering the internal data structure in the absence of primary information. Pattern recognition within the scope of this study aims at:

1. Understanding the nature of data by means of grouping. Data segmentation into groups of similar objects allows to simplify problems of data processing and to make decisions based on the analysis of every cluster;
2. Organizing and summarizing data to break down sets of objects into homogenous groups and, thus, to allow data volume reduction in order to recognize and use characteristic points of load values for optimizing the shape and topology later;
3. Detecting novelties. to ascertain whether or not non-typical objects may be interesting for the modeling of special load cases.

In the first case it makes sense to use small cluster counts. In the second case it is important to provide a high strength of association between the objects in every cluster.

There are different approaches to data clustering. The paper [11] presents an overview of pattern clustering methods from a statistical pattern recognition perspective. The most intuitive and most frequently used criterion in partitional clustering techniques is the squared error. These methods essentially are a probability mixture resolving approach to cluster analysis. Most studies in this area have assumed that the individual components of the mixture distribution are Gaussian, and in this case the parameters of the individual Gaussians are to be estimated by the procedure. The traditional approach to this problem involves a maximum likelihood estimate of the parameter vectors of the distributions using the EM Algorithm [12]. As an alternative approach, pattern recognition with fuzzy logic [13] can be used. The C-means is the simplest and most commonly used algorithm from this family of methods.

This study on significant load case analysis primarily relies on the k-means with the Euclidean distance metric as the simplest and commonly used algorithm employing a squared error criterion. Among reveal shortcomings of approaches are absence of the global extremum of the goal function of clustering quality, results dependence from the choice of initial centers of clusters. Therefore, as an alternative, the k-medoids approach with an intragroup dispersion criterion [14] was used. The k-medoids method could be more robust to noise and outliers as compared to the k-means approach. Both methods require an a priori knowledge of the count of clusters. Figure 4 depicts an example of dynamic force data clustering. The geometric centers of clusters can be used as the character points of loads for the Design Evolution.

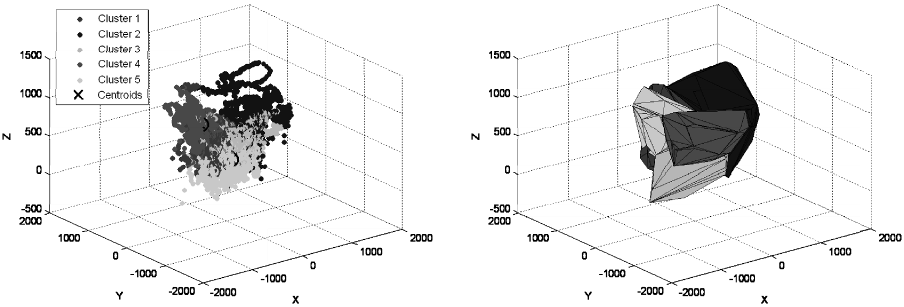

Fig. 4. Example of clustering: k-means (point view) and k-medoids (triangulation) methods

Among the challenges of dynamic load force data recognition are the forming of a probabilistic model of examinee data, the problem of finding the global extremum for the goal function of the clustering quality criterion, and the possible non-robustness of the solution. The statistical operator used for pattern clustering involves the following steps:

1. Optional primary data analysis, noise analysis and data filtration;
2. Forming of the system of variables;
3. Defining a distance function between pairs of objects;
4. Object grouping;
5. Results presentation/visualization;
6. Cluster validity analysis [15].

Possible subsequent research includes two logical directions. The first will be further using a k-means algorithms modification and investigating the posterior effect. The second regards investigations of fuzzy logic or probability clustering with an unknown number of clusters [16].

5 Design Evolution

For an adaption of the wheel carrier of the suspension linking to the calculated critical load cases, a physical product model is necessary. In the case of mechanical loads, an evaluation of the car hub design by a static finite element simulation is feasible. The critical loads at the hard points are entered as boundaries in the finite element model. In this way, an evaluation considering gentelligent application data is done. [17]

By the Design Evolution process, the shape and the topology of the wheel carrier is varied to find the best-adapted design in relation to the gentelligent information. But this process of variation has to be consonant with the gentelligent information feedback. By instancing the wheel carrier and the critical loads, a variation of shape and topology can be done as long as the position of the hard points is fixed. If varying the hard points, the critical load information is no longer invariant to the geometry of the wheel carrier. In this case, the geometrical parameters of the wheel suspension are changed. A modification of the load situation of the wheel carrier itself is the consequence. A correlation of the different designs does not exist any longer in this case. Thus, using critical load case information and a static finite element simulation allows design evolution at component design level only [18].

Focusing the Design Evolution of a dynamic assembly system such as the wheel suspension, a feedback of kinematic information is necessary, the reason being a variation of mass and stiffness by variation of shape and topology. For a Design Evolution on this level, an additional aspect has to be considered: A variation of design is only feasible for kinematic chain elements because, in the space of a kinematic loop, there are always interactions. For a kinematic chain variation without interactions is only possible for a section of a free end. Because of these aspects, a Design Evolution of a wheel suspension considering kinematic and dynamic characteristics is only feasible by feeding back gentelligent information of wheel excitation and driving characteristics [19].

A Design Evolution process always includes an optimization strategy. In the field of mechanical structure optimization there are two fundamental approaches: On the one hand, there are mesh based methods based on finite element formulations; on the other hand, parametric design models coupled with deterministic or stochastic methods are being used. In the field of mesh based methods, topology optimization based on homogenization or BESO method are used in industry. These methods are only feasible for single-component optimizations considering mechanical properties. Parametric design models are applied to multidisciplinary optimization considering several physical domains e.g. multibody systems as well as stress analysis. For the computational solving of such problems, genetic algorithms are widely used. The independence of the physical domain and the possibility to integrate arbitrary restrictions in the optimization are additional important aspects. Thus, for the Design Evolution of the wheel carrier, a parametric design model linked to a finite element model and a genetic algorithm are used [20].

6 Modeling

By implementing Design Evolution based on parametric modeling, the geometry of a component is enriched with intelligence of its variation. For the development of parametric design models, there are features in today's commonly used CAD software packages. These features are suitable for varying an existing geometry, but modeling of new elements based on parametric rules is commonly not available. Thus the design space is restricted and regeneration caused by parameter variation often fails.

For enhanced parametric modeling, there are certain CAE software packages which enable an implementation of extensions by scripting languages. The modeling kernel can be thus used for automatical design generation.

For linking a parametric design model to a simulation environment, a mapping of geometrical and functional representation is necessary. Implementing a meta model to generate the different domain-specific models is a solution for this aspect. This strategy is commonly used in knowledge-based engineering systems. For Design Evolution, a meta model of the wheel suspension is developed. The gentelligent application information is integrated in this meta model. Transformation into the domain-specific models is done by the meta modeling methods [21].

Software Evaluation and Concept. Implementation of a meta model for the wheel suspension requires a previous software evaluation. To minimize interface problems between modeling and simulation domain development, all meta models should be preferably based on a single computer-aided engineering software package. Today there are CAD software systems with an integrated simulation environment as well as finite element software packages with an integrated modeling environment. Because of its open API scripting interface, Abaqus, a finite element software package, is used for an application study of meta modeling of the wheel carrier. Abaqus provides Python as scripting language. Its API is integrated as an object-oriented Python module. Thus, object-oriented programming is possible as well as integrating the far-reaching extension modules provided by Python, e.g. genetic algorithms.

Table 1. Domain-Specific Software Packages

software domain		API
modeling based	• CreoParametric + CreoSimulate • Autodesk Inventor + Autodesk Simulation • CATIA Mechanical Design + Analysis	C++ Visual Basic Visual Basic, C++
simulation based	• ANSYS Mechanical APDL • ANSYS Workbench • Abaqus	Macro lang. APDL Python(limited) Python

The meta-model consists of an object-oriented approach containing individual geometry classes of the wheel carrier. The geometry class itself controls the geometry variation process and provides different modification methods e.g. input of a hole. The global model parameters are initialized by a parameter class. Interaction of the genetic algorithm and the parameter class is controlled by a component control class. The gentelligent information consists of different load cases, is implemented as its own class and linked as boundaries to functional faces of the component. The component class itself manages the simulation routines and calls the corresponding load cases. Simulation results are stored by a result class. The objectives are calculated by an objective class and returned to the component class managing the communication with the genetic algorithm.

This process of Design Evolution is implemented in Abaqus by the above object-oriented Python architecture. An object-oriented architecture is well suited for the meta-modeling of mechanical components because communication between the modules – geometry generation, gentelligent information, optimization – is managed by the modules themselves [22].

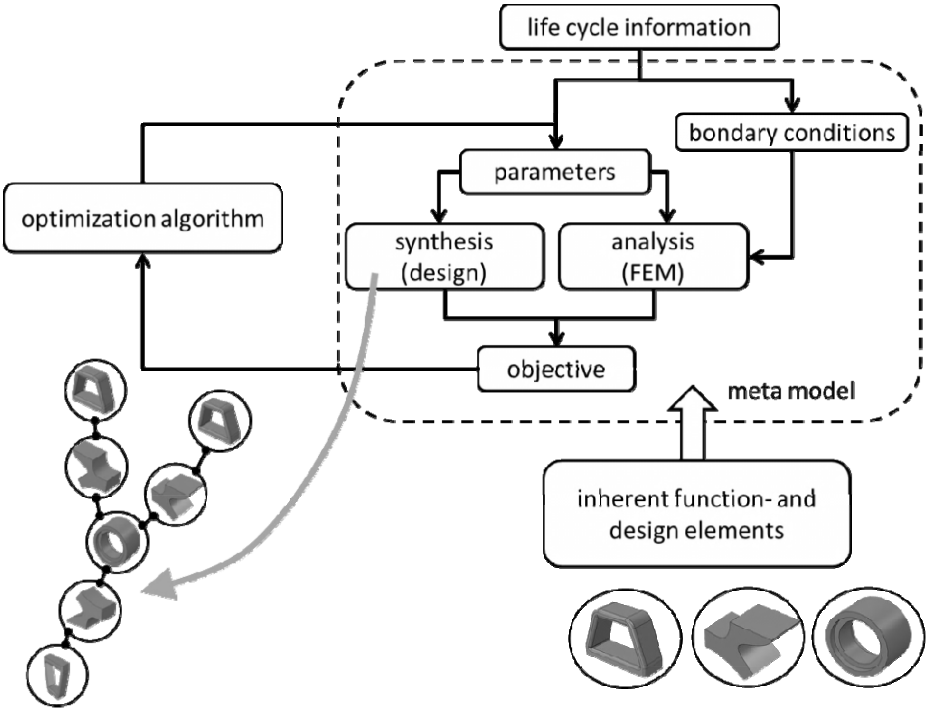

Fig. 5. Architecture of Design Evolution

7 Results and Conclusion

First of all, application of the gentelligent wheel suspension shows that the concept of an inheritance of life cycle information is possible. Studying the research points provided approaches to the three challenges mentioned at the beginning.. With regard to the first challenge about the position of gentelligent technology and in case of non-existent real life cycle information, a multi-body simulation supplied the data pool at the scientific point of the design of gentelligent systems. In that way, the usage datasets could directly be placed at the hard points of the wheel carrier.

The second challenge was studied in the statistical operator. The statistical methods showed that the large datasets could be reduced by cluster analyses. Additionally, the significant load cases of the wheel carrier could be located. This information established the basis for Design Evolution.

By generating product-equivalent models of the wheel carrier in combination with the usage information, the Design Evolution could be arranged. Considering the rules and constraints determined for adaptive design, the wheel carrier was given a new shape. Applying a gentelligent wheel suspension helped to show that the Product Evolution of individual components, here a gentelligent wheel carrier, is possible.

Applications for such gentelligent components mainly include innovative and cost-intensive systems like wind turbines or manufacturing tools. Therefore, the products experience different life cycles due to different manufacturing processes caused by various components on a machine tool, for example.

The next challenges are detected when studying the impact large numbers of gentelligent components have on the statistical operator and also on Design Evolution. In that way, the interfaces between the CAE tools have to transfer the product-equivalent models. Industrial integration of this concept will be sought afterwards, possibly focusing on the automotive or energy branches.

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Early Development of Weight-Optimized Mechatronic Products

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Abstract. Existing process models for the development of mechatronic products are not considering the task of weight optimization – weight reduction and weight distribution – in a specific and sufficient way. The weight optimization is mostly applied at the end or in the late phases of the development process with the consequence that a large number of macro-iterations are necessary when design changes regarding the weight have to be done. These points result in an increase of development costs and time. In previous work, the authors propose a process model which exposes the task of weight optimization as an in-process development goal beside the goal of functionality.

In this paper, a detailed procedure for the design of weight-optimized mechatronic products in early phases is proposed. The process is supported by a set of different methods based on suitable lightweight strategies.

Keywords: mechatronic products, weight optimization, early design phases, process model, product development.

1 Introduction

1.1 Problem Statement

Lightweight design in general – and hence a lower product weight and a better product weight distribution – is seen as one possible approach to a resource and energy conserving realization of products during their production, usage and recycling lifecycle phases. In opposite to this, there are some big interdependencies to other product properties, e.g. growing safety requirements, power enhancement and customer needs regarding comfort and entertainment. These aspects often lead to increasing product weights, e.g. shown on the example of automobile. Their realization is mostly based on the use of mechatronic concepts. This obvious contradictory trend can be disproved by looking at some innovative mechatronic concept solutions, e.g. smart materials, x-by-wire concepts or adaptronics.

However despite these possibilities, the task of weight reduction and optimization is mostly insufficiently and unsystematically covered during the development of mechanical or mechatronic products. Lightweight measures are often only sporadically and locally applied in a few subsystems and during the late phases of the development process with the consequence that the whole system is not covered and sufficiently optimized.

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Some approaches aim at integrating the task of weight optimization, weight reduction and weight distribution, into the development process. But a continuous integration over the whole development process, especially into the early phases due to the large influence on future product properties, has not been considered yet.

1.2 Framework "Design of Weight-Optimized Mechatronic Products"

The methodology "Design of Weight-Optimized Mechatronic Products" has been introduced by the authors to consider the continuous integration [1,2]. It can be understood as an integration of two different disciplines, mechatronic and lightweight design, into one development process. Mechatronics itself is an interdisciplinary and synergetic interaction of the three domains mechanical engineering, electric engineering and IT/control engineering. Thus, there are two development goals existing: on one side the achievement of the functionality by using mechatronic concepts and on the other side obtaining the lowest weight and best weight distribution as possible.

The framework consists of six elements – process model, strategies and methods, system understanding, modeling and simulation, organization as well as knowledge and communication – which are the basis of the methodology representing two different perspectives, the product view and the process view (see Figure 1).

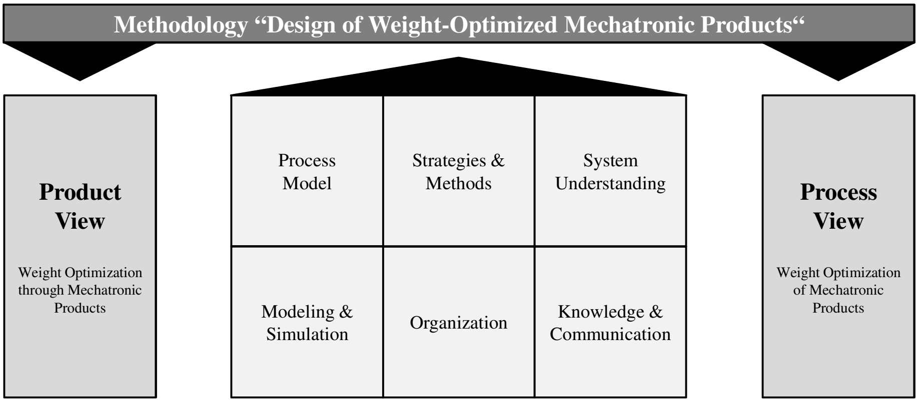

Fig. 1. Methodology for the Development of Weight-Optimized Mechatronic Products

The product view – the weight optimization by application of mechatronic products – needs an analysis of given mechatronic concepts in terms of their ability or of their potential for a weight reduction or an improved weight distribution.

The process view – the weight optimization of mechatronic products – offers a procedure for the development of weight-optimized mechatronic products following the VDI guideline 2206 (see Figure 3).

1.3 Approach

In this contribution, the focus lies on the process view. Especially the early phases of the design of weight-optimized mechatronic products will be investigated. The importance of the early phases during product development is widely recognized.

Based on the macro-level process model (see Figure 3), the analysis gates 0 and 1 as well as the system design stage are the topic of this paper. The different gates and stages are supported by methods and tools of the systemic and the conceptual lightweight design strategies which will be illustrated later.

In analysis gate 0, the desired requirements for the product are investigated in order to point out the requirements which are related to the product weight and product weight distribution as well as their interdependencies and conflicts of objective. Furthermore, it seems to be practicable to perform a comparison of predecessor or competitive products aiming at deriving weight targets for the new product.

Within the stage of system design, the overall system solution will be worked out. There are possibilities to check influences on the subsequent product weight and product weight distribution after different steps are achieved, e.g. functional structure, logical structure or physical structure. In this stage, methods will be given to achieve these structures in a way aiming at weight and weight distribution optimization. These methods are based on the strategies of systemic lightweight design and conceptual lightweight design. In analysis gate 1, a weight analysis of the overall cross-domain solution concept will be performed.

2 Application of Lightweight Strategies in the Early Design Phases

2.1 Basic Principles of the Systemic and Conceptual Lightweight Design Strategy

Systemic Lightweight Design. This strategy is intended to achieve a holistic weight reduction of an overall system. The core objectives of this design measures are the optimization of the system weight and system inertia as well as its positioning or rather its distribution within the system. The systemic lightweight design strategy represents a method which is displayed across material and product choice. It is subject to certain conditions and requirements, e.g. design, manufacturing, quality, safety, environment and cost [3].

Conceptual Lightweight Design. This lightweight design strategy accomplishes weight reduction and optimization through a systematic investigation of certain structure and modules and their matching to the entire system or subsystem including layout and design. Thus, the package and the configuration of the components or the design of one single component can immensely influence the weight or the weight distribution of the whole system. [3,4]

2.2 Classification of Lightweight Strategies to Design Processes

Figure 2 shows the classification of lightweight design strategies to the design stage of mechatronic products demonstrated at the V model of the VDI guideline 2206 [5].

Beside the systemic lightweight strategy including the weight optimization for the whole system, the conceptual lightweight design strategy plays a very important role. The concept in general is significantly responsible for the further design procedure and thus for the application of the resting lightweight strategies.

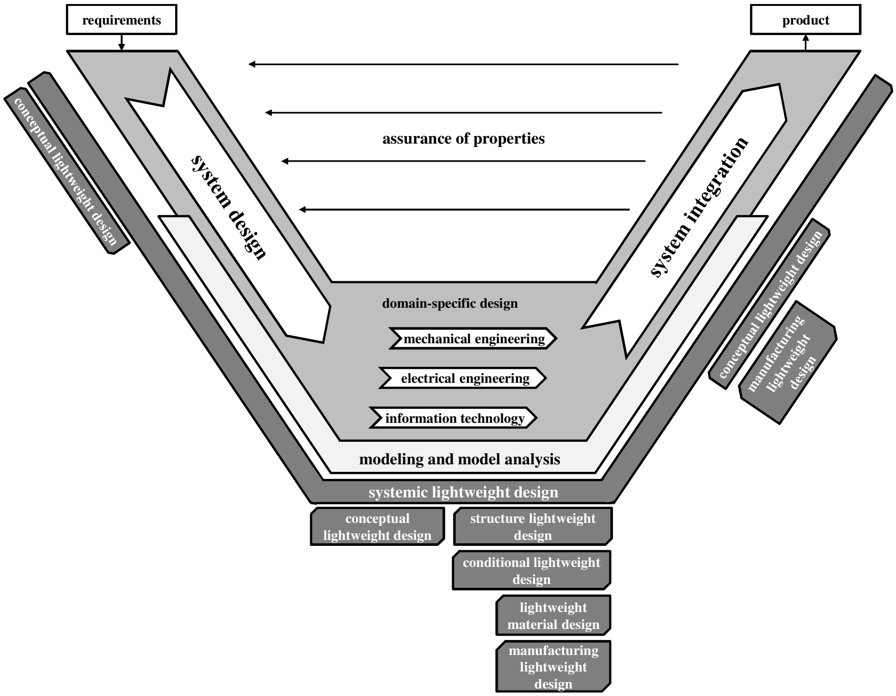

Fig. 2. Classification of Lightweight Strategies to the Mechatronic Design Process [2]

3 Process Model with Focus on the Early Design Phases

The general procedure for the design of weight-optimized, mechatronic products is shown in Figure 3. It can be seen first as a top-down development from requirements to an overall system concept up to domain solutions and then second as a bottom-up design from these domain-specific concepts to an overall system solution and finally the real product.

This paper focuses on the system design stage of mechatronic design between analysis gate 0 and 1. In the early phases particularly the strategies of systemic and conceptual lightweight design are used. The later phases including domain conception and system integration, in which the resting lightweight strategies are applied, will be investigated in further research.

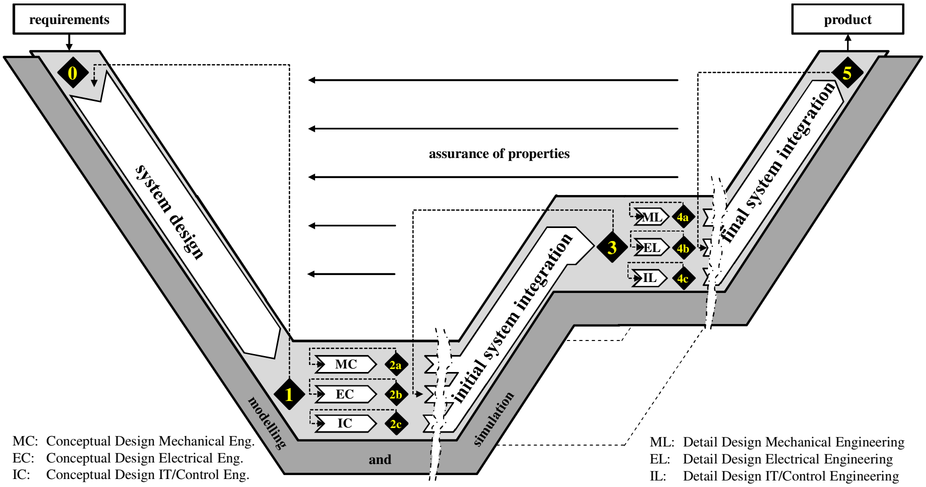

Fig. 3. Process model for the development of weight-optimized products [2]

3.1 Importance of the Early Phases

The early phases of the product development are crucial for the further development process and the success of a product. The possibility to improve and to generate innovative solutions is biggest in these phases due to the large number of degrees of freedom. The potential for improvement decreases exponentially in contrast to the exponential growing of product knowledge and the degree of product concretization. [6]

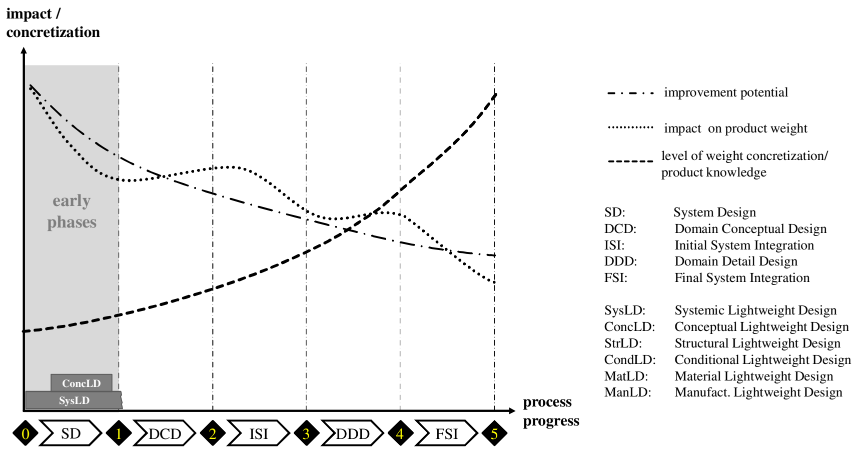

Fig. 4. Impact on product weight [2,6]

For weight optimization the early phases carry a special significance. Traditional lightweight design strategies used alone are not regarding the product weight and product weight distribution at all. The procedure with the strategies and lightweight design techniques [7] is not appropriate enough because they are primarily only applicable on product shape or design. However, a consideration of weight and weight distribution in the planning and the conceptual phase is unavoidable although an estimation of the future product weight is very difficult. But it is possible to detect on one side hints for a weight-optimized product and on the other side potential trade-offs regarding weight and other product properties.

3.2 General Design Procedure

Figure 5 shows the refined steps – which are based on the early design steps of the VDI guideline 2206 [5,8] – of the process model for the development of weight-optimized mechatronic products. It contains the steps *planning and clarifying the task* and *system design* which are represented in more detail in the figure. Additionally to the design stages, there are several analysis gates: *analysis gate 0* for the first step, *analysis gates a*, *b* and *c* within the system design step *and analysis gate 1* as the conclusion of this step. Moreover, the design phases are supported by different lightweight strategies (systemic lightweight design strategy and conceptual lightweight design strategy) and methods (I-VIII) based on these strategies.

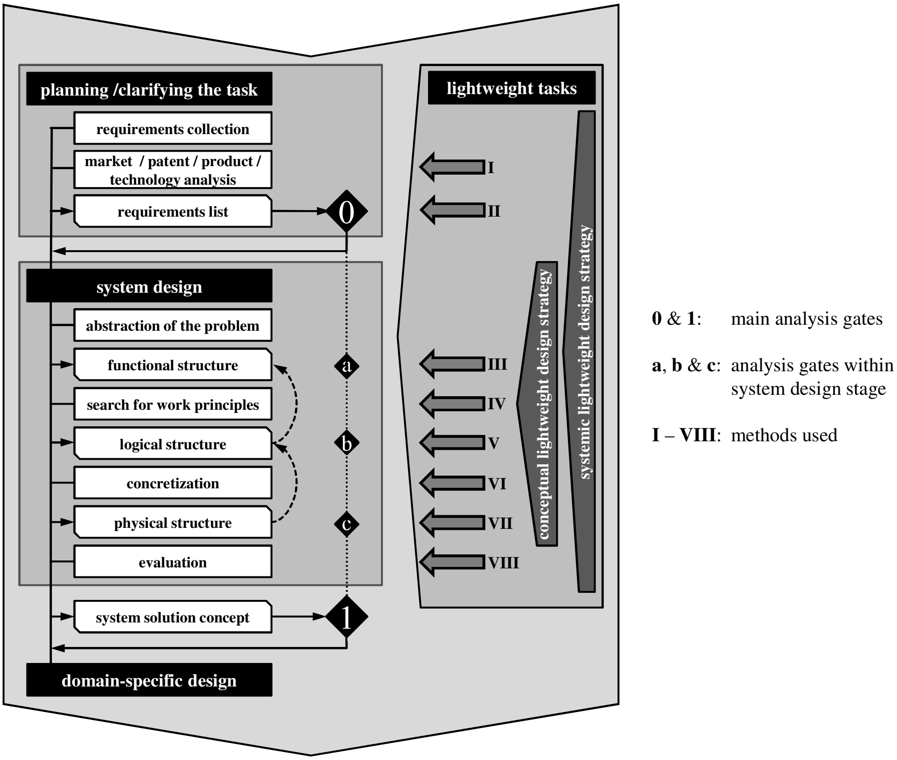

Fig. 5. Early Design Phases for the Development of Weight-Optimized, Mechatronic Products

The following subchapters are describing the methods used in the early design phases.

3.3 Planning and Clarifying the Task

In this phase, the creation of the requirements list comes along with the systemic lightweight design strategy. Methods can be used for the analysis of predecessor and competitive products as well as for the requirements list.

Product Analysis (I). Patent and technology analysis as well as benchmarking of predecessor and competitive products are necessary to identify weight goals. For the determination of these weight goals the method of "Value Analysis Weight" can be very helpful [9]. The methods of the value analysis are transferred from the application to reduce cost to the application to reduce weight. However, a procedure of taking account of weight distribution is not mentioned. Moreover, ABC analysis of weight saving potentials or standards and limiting values (for example standards for ergonomics) can support this identification. It could be helpful to indicate so-called lazy parts which add to a product but have little impact on the performance [10]. It is important to get to know possible trade-offs as soon as possible in the definition phase of requirements and development goals.

Requirements List (II). Derived from a collection of requirements and analysis of predecessor or competitive products a requirements list is generated. The greatest potential of identifying weight optimization options of the final products lies in analyzing the requirements in this earliest phase of product development with the most design freedom. With the aid of a quantitative explicit description of the requirements (e.g. weight < 10 kg) and determination to importance factors weight-relevant requirements can be illustrated. Moreover, relations between different properties have to be filtered out to illustrate occurrent goal conflicts. Potentially, it can be promising to depict the requirements related to the product weight as well as the interdependencies and the effects in a separate refined requirements lists. Furthermore, it is important to create the requirements list with the task of weight reduction and distribution as a main requirement because lightweight design is only implicitly mentioned in conventional lists. A quantification of qualitative tight claims to qualitative final requirements can be helpful if it is done as early and with advanced specificity as possible (e.g. "weight lower than 15 kg" instead of "easy to carry") [11]. A method for the identification of requirements which are critical to mass reduction is proposed by McLellan [12]. After a requirement pre-processing and a mapping of these requirements to components, requirements can be identified which are highly mass intensive and uncoupled from other requirements.

Outcome of the requirements list is the clarity of weight goals and the detection and observance of goal conflicts, e.g. weight ↔ safety or weight distribution ↔ acceleration behavior.

Analysis Gate 0. This gate serves as a revision of the phase outcome, the requirements list. The percentage of weight-related requirements can be measured and compared to the results of later analysis gates.

3.4 System Design Stage

The system design stage is supported by the systemic and the conceptual lightweight design strategy. Different structures are built in analogy to the "Münchener Konkretisierungsmodell" [13]: functional structure, logical structure and physical structure.

Functional Structure (III) and Analysis Gate a. Aim of this step is the identification of weight-relevant or weight-critical aspects and of weight saving potentials although there is usually no information about the future product weight or weight distribution in the functions implemented. With the aid of a functional weight analysis in analogy to the target costing [13], the functions can be investigated if they are weight-relevant and how much or if they are not relevant. With methods of function integration or separation, different functional structures can be built which have to be compared in analysis gate a in terms of the percentage of functions regarding weight and weight distribution. In principle additional functions tend to result in an increase of weight and in a decrease of available space. Different functional structures can cause significant distinctions for the further product weight owing to their realization, e.g. completely mechanical or mechatronic. The one which completely fulfills the functionality with the lowest percentage of weight-influencing functions has to be chosen.

Search for Working Principles (IV). The working principles as the implementation of the functions have to be investigated to determine their weight dependency. Here can be the starting-off point for the integration of the product view: searching mechatronic working principles in a catalogue in which the principles are classified in terms of their weight saving as well as weight distribution improving potential. Mechatronic concepts have often the property that they are integrating several functions in one working principle. As methods could be in consideration the Theory of Inventive Problem Solving with the Matrix of Contradictions where the contradictions have to investigated to get a proposal for solution, e.g. "weight of the moving object ↔ strength" provides one solution "substitution of the mechanics" [14]. Additionally, a comparison with predecessor or competitive products and their working principles can lead to an estimation of the weight of different physical working principles and can be an assessment criterion for the concept solution.

Logical Structure (V) and Analysis Gate b. Based on the working principles, the logical structure is developed. It can be understood as a combination of the different working principles and can show possibly arising problems during the integration of the working principles. Similarly to the functional structure, various logical structures must be in consideration and compared to each other. Analysis gate b serves as check-up of the proportion of working principles regarding weight and weight-distribution.

Concretization of Logical Structure (VI), Physical Structure (VII) and Analysis Gate c. The physical structure represents the preliminary stage to the system solution concept. The initial structure is built up in terms of geometry based on the combination of working principles in the logical structure by choosing suitable effects for the working principles. The effects stored in design catalogues normally consist of geometric and eventually implicit material information. For the first time, traditional lightweight measures are applied, e.g. usage of lightweight design techniques. Thus, there is the first possibility to handle explicit weight information which will be analyzed in analysis gate c.

Evaluation of Possible Solutions (VIII). For the assessment of the best solution the weight has to be in consideration. Thus, the technical-economic evaluation has to be extended to a technical-economic-weight evaluation where functionality, costs and weight are represented. Hence, the aspect of weight being a development goal is fulfilled. Following weight criteria could be in interest: weight itself, weight distribution, center of gravity, mass (moment of) inertia, influence on functionality and on other important product properties.

Solution Concept and Analysis Gate 1. The overall system solution concept is the conceptual elaboration of the assessed solution. Measures for weight reduction and improvement of weight distribution can be applied, for example lightweight design principles and techniques (integrated or differentiated design). Moreover, an initial decision of materials is taken whereat lightweight criteria are regarded. Difficulties can occur by regarding the former identified trade-offs and general conditions (e.g. recycling, manufacturing, assembly,…). Analysis Gate 1 gives estimated information about the weight and the weight distribution of the entire system solution.

4 Conclusions

The weight and weight distribution and their consequences can significantly influence the fulfillment of functionality and other product properties, for example cost, stiffness, safety etc. For that reason, it is relevant to consider the product weight and weight distribution as early as possible in the development process. But in today's development processes the task of weight optimization is mostly considered only in later phases. The methodology "Development of Weight-optimized Mechatronic Products" presented offers a remedy of this drawback. In this paper, the process view of the methodology is presented with special focus on refinement of the early phases – from the requirements to a system concept. With the help of the systemic and the conceptual lightweight design strategy different adapted methods enable a holistic view and estimation of lightweight potential. In further research, the refining of the later development phases will be performed on the basis of the results presented. Furthermore, the product view of the methodology – weight optimization with the help of mechatronic concepts – will be more focused on. The validation of the methodical framework will be demonstrated on specific examples in further research.

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Statistical Tolerance-Cost-Optimization of Systems in Motion Taking into Account Different Kinds of Deviations

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Abstract. The time-depending motion behavior of systems in motion is essentially affected by manufacturing-caused as well as operation-depending deviations (e.g., deformations), which appear during the system's use. Consequently, it is almost impossible for the product developer to define the optimal tolerances, which both ensure the mechanism's functionality and cause minimum manufacturing costs. This paper presents a methodology for the "statistical tolerance-cost-optimization of systems in motion". Therefore two appropriate mathematical optimization concepts are developed. The practical use of the methodology is shown for a non-ideal crank mechanism which is subject to manufacturing-caused as well as operation-depending deviations.

Keywords: tolerance optimization, tolerance-cost-relations, time-depending tolerance simulation, systems in motion, statistical tolerance synthesis.

1 Introduction

A product's functionality depends largely on the interaction of its components and their geometries. Hence, geometric deviations of these components need to be taken into account in order to ensure the functionality. These deviations can result e.g., from manufacturing discrepancies. But also operation-depending deviations (like deformations due to inertia forces) are affecting the product's functionality [1].

Usually a tolerance analysis is used to determine, how the appearing deviations are affecting a system's functional key characteristics (FKCs). According to THORNTON [2] the FKC is "a parameter of a product, sub-assembly, part, process or resource that significantly impacts the final cost, performance, or safety of a product". Already existing approaches enable the product developer to perform statistical tolerance analyses taking into account many aspects concerning products and processes. How-ever, these approaches are not integrating the specific aspects of systems in motion: The different kinds of deviations affect the FKCs in two different ways. Random deviations (e.g., manufacturing-caused deviations of dimensions like length or height) result in a variation of the FKC, while the deterministic deviations (e.g., operation-depending deformations) cause a mean shift of the FKC's distribution. Moreover, the

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time-depending motion behavior and therefore the significantly varying effects of the appearing deviations on the FKCs make it almost impossible for the product developer to define the optimal tolerances. Consequently, the question on “the best (and cheapest) tolerances of a system in motion” still remains unanswered.

This paper focuses on answering this question by developing a methodology to statistical tolerance synthesis of mechanisms taking into account the resulting costs. So the product developer will be able to determine the optimal tolerance specification which ensures the fulfillment of the functional requirements and causes minimum costs. In order to solve this optimization problem with two diverging requirements (small tolerances to ensure the functionality vs. large tolerances to minimize the costs) two appropriate, but fundamentally different optimization concepts are developed.

2 State of the Art

The tolerance analysis and tolerance synthesis – being the two major objectives of the geometric dimensioning and tolerancing – are well known and widely used in today’s product development. The large diversity of analyzed products and processes and therefore the resulting requirements towards the product developer reflect in research dealing with many different tolerance-related aspects of products and processes.

2.1 Tolerance Analysis of Systems in Motion

However, the specific aspects of systems in motion during their use are not integrated in existing approaches of the statistical tolerance analysis. In this context, especially the time-depending effects of the different kinds of deviations, which appear during the product lifecycle, as well as possible interactions between these deviations have to be emphasized. This prompts HASENKAMP to say, that in particular the development of integrated methods, considering all product lifecycle stages, is both a promising as well as a necessary aim of tolerance management and robust design [3].

A mechanism’s kinematic behavior is essentially affected by geometric deviations of its components, which can be traced back to e.g., manufacturing discrepancies. So a time-depending tolerance analysis of the effects of geometrical deviations is required. Several publications consider manufacturing deviations for mechanism with lower [4, 5] and higher kinematic pairs [6]. However, during the product’s use also operation-depending deviations appear and affect the system’s FKCs. The displacement of parts due to joint clearance is taken into account in [6] and [7], while [8] and [9] consider the deformation of parts due to the forces which result from the system’s motion. Further research activities consider both kinds of deviations (manufacturing as well as operation-depending) [10]. However, the time-dependence of mechanisms and thus of the deviations and interactions between these deviations still remain unconsidered. The approach on the “integrated tolerance analysis of systems in motion” is detailed in [1] and [11]. This approach allows the tolerance analysis of mechanisms with manufacturing-caused and operation-depending deviations. Moreover, appearing interactions between the different kinds of deviations can be taken into account [1].

2.2 Statistical Tolerance Synthesis and Optimization

Recently CAMPATELLI identifies the tolerance synthesis as "currently one of the most proficient ways to reduce the cost of machined parts" [12]. The tolerance synthesis is used to distribute the tolerated variation of the functional key characteristic of an assembly among the variations of the product's components according to an allocation scheme. In contrast to a tolerance synthesis, the tolerance optimization uses mathematical optimization methods to determine and apply the optimal allocation scheme according to the tolerance optimization's diverging requirements.

In the early days of research on the field of "tolerance optimization" as one of the first [13] used optimization algorithm (Simulated Annealing) to investigate the single part's tolerances and the corresponding costs. The possibility to reduce the tolerance-caused manufacturing costs by changing the chosen manufacturing process is taken into account in [14]. Hence, the tolerance-cost-relations, which are used as the optimization's constraints are discontinuous functions. The research of [15] and [16] focus on the tolerance optimization taking into account both the tolerance range and the tolerance's mean shift. Therefore [15] uses mathematical optimization algorithm, while [16] uses the Lambert W function to determine the optimal tolerance specification of a non-dynamic (no time-dependence) system.

The tolerance synthesis and tolerance optimization of time-depending systems (e.g., systems in motion) are rarely subject of tolerance-related research. Into the bargain, the effects of different kinds of deviations are hardly considered in these research activities. In [17] an iterative tolerance synthesis process of a non-ideal crank mechanism is detailed. However, the time-depending consideration is limited to just one motion sequence of the mechanism and the needed functional relationship is not time-depend. Moreover, aside of manufacturing-caused deviations no additional deviations (like operation-depending deformations) are taken into account. In contrast to [17], the tolerance optimizations in [10] and [18] use a time-depending functional relation between the functional key characteristic and the appearing deviations. However, also these works are limited to manufacturing deviations, since the effects of additional operation-depending deviations are not considered.

3 Motivation and Identified Problems

As detailed, a variety of research considers the tolerance synthesis / tolerance optimization of non-ideal technical systems. However, especially the two main characteristics of systems in motion – the appearance of operation-depending deviations and the time-dependence of the system and thus of the functional key characteristics and the appearing deviations – are not taken into account yet.

This results in two major problems the product developer has to face: On the one hand, the different kinds of deviations affect the functional key characteristics in two different ways: Random deviations (e.g., manufacturing-caused deviations of dimensions like length or height) result in a variation of the functional key characteristic, while the deterministic deviations (e.g., the operation-depending deformation due to inertia forces) cause a mean shift of the FKC's distribution (Figure 1).

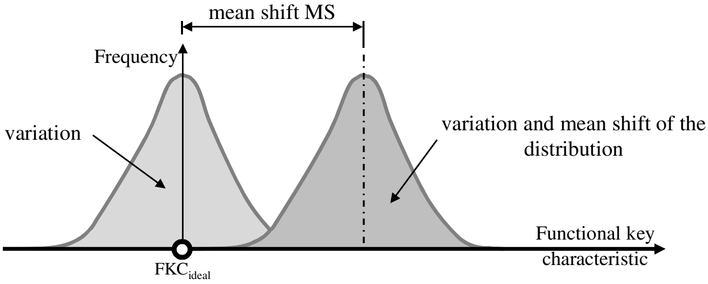

Fig. 1. Mean shift (MS) of the FKC due to systematic operation-depending deviations

On the other hand, the time-depending motion behavior and thus the significantly varying effects of the deviations make it almost impossible for the product developer to define the optimal tolerances. Consequently, the question on "the best (and cheapest) tolerances of the parts of a system in motion" remains unanswered.

4 Work Methodology

The paper focuses on the statistical tolerance optimization of systems in motion taking into account the system's time-depending motion behavior and the effects resulting from systematic operation-depending deviations (mean shifts). So the product developer will be able to define the optimal tolerance specification which ensures the fulfillment of the system's functional requirements and causes minimum costs.

At first, an appropriate mathematical concept must be formulated to solve the considered optimization problem with its two diverging requirements (small tolerances to ensure the functional fulfillment vs. large tolerances to minimize the costs). Therefore, two fundamentally different optimization concepts are developed and presented in section 5. Furthermore, a methodology has to be derived, that supports the product developer when performing the "statistical tolerance-cost-optimization of a system in motion" (section 6). In order to show the concepts' practical use, a tolerance-cost-optimization of a non-ideal crank mechanism inside a 4-stroke combustion engine will be performed in section 7. The crank mechanism's components are subject to both manufacturing-caused as well as operation-depending deviations. The paper closes with a comparison of both concepts concerning the determined tolerance specifications, the resulting manufacturing costs as well as the numerical expense.

5 Mathematical Concepts

In order to develop an appropriate mathematical concept for the needed tolerance-cost-optimization, the verbal formulation of the considered optimization problem is useful. Therefore, the objective as well as the corresponding constraints and restrictions of the optimization problem have to be identified. These can be derived from the challenge the product developer has to face during his/her every day work: The overall objective of a successful product development is to ensure the product's functionality which goes hand in hand with the ambition to realize products of high quality. This should be achieved in less time, causing low manufacturing costs.

Concerning the tolerance specification of non-ideal systems in motion, two different points of view can be derived, based on the verbal optimization problem:

- The deviation of the system's functional key characteristic should be as small as possible at any point in time of the motion sequence, as long as the corresponding manufacturing costs do not exceed a given limit.
- The manufacturing costs which result from the tolerance specification should be as small as possible, as long as the functional key characteristic does not exceed the given upper and lower specification limits at any point in time of the motion.

Consequently, multiple concepts can be developed in order to solve these optimization problems. The following remarks of the subsections 5.1 and 5.2 detail two promising concepts to solve the two different optimization problems.

5.1 Concept 1

The objective of the first concept is to minimize the deviation of the functional key characteristic (FKC) from its ideal value (FKC_{ideal}) at any point in time t of the motion sequence. Therefore, the distribution and the ±3σ quantiles of the FKC are determined statistically, based on the functional relation and weighted by w(t) which corresponds to the FKC's mean shift at any point in time. The optimization constraint is the maximization of the component's manufacturing tolerances T_i within a given cost limit K_{max}. Therefore the lower limits of the tolerances can be defined e.g., by the precision of the used manufacturing processes. This concept corresponds to TAGUCHI's philosophy of quality – saying that a product's deviations should be as small as possible since otherwise the corresponding quality loss increases [19].

$$min \sum_{t=0}^{T} |w(t) \cdot [FKC(t) - FKC_{ideal}(t)]| \quad (1)$$

$$w(t) = E[FKC(t)] - FKC_{ideal}(t) \quad (2)$$

subject to constraints: $$K_{total} \leq K_{max} \quad (3)$$

$$T_i > 0 \quad (4)$$

5.2 Concept 2

In contrast to the first concept, the manufacturing costs (resulting from the tolerance specification) are the objective of the second concept. These manufacturing costs K_{total} have to be minimized, based on the corresponding tolerance-cost-relations of each tolerance T_i. However, the ±3σ quantiles of the functional key characteristic should not exceed its given time-depended lower and upper specification limits LSL(t) and USL(t). Similar to concept 1, also the manufacturing-caused tolerances should be maximized.

$$\min(K_{total}) \quad (5)$$

subject to constraints: $$LSL(t) \leq FKC(t) \leq USL(t) \quad (6)$$

$$T_i > 0 \quad (7)$$

5.3 Considered Parameters of Both Concepts

In addition to the range of the manufacturing tolerances T_i, also a mean shift of these tolerances $MS(T_i)$ will be considered during the tolerance-cost-optimization. This is due to the fact, that the appearing mean shift of a functional key characteristic can only be compensated by an appropriate mean shift of the manufacturing tolerances. Hence, the tolerance-cost-optimization considers both possibilities the product developer has to affect the deviation of a functional key characteristic: Changing the range T_i as well as the mean shift $MS(T_i)$ of the appearing manufacturing tolerances. Consequently, both each tolerance's range T_i and mean shift $MS(T_i)$ must be included in the concept's relation of the total manufacturing costs K_{total} (objective and/or constraints) to be considered during the optimization according to:

$$K_{total} = \sum_i [K(T_i) + 0 \cdot MS(T_i)] \tag{8}$$

However, since the manufacturing tolerances' mean shifts $MS(T_i)$ do not cause additional manufacturing costs these are multiplied by the factor zero in equation (8).

6 Methodology

In order to support the product developer to perform a statistical tolerance-cost-optimization of a system in motion, an appropriate methodology is derived (Figure 2).

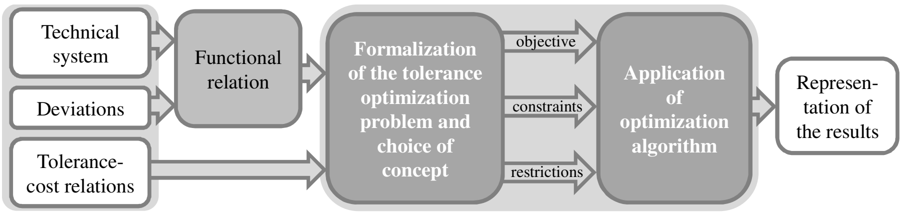

Fig. 2. Methodology: "Integrated statistical tolerance-cost-optimization of systems in motion"

Analogous to the "integrated tolerance analysis" [1], at first the functional relation between the functional key characteristic and the deviations which appear in the system's lifecycle has to be formulated. Therefore closed vector-chains can be used.

Based on the functional relation and the corresponding tolerance-cost-relations of each manufacturing-caused deviation, the tolerance optimization problem has to be formulated. Consequently, as detailed in section 5, also the mathematical concept as well as the objective, constraints and restrictions of the statistical tolerance-cost-optimization are defined thereby. The mathematical optimal solution, which could e.g., mean "the cheapest, but still full functional tolerance specification", is determined using appropriate optimization algorithms. Since the kinematic behavior of systems in motion usually leads to non-linear functional relations, appropriate algorithms must be used to solve the considered optimization problem.

The final step is similar to the closing step of the "integrated tolerance analysis" - the result representation. This includes the tolerances T_i and mean shifts $MS(T_i)$ of the manufacturing deviations as well as the resulting manufacturing costs K_{total}.

7 Demonstrator: Crank Mechanism

The demonstrator, used to show the tolerance-cost-optimizations' practical use, is a crank mechanism inside a 4-stroke combustion engine. The appearing deviations are essentially affecting the precise motion of the crank mechanism's components. These deviations can cause collisions of the mechanism's components among themselves (e.g., piston and crank shaft) or collisions with additional parts of the engine (e.g., piston and valves). Furthermore, the engine's performance (e.g., engine's combustion ratio) is affected due to the varying position of the piston during the motion sequence. Consequently, the functional key characteristic of the crank mechanism is the position of the piston along the X-axis of the global coordinate system (see Figure 3).

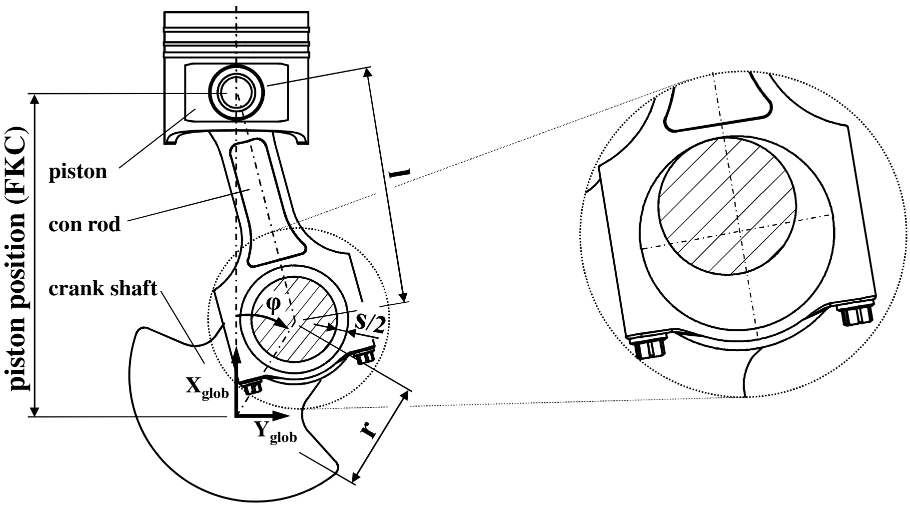

Fig. 3. Crank mechanism with manufacturing-caused deviations and coordinate system [1]

The piston underlies a time-depending combustion pressure with a maximum of 180 bar, which results in a rotation of the crank shaft with 3000 rpm [11]. A motion sequence consists of two rotations of the crank shaft with a total crank angle of $\varphi = 720°$. The considered deviations are:

- Manufacturing-caused deviation of the crank radius $r = 45 \pm 0.02$ mm (distribution: triangle) and the con rod link length $l = 138 \pm 0.05$ mm (distribution: trapeze)
- Operation-depending deformation of the crank shaft and displacement of the con rod due to joint clearance $s = 0.06$ mm in the lower con rod bearing

8 Tolerance-Cost-Optimization of the Crank Mechanism

In order to ensure the crank mechanism's functionality, the deviation of the piston from its ideal value is limited to the specification limits of ± 0.2 mm. At the beginning of the crank mechanism's motion sequence ($\varphi = 10°$), the lower 3σ-quantile of the deviation of the piston Dev_{Piston} exceeds its lower specification limit (LSL = -0.2 mm) and consequently causes defective crank mechanisms, which do not fulfill the functional requirements. In order to reduce the number of defective mechanism, a redesign of the tolerances of the crank mechanism's components should be done by the product developer. Hence, the presented methodology of the "statistical tolerance-cost-optimization of a system in motion" will be used.

Therefore the so-called reciprocal power cost-tolerance relations are used, according to [20]. This tolerance-cost-model considers the component's fixed costs A_i, which include e.g., the needed tools. The costs B_i represent the individual manufacturing costs of the considered tolerance T_i.

$$K(T_i) = A_i + B_i \cdot (T_i)^{-1} \tag{9}$$

Consequently, the needed tolerance-cost-relations can be formulated for the crank radius r (A_r = 25€, B_r = 1.50€) and the con rod length l (A_l = 30€, B_l = 2€). Since the initial tolerance specification (r: ± 0.02, l: ± 0.05) causes manufacturing costs of 112.50€, the limit of the first concept's manufacturing costs K_{max} should be 100€. Consequently, the optimization of concept 1 should lead to a fully functional tolerance specification at even lower costs. The optimization runs are done for 100 (concept 1) and 5000 (concept 2) Monte-Carlo-based samples. Table 1 details the results.

Table 1. Results of the tolerance-cost-optimizations of the crank mechanism

	Time in h	$MS(T_r)$ in mm	T_r in mm	$MS(T_l)$ in mm	T_l in mm	Costs in €	Defects
Concept 1	4.9	0.010	0.149	0.077	0.180	76.18	Yes
Concept 2	29.0	-0.008	0.083	0.089	0.081	97.76	No

It can be noticed that the tolerances of the first optimization concept result in lower manufacturing costs, but still lead to defective mechanisms, exceeding the upper specification limit. However, concept 2 results in a tolerance specification, which ensures the product's functionality and even reduces the corresponding manufacturing costs. The numerical expense of both concepts, but in particular of concept 1 (~5 hours for 100 Samples), is immense. Consequently, the second concept should be the product developer's first choice to determine the optimal tolerance specification. The time-depending deviation of the piston Dev_{Piston} as well as its upper and lower specification limits are shown in figure 4.

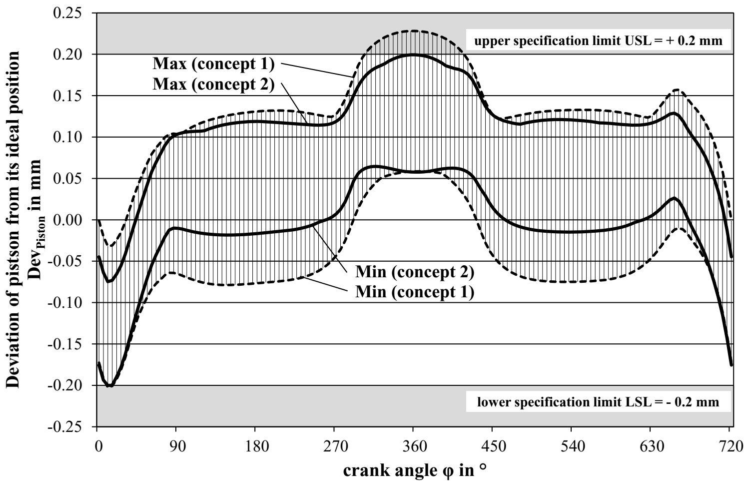

Fig. 4. Deviation of the Piston during one motion sequence of the crank mechanism

9 Conclusion and Outlook

This paper focused on the tolerance-cost-optimization of a system in motion taking into account the two main characteristics of systems in motion during its use – the appearance of different kinds of deviations and the time-dependence of the system and thus of the functional key characteristics and the appearing deviations. Therefore both each tolerances' range T_i as well as the corresponding mean shifts $MS(T_i)$ must be considered – since those two parameters have to be defined by the product developer during the product development process.

A methodology was presented which supports the product developer to systematically determine a mechanism's optimal tolerance specification. Therefore, two different mathematical optimization concepts were derived and implemented. The practical use of the statistical tolerance-cost-optimization was shown for a crank mechanism, which is subject to both manufacturing as well as operation-depending deviations.

Basically, the tolerance-cost-optimization of systems in motion (using concept 2) enables the product developer to determine the tolerance specification, which ensures the time-depending system's functionality during the system's use, while causing low manufacturing costs. However, the possibility of choosing alternative manufacturing processes and the effects on the tolerance-cost-relations is an important aspect that is not considered yet. Furthermore, possible interactions between the appearing deviations are currently not taken into account. Consequently, the presented tolerance-cost-optimization has to be improved towards more complex systems.

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Forecasting Environmental Profiles in the Early Stages of Product Development by Using an Ontological Approach

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Abstract. Considering environmental aspects in early product development stages is a complex endeavor. Product life cycle data are fuzzy and subject to changes. Additional workload due to data handling is a common reason why it is withdrawn by engineering designers. Some studies suggest parameterization of products in order to gain a limited set of parameters to handle, some others suggest integration of Life Cycle Assessment into CAD or Product Data Management systems. However, the handling of heterogeneous data from multiple sources is not paid much attention. This paper suggests an ontological approach that allows considering data from multiple sources to set up an environmental profile of the product and allow for adaptations in the product concept.

Keywords: ecodesign, life cycle assessment (LCA), sustainability.

1 Introduction

The integration of Life Cycle Assessment (LCA) into early stages of product development is an important and efficient way to strive for environmental benign products. However, conducting an LCA in the early design stages is a difficult and complex endeavor: in these early stages, the product is subject to many changes which affect the life cycle of the product and its environmental performance. Later in the development process, more specific data may be available, but the possibility to influence the product decreases; a phenomenon known as the design paradox [1].

Recently, some studies have suggested comparing the environmental performance of a new product being developed with similar products in the market [2]. The so-called Life Cycle Comparison Family (LCP-family) includes products that have similar functional units. Product similarity can therefore be understood as similarity in regard of similar functionalities or similar structures (e.g. similar hierarchy of parts and components, similar platforms, etc…). In this paper, products that fulfill the same or similar requirements are taken to infer the environmental performance of a new product that shares similar requirements.

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Design process is already complex, and engineering designers are not necessarily environmental experts. Any approach to integrate LCA into early product development and design stages will fail if it adds to workload or complexity to the process. Engineering designers usually have a good understanding of the product they are developing as well as of the benchmarks and competitors. To implement a methodology for environmental assessment at this phase of data availability, Ostad-Ahmad-Ghorabi and Collado-Ruiz [3] have proposed a methodology that uses only information available and commonly known by engineering designers in the early product development stages; this information is called *primary parameters*. The methodology asks for technical data, which is usually defined in the list of requirements of the product. This data is then linked to life cycle inventory data to infer environmental performance. This can be compared to similar products, as described above. However, this methodology has been developed for a specific product type, namely cranes. A systematic approach to derive primary parameters is missing.

In this paper, authors are proposing an ontological approach to set up primary parameters systematically for particular product categories. The aim of using an ontological approach is to enable the management and use of heterogeneous data along the product development process [4] [5]. In fact, data defined in the proposition of requirements are taken and processed to set up primary parameters suitable for a specific product category. Further, an ontology can be used to establish a pool of proper products serving as references to compare the environmental performance of the product with as well as to position it within the benchmark.

A case study of hydraulic machines is presented. A proper ontology is developed and suitable primary parameters are derived by considering the requirements of hydraulic machines. A specific product among hydraulic machines serves as case study and withthe help of the primary parameters, a forecast for the environmental performance of this product is derived and compared with a suitable benchmark. The paper demonstrates how data from various sources, i.e. data found in the definition of requirements, data considering the functional structure or data from the process structure can be efficiently handled by using the developed ontologapproach that links this data with environmental life cycle data and allows for the forecast of an environmental profile and a comparison with similar products. The main goal of the methodology proposed in this paper is to bring together all relevant data for environmental assessment into the early product development stages. At the same time, it is of highest priority to avoid confronting any user with all the detail information and flood of data needed to proceed with a full LCA. However, the assessment shall be representative enough to allow for strategic decisions regarding the preliminary development of the product; may it be the conceptualization of parts and components, material composition, realization of functionalities or else.

2 State of the Art

The start of the product development process is characterized by giving answer what requirements the product has to fulfill. Two types of requirements can be distinguished: general requirement, valid for a product category, and specific requirements, valid for specific products within a category. An example for general requirements is the minimum safety requirements a car has to fulfill in accordance with standards and regulations, e.g. requirements to be fulfilled for frontal-impact test. Specific safety requirements can be defined by a car manufacturer and constitute all additional features (e.g. realization of tiredness sensor for the driver or realization of vehicle-interval radar) which add to safety, but are not demanded by any regulation.

Once requirements are defined, the next step is to think about how the requirements can be realized, which functions have to be realized and what parts and components are needed . Usually, the first approach would be to gather as much information as possible from previous or similar products or to take a deeper look into products from the benchmark.In fact, there are four main source of information that are available and can therefore be handled in the early product development stages:

1. Information that are used to set up requirements
2. Information regarding the realization of functions and processes
3. Information from previous product concepts or variants
4. Information from similar products or benchmarks

Most of the available information is either of general nature or, specific to a product but fuzzy and subject to changes and adaptations.

The aim of conducting an environmental assessment of a product in early product development stages may therefore suffer from insufficient data quality. However, Ostad-Ahmad-Ghorabi and Collado-Ruiz have shown that it is possible to conclude to a reliable environmental profile and assessment results by developing a parametric model of the product. Furthermore it is possible to benchmark the environmental profile by setting up a proper family [2,3,6]. However, some existing shortcomes withdraw the concepts to be practicable for daily use. Firstly, the parametric model was derived for a specific product and no automated process was used to derive the model. Secondly, the concepts of a parametric model and benchmark family are not linked.

What can be taken as an essential module for the development of an ontological approach is the concept of primary parameters, defined as "…the most important design parameters that are defined in the very early conceptual design stages". Also the concept of secondary parameters, through which data in the LCA inventory can be described, is of important need for the methodology being developed in this paper. [3]

3 Method and Concept

To be able to consider all sources of information, an ontology [7] is developed to enable information handling during early product development stages. In this paper, the method of Noy and McGuinness is used to develop the ontology [8]. Their method premises that the development of an ontology is an iterative approach [9]. Ontology concepts shall consider objects and relations of the domain. Objects are described by nouns and relations by verbs.

According to Noy and McGuiness, seven steps have to be followed to create an ontology:

1. Determining the domain of the ontology: This is done by giving answer to the following questions: What is the ontology going to be used for? What types of questions shall be given answer to by the use of the information contained in the ontology? Who will use and maintain the ontology?
2. Reusing existing ontologies: Existing ontologies may be adapted for the particular domain. Many available ontologies can be accessed through different libraries in the internet, e.g. Ontolingua ontology library [10].
3. Specifying the important terms and listing them: The aim is to create a comprehensive list of terms, without worrying about overlap thoughts. Giving answer to "What are the terms the ontology should talk about?" and "What properties do those terms have?" can help in this endeavor.
4. Defining and creating classes and class hierarchies: They are described using formal (mathematical) descriptions that state precisely the requirements for membership of the class. For example, the class Product would contain all the individuals that are Products in our domain of interest. Classes may be organized into a superclass-subclass hierarchy, which is also known as taxonomy.
5. Determining properties of the classes: To answer the questions defined in step 1, more information is needed, in particular the relation between different items of the class. Formulation such as "has a" or "is part of" can be used. Subclasses inherit all slots from superclasses.
6. Determining the facets of the slots: a slot can have different facets describing: value type, cardinality or permissible values (domain and range). Common value types are: string or number. The slot cardinality defines how many instances a slot can have
7. Creating individual instances in the hierarchy. The approach is as follows: First a class is chosen, second an individual instance for that class is created, and third, the slot values are defined.

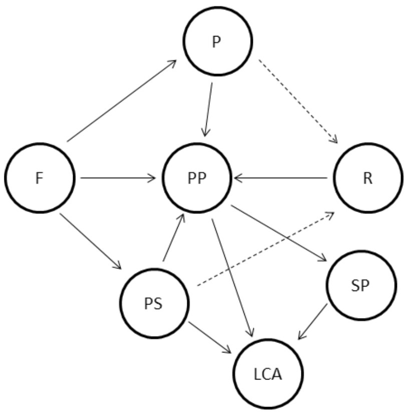

Fig. 1. Top Level Ontology: R: Requirement, F: Function, P: Process, PS: Product structure, LCA: Life cycle Assessment, PP: Primary Parameter, SP: Secondary Parameter

The ontology serves as a semantic network, which represents and provides information in a structured way [11]. Product functions, product structures and processes are determined by *requirements*. *Product structure* refers to information that can be extracted from pervious products and product variants as well as from benchmark products. It implies information about the hierarchical structure of parts and components. *Process* implies all activities needed to develop a product; including design processes or manufacturing processes. Information processed from the requirements is used to set up primary parameters. Secondary parameters are derived from the LCA model, which can be set up once the product structure, functions and processes are known. LCA inventory data can be assigned to secondary parameters.

4 Case Study and Results

The ontology in this paper is developed for hydraulic machines. This product category contains products such as hydraulic cranes, loaders, pumps or similar. The example of knuckle-boom cranes is further detailed. The ontology shall help to retrieve an environmental profile of the product in early design stages.

To fill the ontology sketched in Fig.1, a list of requirements of hydraulic machines was consulted first. For the example of knuckle-boom cranes, the most important requirement is to lift a certain load over a certain length. At the same time, the dead weight of the crane has to be minimized in order to allow for maximum lifting load. To implement the requirements, certain functions have to be realized. To lift a load, cylinders have to be moved; in fact hydraulic oil has to be pumped into the cylinders. This function on the other hand accounts for further requirements, e.g. those regarding the flow rate of the oil pump. Considering product development processes, more interrelations between the parameters occur. Table 1 shows an excerpt of the list of requirements, the functions and processes and how they interlink.

Table 1. Requirements, functions and processes for crane

Requirement	ID	Interlinks with
Total weight of crane	R-1	F-1
Maximum lifting moment	R-2	F-1, F-2
Operating time of crane over lifetime	R-3	F-1, f-2
Function		
Lift load	F-1	
Pump oil	F-2	
Rotate main boom	F-3	
Process		
Determine output power	P-1	F-2
Determine specific fuel consumption	P-2	F-1
Determine necessary oil volume	P-3	F-1

The information above shows what is available in the very early design stages. On the one hand, this information can be taken to generate primary and secondary parameters. The result is taken into account when aiming at conducting an environmental evaluation.

For the aforementioned main requirement of the crane, the primary parameter that maps this requirement is *Maximum lifting moment*, its unit in meter tons (mt). Accordingly, the parameter that is able to map the requirement of minimum dead weight is *Maximum weight of crane,* its unit in tons (t). The complete list of primary parameters for the requirements listed in Table 1 is retrieved according to the method in described in [3]. An excerpt is listed in Table 2.

Table 2. Primary parameters for a crane

Parameter	Unit
Maximum lifting moment	meter ton
Total weight of crane	Ton
Estimated weight distribution of each component	Ton
Manufacturing site	-
Weight of packaging	Ton
Flow rate of oil	dm^3/sec
Etc…	

Secondary parameters are derived out of information needed for LCA. This requires the handling of inventory data, usually available through LCA databases. Primary parameters and secondary parameters are linked through either guidelines, physical independencies or statistical data. The latter refers to information from previous product concept and variants or benchmark information.

Information at hand is different in quality and heterogeneous in their sources. To be able to handle the information properly, an ontology is developed by following the seven step approach discussed earlier in the paper:

- Step 1: Domain: Life Cycle Assessment in early stages of product development.
- Step 2: Does not apply to this case study, since there is no ontology available that can be reused, adapted or extended.
- Step 3: Important terms: LCA, Part, Primary Parameters, Environmental Performance, Requirements, Engineering
- Step 4: Classes and class hierarchies: Classes: *Function*, *Condition*, *Life Cycle Assessment*, *Primary Parameter*, *Process, Product, Requirement, Result, Secondary Parameter*; Class hierarchies: Relationen: e.g. *Condition to Process*, *Function to Product, Process to Product, Requirement to Function* etc.
- Step 5: Properties of the product classes: *has amount, has ID-number, has Material, is Part of, has Weight, has Version* etc.
- Step 6: Determining the facets of the slots: Value types for Life Cycle Assessment class: Potential for global warming indicator, expressed in g-CO_2-eq, for all life cycle stages (Raw materials, manufacturing, distribution, use and end of life)
- Step 7: Instances: Product: *Crane_20LM*

The result is partly shown in Fig. 2.

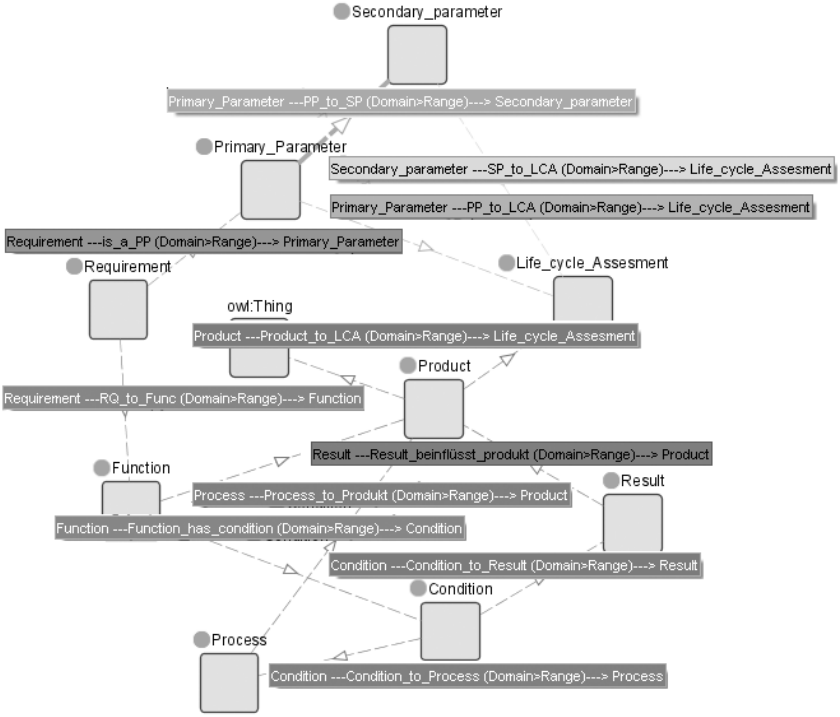

Fig. 2. Protégé [12] screenshot of the ontology) with Protegé Jambalaja Plugin [13]

To demonstrate the usage of the ontology, first a reference crane is considered. The reference crane has a maximum lifting moment of 20mt. Since maximum lifting moment is the most important design parameter for a crane, it is assumed that for a new model of the crane, this parameter is changed from 20mt to 78mt. This results in a bigger crane that has to fulfill different requirements, may have additional functionalities or asks for different processes in the development process. All these changes influence the environmental performance of the product.

With the help of the ontology, it is now possible to track how the change in the parameter maximum lifting moment will finally influence the environmental evaluation results. Using SPARQL [14] as ontology querying language, all information interlinked with the parameter maximum lifting moment will be listed. The query indicates that the primary parameter maximum lifting moment is interlinked with the functions *lift_load*, *move_cylinder*, *move out crane*, *pick_load*, *transmit_torque*, *pump_oil* or *operate_hydraulich_pump*. These functions on the other hand, are linked to processes such as *testing cylinder with load*, *determine oil volume*, or *determine output power of oil pump*. Some of these processes are already linked to LCA inventory data, for example oil volume is linked to LCA inventory data of oil, and CO_2 value for oil can directly be linked to its volume.

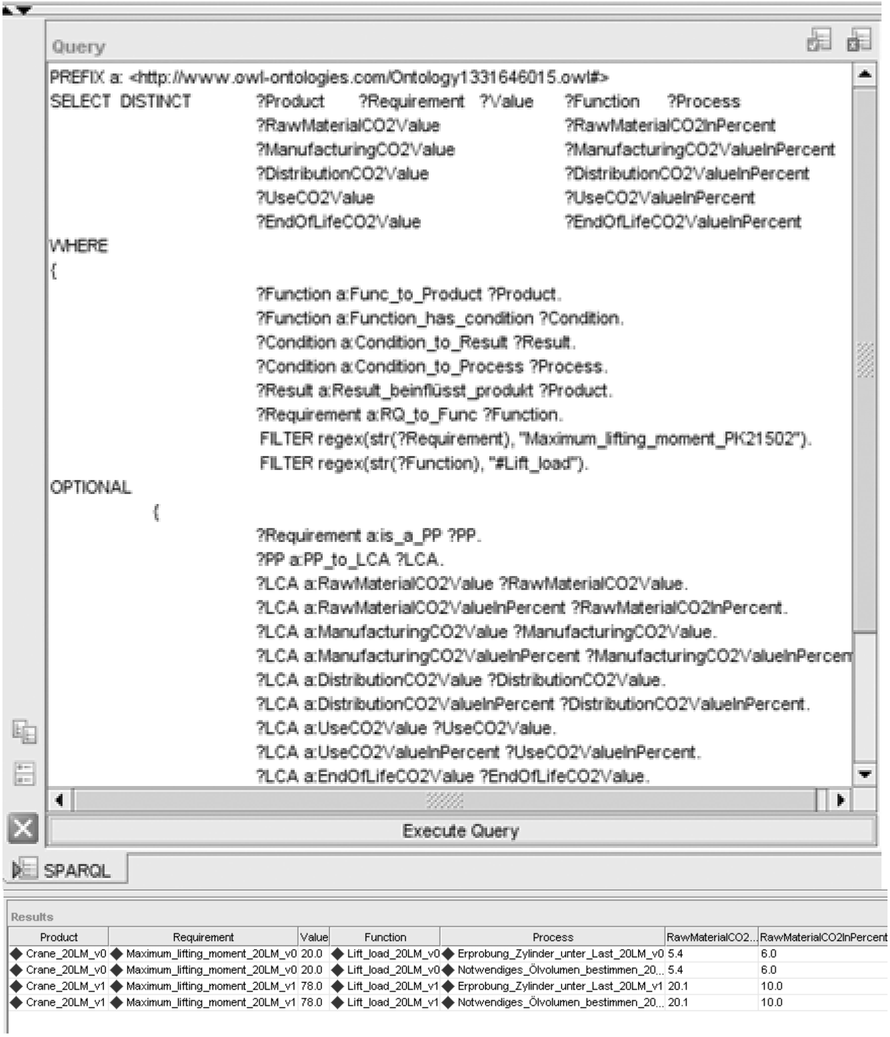

Fig. 3. SPARQL query [15] and results

The results further indicate that 89% of the total environmental impacts of the crane occur in its use phase. The impact sin the use stage are dominated by the fuel consumption for crane operation. Improvements can be achieved by installing affective oil pumping systems (e.g. variable displacement pumps rather than fixed ones) or thinking of alternative power supply for the crane (e.g. electric power supply on construction sites and whenever possible). The impacts in the other life cycle stages are negligible compared to the use phase (materials 6%, manufacturing 7%, distribution negligible, end of life -2%, due to recycling processes).

5 Summary

In the early stages of product development a mixture of qualitative and quantitative data is available. This data can be taken to forecast the environmental profile of the product. To avoid additional workload for engineering designers for handling data and providing relevant data at any step of the product development process, it is important to extract as much information automatically as possible. The interrelations of information from different sources are an important aspect in this process. The ontology described in this paper shows how different data found in the list of requirements, in the qualitative description of functions and processes can be interlinked. The SPARQL query provides a platform where the query asks for the relevant information and where the user can input as much information as is known at a particular time. The ontology links the data with primary and secondary parameters; the latter itself is linked to LCA inventory data. The LCA inventory data can then be used to set up o first environmental profile of the product.

In future research steps, more ontologies will be developed for the same purpose for different product types. The aim is to provide suitable ontology elements for as many product types and categories as possible.

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Leveraging Product Development for a Sustainable Future: Energy and Resource Efficiency in Lifecycle Analysis

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Abstract. Life Cycle Assessment (LCA) and eco-efficiency analysis are powerful tools to support the lifecycle engineering and to become a part of Product Lifecycle Management (PLM). This paper presents an approach of the implementation of LCA tools as fully integrated within the PLM supporting the design engineer in terms of sharing relevant product data across modules and lifecycle phases, thereby reducing the overall amount of data management related work performed by engineers and increasing data availability. In a case study the capabilities of an existing LCA solution are examined and presented at the example of a wheeled excavator.

Keywords: Sustainable Development, Life Cycle Thinking, Product Lifecycle Management, Life Cycle Assessment, Energy and Resource Efficiency.

1 Introduction

Sustainable Development, conceptually founded on the three dimensions economical, ecological and social sustainability is the main paradigm for the future improvement of humankind in the 21st century. One of the guiding principles for engineering design is to develop products that conform to the sustainability paradigm. Already in the early phases of the product lifecycle, the engineer defines key properties of a product, implicitly including the definition of the resulting lifecycle costs as well as environmental and social effects. The process of creating more a clearly sustainable product needs to be monitored and managed, whether a new product is to be designed or an existing one is to be improved. To address an engineering design process and the product development, appropriate methods and tools are required. [1]

This paper considers Product Lifecycle Management (PLM) [2] as one key concept for the establishment of sustainable engineering design processes.

2 Sustainable Development

The awareness of limited resources availability, environmental problems and pollution, the increasing demand for goods, energy and materials from the already

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developed and the new developing countries, as well as the increase of costs of scarce resources, all are calling for a new paradigm of life, overcoming the obsolete consumerist model of modern societies [3]. Sustainability became even more than a buzzword these days. The visionary paradigm of Sustainable Development was introduced in 1987 by the World Commission on Environment and Development of the United Nations in a very basic term within the Brundtland Report. Five years later the vision of Sustainable Development was globally accepted at the United Nations Conference for Environment and Development. Once again ten years later the United Nations World Summit on Sustainable Development stipulates Lifecycle Thinking as one self-contained principle within the sustainability paradigm. [4]

However, in current literature, sustainability denotes a development which meets the needs of the present generation without compromising the ability of future generations to meet their own needs [5]. It identifies three dimensions – economic, environmental and social issues – which, in regard to the characteristic of the model of sustainability, are considered equivalent and standing side by side, or in other words, harmony has to be brought between them [3].

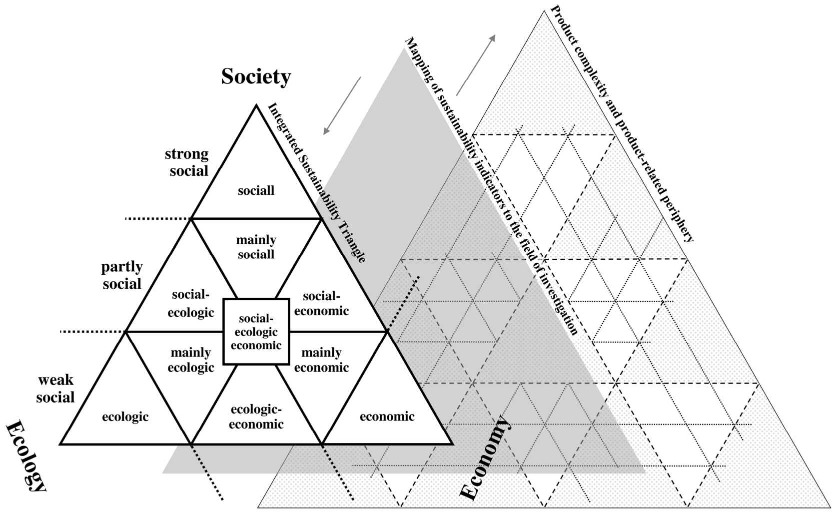

Fig. 1. Monitoring of Sustainability performance within the Integrated Sustainability Triangle (adapted from [4], [6], [7])

The Integrated Sustainability Triangle (IST) (see Figure 1) is a promising new instrument for systemizing the sustainability performance of a company, currently used for monitoring the product development process regarding sustainability management [8]. In the case of products total lifecycle approach is necessary for a sustainable management.

2.1 Lifecycle Thinking

The economic system as well as science and politics are claimed to enable a sustainable change. For that a tremendous improvement of current technologies is also required. In such a setting, sustainable manufacturing will become one of the most relevant topics in future engineering. Within this rethinking, the product concept with all participating and involved processes has to be reshaped, especially taking into account the lifecycle view [9]. This rethinking causes new requirements related to sustainability assessment of a product and all lifecycle phases, ranging from raw material extraction, across production, to use and recycling or waste disposal. This ecological view of the product lifecycle refers to the material flow. To organize the product development, a consideration of the information flow is of central meaning. Already in the early lifecycle phases, the engineer defines key properties of the product. Here up to 80% of the resulting lifecycle costs as well as about the same percentage of environmental effects are defined [10-11]. Assuming a similar rate of social effects a sustainable improvement of the product development process is appointed in this early step.

2.2 Product Development Process

Enterprises today have to deal with new arising challenges such as globalization. As a result they have to collaborate more directly with others like their suppliers and customers. Furthermore the rising demand for product innovation, product reliability and product liability have caused new challenges in the product management and process management. The information about a product throughout its complete lifecycle - from the early phases up to the recycling or disposal - is often distributed across a global network of data handling systems supporting different lifecycle phases and different engineering disciplines [12].

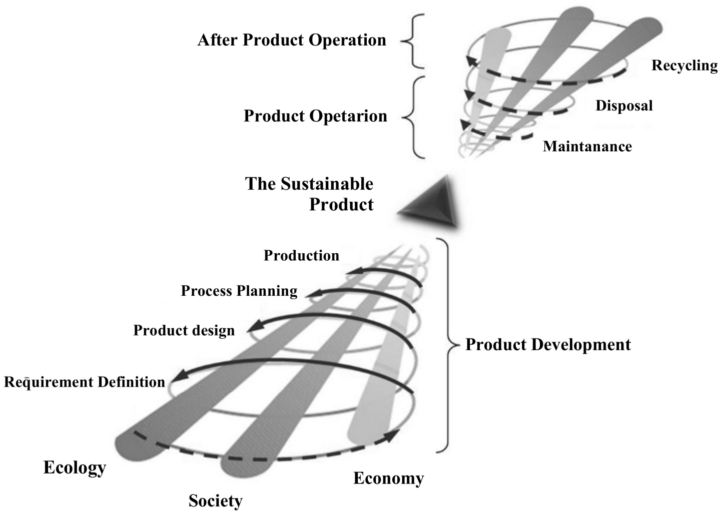

Fig. 2. Sustainability influencing the Product Development Process

A holistic approach, almost in the sense of a "product biography", has to begin in a phase when the physical product does not yet exist and end when it can no longer fulfill its original purpose. The criticism of the classical - partly economically, partly ecologically oriented - product lifecycle models stipulates for rethinking in terms of an integrated approach. The sustainable economical activities of a company should be understood as an ongoing search and learning process with the objective to conquer new markets through sustainable products. The sustainable product itself should be seen as environmentally friendly, economically viable and socially acceptable (see Figure 2). Therefore an entire view of the product is necessary. Central here is the potentially sustainable, intellectual product, which is accompanied transparently from the initial idea, through all lifecycle phases, to the recycling and reuse. Furthermore a consideration of the three dimensions – economy, ecology and social – is required.

Bearing in mind that a lifecycle product model is a multidimensional network of requirements, functions, behaviors, development, test and production structures across all disciplines involved with the product, across all internal and external development and manufacturing sites, all resources used for manufacturing and assembly of the product, as well as across all relevant documentation, the existing manual and separate handling techniques fail.

3 Product Lifecycle Management

In order to manage an engineering design process and handle the product complexity the engineer has to administrate all kinds of data and information about the product. This would not be possible without using modern IT tools. The use of IT tools for support of the integration and federation of distributed product data and their related processes, as well as the administration of high number of product variants have already been recognized as a driving factors for success, survival and competitiveness [12]. Product Lifecycle Management is the administrative and managing backbone for all these tasks in product engineering [2] [13].

3.1 Product Data Management

One benefit of computer aided engineering design is that it facilitates the development of sustainable products by a better availability of relevant information. Even as early as today, a computer aided lifecycle assessment with an automatic calculation and monitoring of energy and material flows caused by the processes of the product and the linkage with conventional lifecycle databases could be customized. Therefore, the product structure - available in a Product Data Management (PDM) system - has to be extended with lifecycle processes like production, transport, use and end-of-life processes [1]. Product Data Management systems offer first answers to these problems by linkage to tools for Life Cycle Assessment (LCA).

3.2 Life Cycle Assessment

Product related Life Cycle Assessment (LCA) with an emphasis on energy, resource and waste was started back in the 1970s, the time of the famous report ´The Limits to Growth` addressed to the Club of Rome and the first worldwide oil crisis, which brought awareness of the finiteness of oil and revealed the vulnerability of the global economic system. In the 1990s the LCA was developed as a method, mainly driven by the Society of Environmental Toxicology and Chemistry (SETAC), and standardized by the International Organization for Standardization (ISO). Later on, in 2006 the international standards have been slightly revised to their current version of ISO 14040 and 14044 [14]. The basic principles of any Life Cycle Assessment are the "cradle to grave" analysis and the use of functional unit. All mass and energy flows, resource and land use, and even the potential impacts and probable interventions are set in relation to the functional unit as quantitative measures of the benefit. A main characteristic of the current ISO standard is the clear structure which consists in the four components: "Goal and Scope Definition", "Inventory analysis", "Impact Analysis" and "Interpretation" [15]. The LCA is an essential comparative method to estimate the environmental aspects of a product system. It explores environmental aspects and potential environmental impacts across the life cycle, from raw material extraction, across production, to reuse of recyclates and waste disposal. A Life Cycle Assessment can assist engineers and decision-makers in the industry by identifying opportunities to improve the environmental performance of product systems and providing them with a platform for observing the environmental product declarations and compliance, thus support the design of more eco-efficient products [16-17].

3.3 Eco-efficiency Analysis

A first step towards an integrated sustainability assessment provides the link between economic and ecological issues and is represented in the new international standard ISO 14045 - Eco-efficiency assessment of product systems: principles, requirements and guidelines, adopted in 2012 [18].

The principles of eco-efficiency are combined with the lifecycle thinking and translated into certain goals [2]:

- Minimize energy intensity
- Minimize the material intensity of goods and services
- Maximize the use of renewable resources
- Minimize toxic dispersion
- Extend product durability
- Increase product efficiency
- Promote recycling

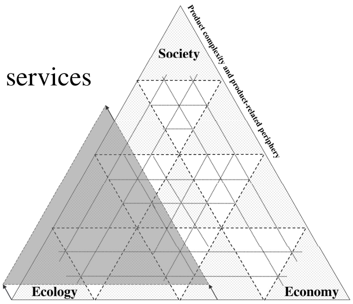

Fig. 3. Goals of eco-efficiency analysis

The objective of the eco-efficiency analysis is to support the evaluation of different optimization solutions by providing an overall life cycle view. The concept shown in Figure 4 refers to such kind of eco-efficiency analysis and is linked to PLM [19-20]. It extends the product model as well as the process model by technical-economical attention of ecological parameters, thus it allows an aggregated evaluation of energy and resource efficiency of the product over the product lifecycle. Energetically improved technical products will assert themselves in enterprise practice only if they are advantageous in economic regard. Hence, the deliberate design of eco-efficiency products is as important as both economic balance and life cycle assessment. The concept deals with both and is outlined in a way, that it corresponds to a multidimensional, interdisciplinary and federated lifecycle management.

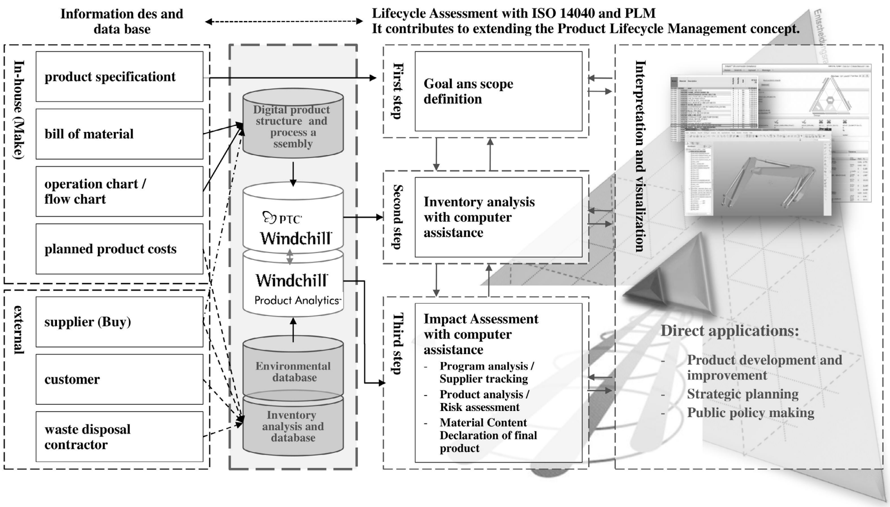

Fig. 4. Concept of an eco-efficiency analysis as part of PLM (adapted from [19])

The main topic of the research project underlying the following case study is to develop energy-efficient concepts and technologies for mobile working machines. Major focus is put on the powertrain, energy management, friction management and lifecycle management. [20]

4 Case Study

In the sector of construction equipment the importance of LCA and eco-efficiency analysis is very high. Similar to passenger cars sector, where the political and technical requirements are already very high, the sector of construction equipment is currently in change. The scarcity of fossil resources and raw materials, as well as the rising energy costs in the last years have brought industry to a massive rethinking. The reduction of energy consumption and the successive use of renewable energy are one of the most important innovation topics in this industry branch. In order to fulfill the high energy requirements in the near future, extensive concepts, new structures and innovative technical approaches for increasing the total energy efficiency of the machines are needed. Looking at the lifecycle of a wheeled excavator for example, LCA helps to identify environmental key factors and cost drivers within the use phase where CO_2 emissions (resulting from fuel consumption) are still very high [20]. Furthermore the approach helps to estimate lifecycle based efficiency for future concepts of the excavator. For this purpose, an overall numerical full simulation model of the machine is designed. The developed simulation tool is used to calculate the energy consumption of the machine with respect to specific user profiles. Based on this, it will become possible to analyze and optimize the current wheeled excavator focusing on new and innovative mechanical, hydraulic and electric/electronic components and systems (see Figure 5). Product Lifecycle Management guides the whole analysis and optimization process.

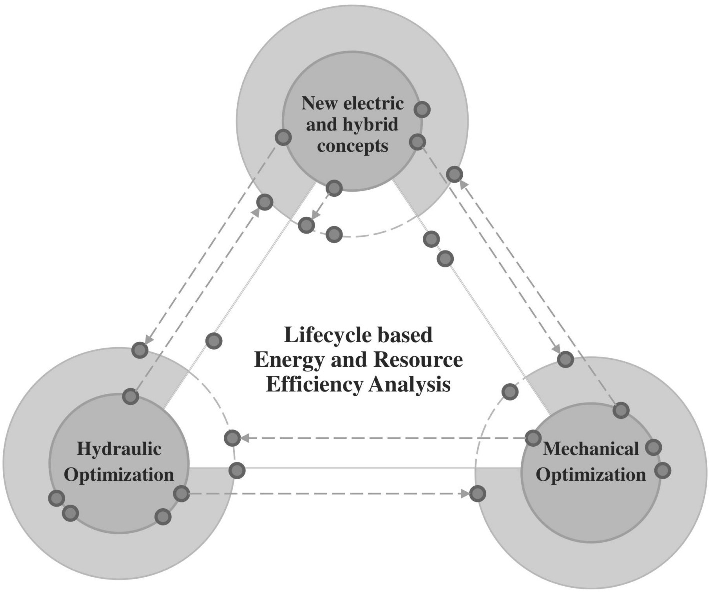

Fig. 5. Interdisciplinary Optimization supported by Lifecycle based Eco-Efficiency Analysis

Aim of the analysis made with the PLM solution is to measure multiple dimensions of the product performance in two of the three sustainability areas – ecological and economical (see Figure 6). The modules share common, scalable infrastructure and support multiple methods for supplier data acquisition. Bi-directional integrations with multiple enterprise systems such as authoring systems and PDM is also supported [21], it is however not functioning to the desired extend.

Product Analytics: The Product Analytics module uses streamlined Life Cycle Assessment approach for qualifying the environmental impact over the life of a product. This means that relies primarily on secondary (existing) life cycle impact data and, but not necessarily, third party data such as the "ecoinvent" eco-balance data base, to produce quick, relatively robust information. It has the capabilities to model and analyze embodied environmental impacts throughout the lifecycle utilizing supplier material disclosures for that, it can identify highest impact areas among products, parts, material and suppliers. It provides relevant eco-efficiency data in report dashboards, which are of help for design engineers in the evaluation of improvement opportunities.

Environmental Compliance: The Environmental Compliance module is used to analyze and report compliance of company products to multiple standardized regulations and requirements such as RoHS, JIG, REACH using supplier material declarations as data source. It helps to measure and manage compliance risk early in the product development phase.

Lifecycle Costing: The Cost Module enables users to easily estimate and display cost information for company or supplier parts or products based on different estimation models and maintain them as dynamical database. It supports cost breakdowns and cost confidence levels and gives an overview of the cost history of a part or product.

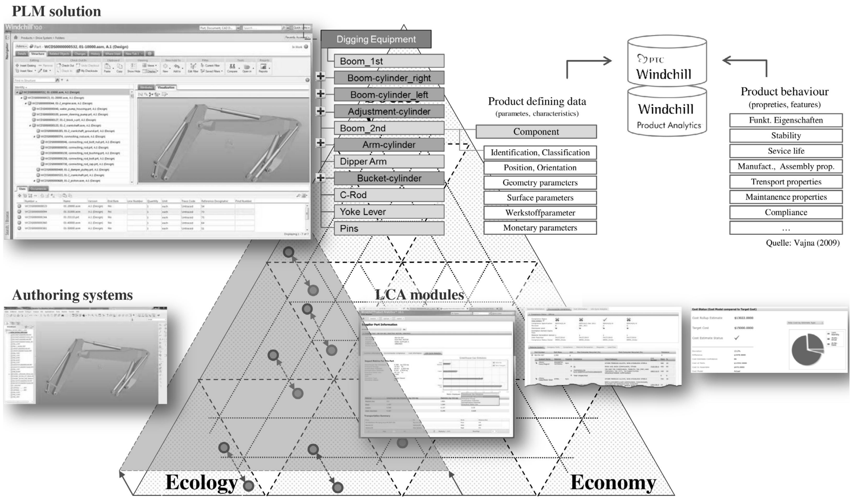

Fig. 6. Boom of a wheeled excavator – Extended Product Structure in a PLM solution

5 Conclusion

Product Lifecycle Management, as the overall engineering concept is based on the idea of connecting knowledge and seeks to provide the right information at the right time in the right context and extent. It offers a solution to systematization of the various operational tasks in design and production so that processes are rationalized and optimized for a Smart Product Engineering. Internationally standardized tools for the assessment of environmental-economical sustainability of a product do already exist – Life Cycle Assessment and eco-efficiency analysis. They are powerful tools for environmental management whose use, together with the incorporation of lifecycle thinking in the company policy, is a necessary requirement for successful lifecycle engineering. With the increasing importance of Design for Environment, due to the scarcity of resources and stricter requirements on the products, a close collaboration between design and environmental engineers is needed. Therefore it makes complete sense LCA tools to be fully integrated in the PLM solution, which means that relevant product data should be shared across all modules of the PLM and authoring systems infrastructure and limitation should come only from user related permission restrictions. With the current tools for Life Cycle Assessment very complex products with huge variety of different material and complex value chain can be assessed with a reasonable work demand providing satisfactory results and presenting them in neat dashboards. However an improvement potential can be seen in the area of data sharing between modules of the PLM and authoring systems in order to achieve the state, in which no work for entering data defining a particular product or part property needs to be repeated at different nodes of the infrastructure.

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Exploring Opportunities to Improve Life Cycle Environmental Performance of a Complex Product

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Abstract. Life cycle assessment (LCA) is an essential tool for achieving design for life cycle. An LCA examines all stages of a product's life cycle and gives a quantitative assessment of its potential environmental impact. The results of the LCA help identify priority areas for improvement and ways to reduce environmental impacts. This paper presents a comprehensive LCA approach to quantitative assessment of environmental impact for industrial off-road equipment. This paper describes how LCA can be applied to off-road equipment and how it can be used to improve the environmental performance of a product. Six potential opportunities for reducing the environmental impact of off-road equipment are explored, and sensitivity analyses are presented as a tool for evaluating the effectiveness of those solutions. The LCA approach is demonstrated with the example of a construction machine.

Keywords: Product life cycle, life cycle assessment (LCA), design for life cycle, design for environment.

1 Introduction

Life cycle stages of a product – design, manufacturing, usage, and end-of-life treatment – are closely linked from the environmental perspective. The link is particularly important when the environmental impact from the usage phase is dominant, which is shown in products such as automotive vehicles and heavy-duty off-road equipment. This type of products – products with major environmental impact during usage phase – must be designed carefully so that the entire life cycle of a product should be more sustainable with less adverse environmental impact.

Life cycle assessment (LCA) is an essential tool for achieving design for life cycle. LCA evaluates the potential environmental impact associated with a product, considering its entire life cycle. An effective LCA can demonstrate how much environmental impact is caused by a product and how different life cycle phases and/or product subsystems contribute to the total impact. With such LCA, a company can identify priority areas for improvement and become proactive in its sustainability initiatives.

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This paper presents a comprehensive LCA study of industrial off-road equipment. Off-road equipment is a complex product characterized by a large number of constituent parts and high fuel consumption throughout the long life cycle. Although LCA has gained popularity in various industries, only few studies have examined off-road equipment due to the complexity of the product. This paper describes how LCA can be applied to such a complex machine and how it can help improve the environmental performance of the product. More specifically, six potential opportunities for reducing the environmental impacts are discussed; four of the opportunities relate to product design (i.e., reduced fuel consumption rate, reduced emission rate, improved durability, and improved productivity) while the other two relate to usage behavior (i.e., reduced idling during operation and increased use of biodiesel). Sensitivity analyses are used to evaluate the effectiveness of those solutions, and the results highlight opportunities with the greatest potential for reducing the environmental impact.

The remainder of the paper is organized as follows. Section 2 describes the modeling for an LCA of off-road equipment. Section 3 presents an illustrative LCA study with the example of a construction machine. Section 4 explores the potential opportunities for reducing the environmental impacts of off-road equipment. Section 5 provides a summary of the study and concludes the paper.

2 Life Cycle Assessment of Off-Road Equipment

2.1 Goal and Scope Definition

This section describes how an LCA can be applied to an off-road machine. An LCA considers the entire life cycle of a machine, which consists of three phases: manufacturing, usage, and end-of-life treatment. The manufacturing phase includes the extraction of raw materials and the production of the entire machine. The usage phase encompasses the operation and maintenance of the machine, and fuel consumption and emissions from machine operation and the replacement of spare parts, filters, oils, and fluids are all taken into account. The end-of-life phase involves recycling and disposal activities. It incorporates processing of the used machine and all the waste from the maintenance (i.e., used spare parts and refills).

Equation (1) computes the total life-cycle impact of a machine, where I^{total}, I^{mfg}, I^{usage}, and I^{eol} denote the impacts of manufacturing, usage, and end-of-life treatment, respectively. In the remainder of the section, it is discussed how to assess the impact of each life cycle stage.

$$I^{total} = I^{mfg} + I^{usage} + I^{eol} \tag{1}$$

2.2 Modeling the Life Cycle of a Machine

Manufacturing. The impact of manufacturing is determined by the design of a machine. More precisely, it is defined by the material composition and manufacturing processes of the machine. Transportation is also included. In general, three types of transportation occur during the machine manufacturing: (1) the transportation of raw materials to parts manufacturers, (2) the transportation between part manufacturers and the assembly factory, and (3) the delivery of the finished machine to the customer (or dealership). The mass, travel distance, and transportation mode (by truck, train, and/or oceanic freight shipping) determine the impact of transportation.

$$I^{mfg} = \sum_{i \in I} e_i^{matl} \cdot x_i + \sum_{p \in P} e_p^{mproc} \cdot x_p + \sum_{q \in Q} e_q^{tproc} \cdot x_q \tag{2}$$

Equation (2) computes the impact of manufacturing, where e_i^{matl}, e_p^{mproc}, and e_q^{tproc} denote the per-unit impacts of material $i\,(i \in I)$, manufacturing process $p\,(p \in P)$, and transportation mode $q\,(q \in Q)$, respectively; x_i, x_p, and x_q denote the total number of units of material i, manufacturing process p, and transportation mode q, respectively, that are used for the manufacturing of the machine.

Usage. The impact of usage is originated from two sources, i.e., machine operation and maintenance. The impact of machine operation can be further divided into the impact of diesel fuel consumption and the impact of emissions. The former includes the impact from extracting, producing, and delivering fuel. The latter focuses on the emissions from diesel fuel combustion. The impact of usage is affected by machine lifetime (i.e., the total number of hours the machine is used over its life cycle), and how the machine is utilized over the lifetime.

Impact of Fuel Consumption. Equation (3) formulates the environmental impact of fuel consumption, where e^{fuel}, FR, and TH denote the per-unit impact of diesel fuel, the average fuel consumption rate (in kg/hr), and the machine lifetime, respectively.

$$I^{fuel} = e^{fuel} \cdot FR \cdot TH \tag{3}$$

$$FR = EP \cdot \left(\alpha \cdot y_{idle} \cdot BSFC(y_{idle}) + (1-\alpha) \cdot y_{nonidle} \cdot BSFC(y_{nonidle})\right) \tag{4}$$

Assuming that the machine operates in two modes, i.e., idle and nonidle operations, the average fuel consumption rate FR is given by Equation (4), where α denotes the ratio of idle operation over the machine's lifetime, and y_{idle} and $y_{nonidle}$ denote the engine load factors. For an operation, the fuel consumption rate is determined by three factors: the rated power of the engine (i.e., EP in kW), the engine load factor for the specific operation (i.e., y_{idle} or $y_{nonidle}$), and the engine's brake-specific fuel consumption rate at the given engine load factor (i.e., $BSFC(y)$ in kg/kWh). The rated power EP refers to the maximum power (in kW) that an engine is capable of producing at its rated speed. Machines typically operate at a variety of speeds and workloads, depending on the severity of the application and the operator's skill. It is rare for a machine to operate at full load using the engine's rated power. To take into account partial load operations, Equation (4) uses the concept of engine load factor y, which indicates the fraction of the rated power used [1]. The brake-specific fuel consumption rate is an engine-specific characteristic that indicates the engine's fuel efficiency. It represents the amount of diesel fuel needed to produce a kilowatt hour of energy. Since it varies at different engine load factors, it is represented as a function of engine load factor.

Impact of Emissions. Equation (5) formulates the impact of emissions, where $e_j^{emission}$ and ER_j denote the per-kilogram environmental impact and the average emission rate (in kg/hr) of emission j, respectively. In this study, six types of emissions are considered, i.e., carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrocarbons (HC), nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM).

$$I^{emission} = \sum_{j \in J} \left(e_j^{emission} \cdot ER_j \cdot TH \right) \tag{5}$$

$$ER_j = EP \cdot (\alpha \cdot y_{idle} \cdot EF_j(y_{idle}) + (1-\alpha) \cdot y_{nonidle} \cdot EF_j(y_{nonidle})) \tag{6}$$

The emission rate ER_j is given by Equation (6). Similar to the fuel consumption rate in Equation (4), the emission rate of an operation is determined by three factors: the engine's rated power, the engine load factor, and the emission factors of the engine for a specific engine load factor (i.e., $EF(y)$). The emission factors (in kg/kWh) represent the amounts of emissions that are emitted per unit of energy produced. They are determined by the engine and after-treatment performance.

The emission factors for HC, NO_x, CO, and PM can be obtained from machine emission testing. For CO_2 and SO_2, the emission factors are calculated based on the brake-specific fuel consumption rate, as shown in Equations (7) and (8) [2, 3]:

$$EF_{CO_2}(y) = (BSFC(y) - \mathrm{HC}) \times 0.87 \times (44/12) \tag{7}$$

$$EF_{SO_2}(y) = (BSFC(y) \times (1 - soxcnv) - \mathrm{HC}) \times 0.01 \times soxdsl \times 2 \tag{8}$$

where HC is the hydrocarbon emission factor (in kg/kWh), 0.87 is the average carbon fraction of the diesel fuel, 44/12 is the ratio of CO_2 mass to carbon mass, *soxcnv* is the fraction of fuel sulfur converted to direct PM (assumed to be 0.3 in this study), 0.01 is the conversion factor from weight percent to weight fraction, *soxdsl* is the weight percent of sulfur in the diesel fuel (assumed to be 0.0015 in this study), and the number 2 is the grams of SO_2 formed from a gram of sulfur.

Impact of Maintenance. Maintenance activities, including parts replacements and oil and filter changes, are another factor that affects the environmental impact of the machine usage. To capture the impact of maintenance, one should know the number of replacements during the life cycle and the impact of each replacement.

$$I^{maint} = \sum_{k \in K} \mu_k \cdot RN_k \cdot e_k^{maint} = \sum_{k \in K} \mu_k \cdot \left\lceil \frac{\max(0, TH - \lambda_k)}{\lambda_k} \right\rceil \cdot e_k^{maint} \tag{9}$$

Equation (9) computes the impact of maintenance, where μ_k denotes the number of units of part k in the machine, RN_{ik} denotes the number of replacements of part k over the machine lifetime TH, e_k^{maint} denotes the per-unit impact of a replacement part k (i.e., the impact of producing, transporting, and replacing a part k), and λ_k denotes the replacement cycle of part k in hours. In Equation (9), the first replacement cycle is subtracted from *TH*, since the first part is included in a new machine at the manufacturing stage and does not constitute a replacement.

End-of-Life Treatment. The impact of end-of-life treatment (i.e., recycling, landfill, and/or incineration) includes both the impacts of processing the end-of-life machine and processing all replacement parts and fluids consumed over the machine lifetime. The impact is modeled as Equation (10), where e_{prod}^{eol} and e_k^{eol} denote the per-unit impacts of end-of-life treatment for a machine and for part *k*, respectively. The per-unit impact includes the impact of transporting the end-of-life unit to the treatment facility.

$$I^{eol} = e_{prod}^{eol} + \sum_{k \in K} \mu_k \cdot \left\lceil \frac{\max(0, TH - \lambda_k)}{\lambda_k} \right\rceil \cdot e_k^{eol} \tag{10}$$

3 Case Illustration: LCA of a Construction Machine

This section presents an illustrative LCA study of a typical piece of off-road equipment (Fig. 1). The machine is typically used in construction settings to lift and move heavy material around a worksite. In this study, the machine lifetime is assumed to be 20,000 hours of operation including 30% idle operation. The load factors during the idle and nonidle operations were assumed to be 0.1 and 0.5, respectively.

Fig. 1. Target machine (picture courtesy of Deere.com)

For the impact assessment, this study used the LCA software *SimaPro* (version 7.3). Most of the life cycle inventory data were taken from the Ecoinvent database. Among various impact-assessment methods, *Eco-Indicator 99* (*H/A*) was used [4].

3.1 Data Collection and Model Construction

Manufacturing. To examine the weight and material composition of the target machine, this study analyzed the bill-of-materials obtained from the manufacturer. The total weight of the target machine is approximately 18,000 kg. Table 1 shows the material composition of the target machine collectively by material type.

Table 1. Assumptions on material composition of the target machine

Material type	Weight percent (%)
Steel	71.49
Cast iron	17.59
Rubber & Plastics	7.37
Aluminum	1.12
Lubricating oil	0.89
Glass	0.89
Others	0.65

In this study, manufacturing processes were taken into account as follows. When process data was not directly available from the manufacturer, "General Manufacturing" data from the Ecoinvent database was used. For manufacturing of metal parts that accompanies scrap, a scrap rate was defined as 0.227 kg per kilogram of finished part. The welding rate was defined to be 0.146 m of welding per kilogram of steel in the machine. Finally, it should be noted that transportation for parts manufacturing was not included in this analysis due to lack of data.

Usage. Equation (11) shows the brake-specific fuel consumption rate assumed for the target machine; based on engine testing data, it was modeled as an exponentially-decreasing function of engine load factor. Using the equation, the average fuel consumption rate was calculated as 18.52 kg/hr. Table 2 shows the emission rates assumed for the target machine. Note that all rates are represented in grams per hour.

Table 3 summarizes the amount of various parts, fluids, and filters that were assumed to be consumed throughout the machine lifetime. The maintenance activities were assumed based on the maintenance schedule recommended by the manufacturer.

$$BSFC(y) = \left(850.9757 \cdot \exp(-y / 0.1692) + 215.6509\right) / 1000 \tag{11}$$

Table 2. Assumptions on emission rates (g/hr)

Rate	Idle	Nonidle	Total operation
Carbon dioxide (CO_2)	36372.28	68824.29	59088.69
Sulfur dioxide (SO_2)	0.24	0.45	0.39
Hydrocarbon (HC)	0.42	2.08	1.58
Nitrogen oxides (NO_x)	28.55	142.76	108.50
Carbon monoxide (CO)	1.83	9.13	6.94
Particulates (PM)	0.13	0.66	0.50

Table 3. Assumptions on maintenance

Maintenance type	Total amount
Filters	311 Filters
Fluid (coolant and oils)	2282.9 Liters
Replacement parts	12 Tires / 34 Parts

End-of-Life Treatment. The machine and all replacement parts and refills follow the same end-of-life scenario. It was assumed that 90% of steel and iron is recycled while the rest 10% is discarded by landfill. The other materials are assumed to be discarded either by landfill (80%) or incineration (20%). For end-of-life processing, the "cut-off approach" was used for allocation. In other words, the environmental impacts or benefits from recycling were not allocated to the current life cycle [5, 6].

3.2 Life Cycle Assessment Results

Assuming the baseline usage scenario (i.e., 30% idle operation; 0.1 and 0.5 engine load factors for idle and nonidle operations, respectively; 20,000 hours of machine lifetime), Figure 2 and Table 4 provide Eco-indicator 99 scores associated with the target machine's life cycle. The total environmental impact results in 120,600 points. The manufacturing phase accounts for approximately 8%, usage approximately 91%, and end-of-life phase accounts for less than 1% of the total impact. Table 4 gives more detailed results clustered by impact category. Among 11 impact categories, fossil fuels, respiratory inorganics, and climate change are three main impact categories; they together cause over 93% of the total environmental impact.

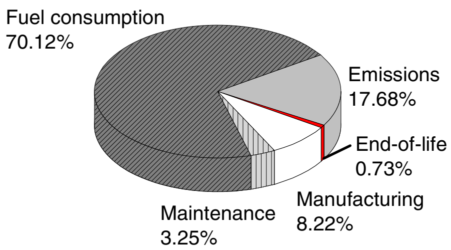

Fig. 2. LCA results (Method: Eco-indicator 99 H/A)

Table 4. LCA results: Eco-indicator 99 scores (Method: Eco-indicator 99 H/A)

Impact category	Manufacturing	Usage	End-of-life	Total
Carcinogens	1655.92	1399.34	223.55	3278.80
Respiratory organics	2.99	35.24	0.39	38.63
Respiratory inorganics	3727.53	19188.88	219.05	23135.47
Climate change	704.41	13405.98	89.63	14200.02
Radiation	18.55	32.03	0.43	51.01
Ozone layer	0.30	8.53	0.03	8.86
Eco-toxicity	735.28	458.61	89.49	1283.38
Acidification	89.76	1282.94	14.85	1387.55
Land use	84.14	993.12	5.22	1082.48
Minerals	658.13	155.19	2.20	815.52
Fossil fuels	2233.91	72842.64	235.43	75311.98
Total score (Pt)	9910.93	109802.50	880.27	120593.70

4 Exploring Opportunities for Reducing Environmental Impact

4.1 Potential Opportunities

This section explores potential opportunities for reducing the environmental impacts of the target machine. Assume that there are six potential solutions for reducing the environmental impact of the target machine. Four of the solutions relate to product design, i.e., reduced fuel consumption rate, reduced emission rates, improved durability, and improved productivity. The other two solutions relate to usage behavior, i.e., reduced idling during operation and increased use of biodiesel. Different solutions have different environmental implications, as indicated below:

- *Reduced fuel consumption rate*: A machine that has improved energy efficiency requires less fuel to finish the same amount of work. The decrease in fuel consumption can contribute to reducing the impact of usage, more precisely, the impact of machine operation.
- *Reduced emission rates*: A machine that has lower emission factors produces less gaseous emissions during operation, thereby lowering the impact of usage.
- *Improved durability*: A more durable machine requires less frequent maintenance, thereby lowering the environmental impact of maintenance. Reduced maintenance also provides an additional benefit in the end-of-life stage, i.e., since less parts are consumed over the machine's lifetime, less waste is generated, which, in turn, reduces the impact of end-of-life treatment.
- *Improved machine productivity*: A machine with better productivity can accomplish more amount of production in the same period of time. Accordingly, the total impact remains the same, but the impact per unit amount of production (e.g., impact per ton of material) decreases as the machine's productivity increases.
- *Reduced idling*: Reduced idling indicates that more time is spent on non-idling operation during an hour. Since non-idling operation consumes more fuel and generates more emissions than idling operation, the total impact per hour may increase as the idle-time ratio increases. However, an increased amount of production can offset the downside, when the impact per unit of production is considered.
- *Use of biodiesel*: Using biodiesel, such as B20 (20% biodiesel), is a potential solution for reducing the impact of machine usage. Biodiesel is known to have both pros and cons. With biological recycling of carbon, biodiesel can reduce the emission of CO_2, which is a major greenhouse gas. Biodiesel also reduces the emission of SO_2; no SO_2 is emitted from biodiesel. However, Biodiesel may require more energy and resources for fuel production. In addition, its energy content is less than that of conventional diesel, so, as the percent of biodiesel increases, more fuel is required to accomplish the same amount of work. To assess the effect of biodiesel, fuel consumption and emission rates were assumed based on Ref. [7, 8]. Taking into account differences in energy and carbon contents and fuel density, the average fuel consumption rate of biodiesel was assumed to be 112.5% of the conventional diesel fuel's average rate. Table 5 shows how the emission rates of HC, NO_x, CO, and PM would change as biodiesel is blended with conventional diesel fuel.

Table 5. Percent change in emission rates (%) (calculated based on Ref. [7, 8])

	B5	B10	B20	B100
HC	-5.44	-10.59	-20.06	-67.36
NO_x	0.49	0.98	1.98	10.29
CO	-3.23	-6.35	-12.30	-48.11
PM	-3.14	-6.18	-11.99	-47.19

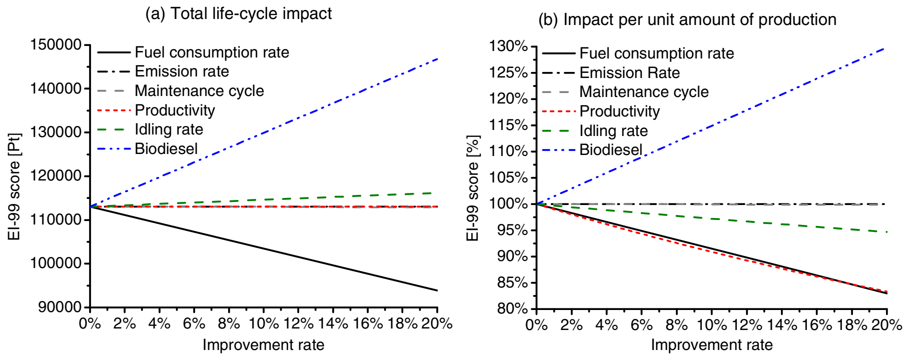

Fig. 3. Improvement analysis

4.2 Sensitivity Analysis

LCA can help assess the effect of each solution quantitatively and provides a means for prioritizing the solutions. In this study, a sensitivity analysis was conducted for each of the six solutions by varying the improvement rate from 0% to 20%. For example, the lifecycle impact of the target machine was calculated when the fuel consumption rates were assumed to be reduced by 0% to 20%. The total impact for zero percent improvement is the same as shown in Section 3.2. For biodiesel, a 20% improvement rate indicates that biodiesel B20 was used.

Figure 3 illustrates the results of the sensitivity analyses. When the total impact is considered, reducing the rate of fuel consumption is shown as the most effective solution. If the impact per unit amount of production is considered, improving the machine's productivity is identified as the most effective solution. Using biodiesel shows an interesting result; the increasing trend of the EI-99 score implies that using biodiesel may not be environmentally sustainable, even though it can reduce a significant amount of greenhouse gas emissions.

5 Conclusion

This paper presented an LCA study for a typical piece of off-road equipment. Due to the maintenance and machine operation, the usage phase accounts for most of the total environmental impact, over 90%. Specifically, 70% of the total environmental impact comes from fuel consumption at the usage stage. This implies that improving the usage stage should have a higher priority than any other consideration when attempting to improve the environmental performance of off-road equipment.

LCA can help improve the environmental performance of the product. In this study, LCAs helped examine six potential opportunities for reducing the environmental impacts (i.e., reduced fuel consumption rate, reduced emission rate, improved durability, improved productivity, reduced idling during operation, and increased use of biodiesel); sensitivity analyses were conducted to evaluate the effectiveness of those solutions from the environmental perspective. The results highlight reducing fuel consumption rate and improving machine productivity as the two opportunities with the greatest potential for reducing the environmental impact.

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Cost-Effects of Product Modularity – An Approach to Describe Manufacturing Costs as a Function of Modularity

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Abstract. In recent years modularization has been used to solve the trade-off between the diversity of variety and the effort to optimize product complexity or product standardization. In the context of the implementation of an optimal product strategy and the conduction or extension of a modularization concept, it is required to evaluate the costs to support engineering decisions. The outcome of this paper is an approach to support modularization decisions of an engineer. With it, a structured procedure is introduced to identify factors which influence the costs and which depend on the product modularity.

Keywords: modularity, modularization, cost, development cost, product.

1 Introduction

Modularization of products is a generally accepted method for reducing the total expenditure of a company (e. g. [1], [2], [3], [4]). Although the financial success of a company is affected by product modularity [5], a higher modularity is not necessarily more cost-effective than a lower modularity [6].

In the context of product development, two pieces of information are needed to achieve a cost-optimum product modularity. On the one hand, a method is required to analyze and quantify product modularity. On the other hand, it is necessary to know about the relation between modularity and product costs. This relation depends on many, partly company-specific factors (cf. [5]). Hence, the knowledge of these factors and the quantitative specification is crucial to determine modularity concerning its cost-optimum [6].

In general, the economies of a higher modularity are mainly caused by economies of scale and scope (cf. [7], [8]). On closer inspection, it becomes apparent, that this simplified view is insufficient. For example, a division of one part into two identical parts could double the number of parts, this separation causes additional assembly and test steps. The cost reduction of the single part by an increasing lot size is accompanied by additional assembly and test costs. So it is possible, that the overall costs increase due to modularization. Hence, the relation of product modularity and product costs should be analyzed more detailed to identify the cost-optimum. As the direct

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relation between cost and modularity is not concretely describable yet, an approach is presented in this paper.

Before the approach is presented in section 3, in section 2 the general relation of cost and modularity is introduced. Afterwards in sections 4 and 5 several qualitative relations are displayed based on a literature research. Here, this paper focuses on the relation of modularity and manufacturing costs.

2 State of Art

2.1 Terms and Definitions

The terms modul, modularization and modularity are well known in industry and science [4]. Despite of that, those terms are not exactly defined in literature [9], so that there can be found different interpretations [4, 10].

VDI-guideline 2221 demands structuring the general solution into modules. Here, the term modul describes, in contrast to the function structure of a product, the classification of the solution in real sub-systems, system elements and their interfaces. [11]

This article therefore defines the term *modul* corresponding to Baumgart [12] as a functionally and physically describable entity, which is almost independent from other product modules. The transformational structure between the functional structure of a product and its physical building structure is called, according to Pahl [1], *product architecture*. The gradual character of product architecture in terms of advantageous structuring and thereby a possible description of product architecture is according to Pahl *modularity* [1].

A product is called ideal-modular at the point of its highest modularity. That means (among other things) that it is possible to assign function and components on a one-to-one basis. If a product is ideal-integral, then all functions are met by one component. [13]

Modularization aims at product structuring by increasing product modularity. So, existing product architecture is optimized in regard to product requirements or to achieve economy of scale in products' formation phases. (acc. to [1] and [12])

According to Gershenson [10] there are no existing standardized measurement methods for quantifying product modularity. Literature presents different methods; see for example approaches of Ericsson et al. [4], Sosa et al. [14], Stryker [15] or Hohnen et al. [13]. With the help of these methods, different aspects of product architecture are rated. It is for example possible to quantify dependency and cross-linking of functions and corresponding construction components with just one operating figure called functional modularity index (FMI) (cf. [13]).

2.2 Cost Functions of Product Modularity

A study shows that the financial success of a company depends on product modularity [5]. However, the effects of modularity like increasing complexity or costs influence are still unknown, [16], [17]. A general description of the relation of product modularity and product costs could neither be identified in a detailed literature research. Hence, there is no system to support an engineer in optimizing modularity regarding costs.

Literature just gives relative statements about how a higher product modularity can influence product costs. Within these literature, the possible economical savings of a higher modularity are on the one hand justified by the achievable scale effects and learning curve effects as a result of reuse (e. g. [7], [8] or [18]). On the other hand, literature also refers to increased costs due to a higher modularity, which can arise for example by specification and design of modules and their interfaces (e. g. [7], [19]). A qualitative figure of a modularity function could be abstracted from these statements, cf. Fig. 1.

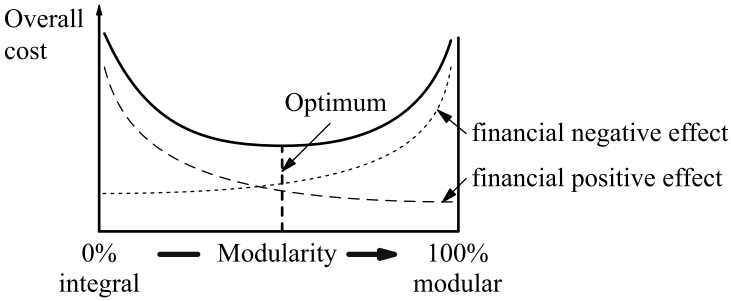

Fig. 1. Qualitative modularity influence on overall costs (cf.[6])

The knowledge of the financial negative and positive effects are necessary in order identifying the cost optimum regarding modularity.

It is assumed that the curve progression is highly effected by company specific factors like the product itself, manufacturing resources or overhead costs. Consequently, it is crucial to identify and consider these specific factors by developing a method to describe the functional relationship of costs and modularity.

3 Introduction of Approach

The superior objective of modularization is cost optimization. A determination of the absolute product costs is therefore not necessary in the context of modularity. Hence, product costs which are independent of product modularity are neglected in this approach.

The main aspect of this approach is to determine the relationship of modularity and cost indirectly. Several factors are rather analyzed to determine modularity costs. In the following these factors will be called properties. In this approach it is required that on the one hand the properties' values depend on modularity. On the other hand the properties' values influence the product costs. Fig. 2 shows the basic steps of this approach.

As mentioned before, the properties must be identified in the first step. Afterwards the cost function $f_{cost}(property_i)$ and modularity function $f_{modularity}(property_i)$ of each property must be determined in steps two and three. Here the interactions of the properties are neglected. A change of the properties' value influences different divisions like development or manufacturing. Because of that, a separate consideration of these divisions is suggested. Combining the functions (2) and (3) using nomograms, the direct relation of costs and modularity is derived in step 4. Last the modularity costs of each property can be accumulated.

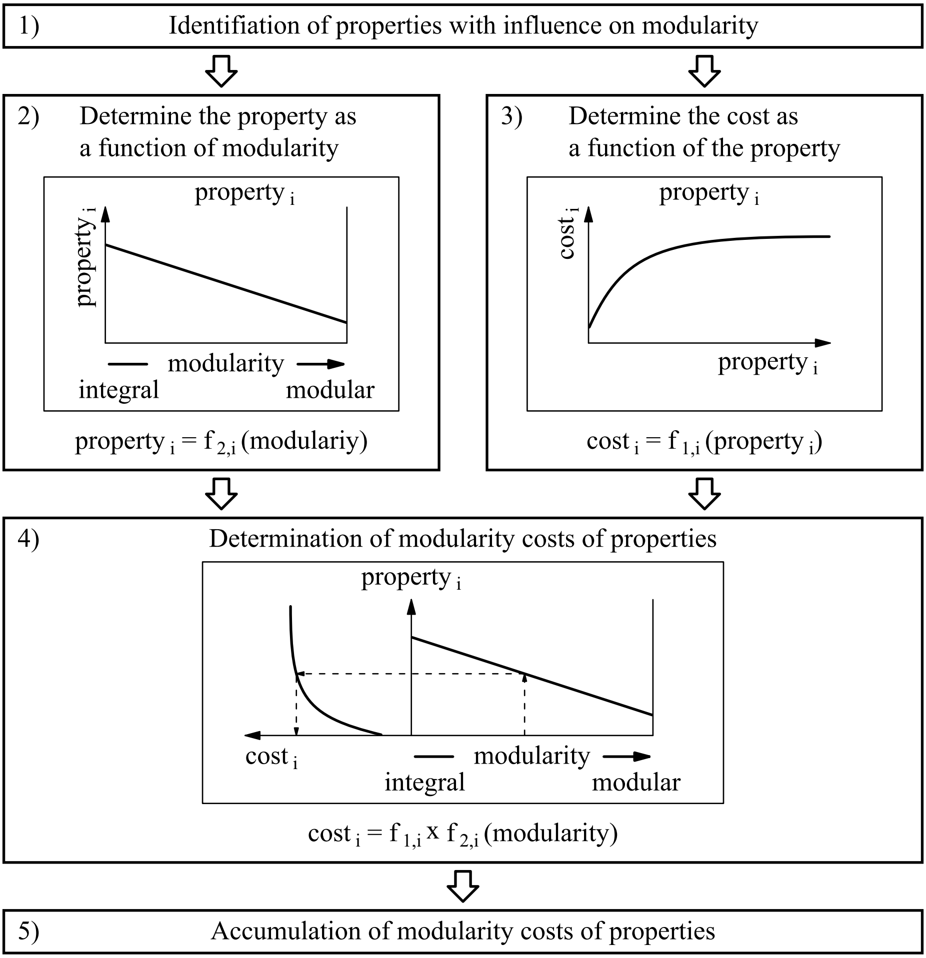

Fig. 2. Basic method to determine the modularity costs

4 Description of Manufacturing Costs as a Function of Modularity

In this chapter the introduced approach is implemented using literature data. Additionally, hypotheses were added to expand this showcase.

4.1 Identification of Properties with Influence on Modularity (Step 1) and Determination of Properties as a Function of Modularity (Step 2)

As outlined above, properties which depend on modularity and influence the products costs are identified. Following properties were identified based on an in-depth literature research and interviews with experts. Following properties show a context to the costs of manufacturing.

Number of Units of a Component

The number of units of an existing component is generally independent of a changing modularity. But additional modules can be defined by an increasing modularity. This functional and physical separation will increase the chance of reuse of these new modules in other products or orders. At the best, the batch size of these components will rise, too. In literature the relation of modularity and the number of units has not been analyzed in detail yet. So the authors assume a linear progression between modularity and the number of units, cf. Fig. 3.1. Based on the same reason, all other progressions are assumed as linear, too.

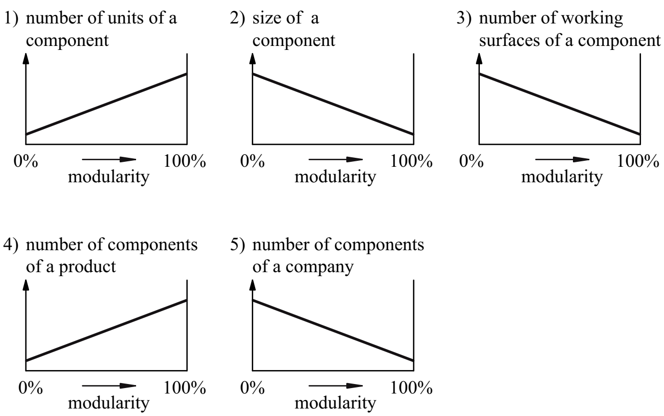

Fig. 3. Number of units of a component as a function of modularity

Size of a Component

The size of a component basically depends on the function, which has to be fulfilled, and the material. The more functions should be met by a component, the higher the requirements to the material are. This usually means, that more material is needed. If you follow the above mentioned definition (cf. section 2), then the modularity of a component is getting lower, the more functions it should meet. This leads to the conclusion that with an increasing modularity, the size of a component decreases, cf. Fig. 3.2.

Number of Working Surfaces of a Component

Each component has got several surfaces. Some of these surfaces are so called working surfaces, which are needed to execute a function. The more functions a component fulfills, the more working surfaces are needed. As defined, an ideal modul executes a single function, cf. [13]. The higher the modularity, the less the number of working surfaces of a component is, cf. Fig. 3.3.

Number of Components of a Product

It is assumed that the number of functions, which have to be fulfilled by a product, is independent from modularity. The above mentioned definition shows that with a rising modularity more modules are necessary to break up the relation of functions and components. So, the number of a product's components rises theoretically with an increasing modularity, cf. Fig. 3.4. This fact could be proved by comparison of similar products with a different modularity. For example the number of components of a modular desktop phone is higher than an integral cell phone (cf. [20]). Obviously this comparison is simplified, because different requirements cause a different number of product functions. Based on the mentioned definition, the modularity of these products is different.

Number of Components of a Company

While the number of a product's components rises according to an increasing modularity, the possibility to reuse the newly defined modules (see property ‘number of units of a component’) rises as well. As a consequence the number of a company’s components decreases because it is no longer necessary to develop specific modules for each of the company’s products, cf. Fig. 3.5.

4.2 Determination of Costs as a Function of Properties (Step 3)

This paper focuses on the identification of the manufacturing costs as a function of modularity. So, in this chapter the identified cost-functions are described. Based on a detailed literature research Fig. 4 illustrates all identified relations between costs and properties. To expand this approach, several hypothesis were added.

Number of Units of a Component

Three financial influences could be identified, which dependent on the number of units of a component. The higher the number of units, the smaller the influence of setup costs is [21]. From this, a declining progression of the cost can be deducted, cf. Fig. 4.1. Furthermore, DIN ISO 2859-1 [22] suggests that the number of parts, which should be tested, show decrease declining, if the lot size increases. As the testing time is proportioanl to the number of units to be tested, testing costs will decrease declining, too, cf. Fig. 4.2. Moreover, an influence of manufacturing technologies to unit costs could be identified. With a growing lot size, alternative manufacturing technologies (e. g. welding, casting) might be cheaper and this could create cost progression like shown in Fig. 4.3 [21], [23].

Size of a Component

The size of components influences, among others, the manufacturing time. With an increasing size, manufacturing costs rise on a progressive scale [24], cf. Fig. 4.4. Additionally, it is assumed, that with an increasing size of components bigger and more expensive manufacturing machines are needed. Each machine can cover a certain range and this results in escalating costs, cf. Fig. 4.5.

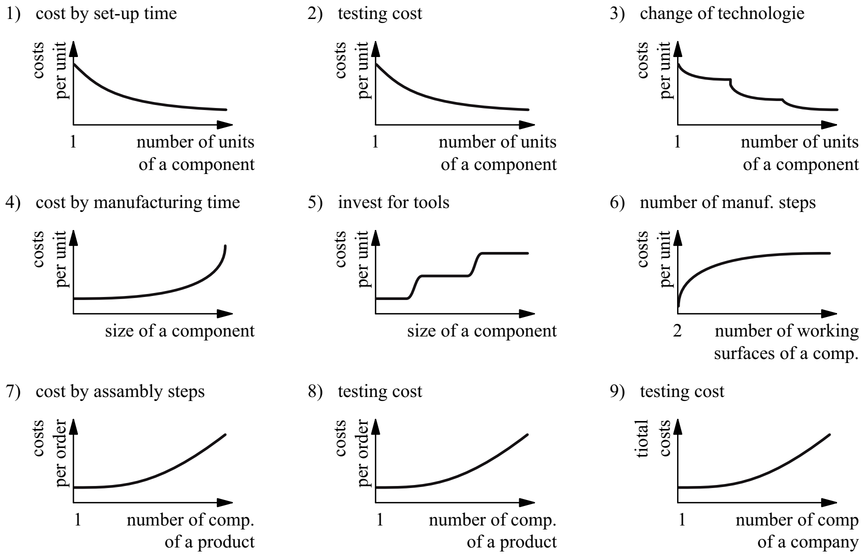

Fig. 4. Cost functions influencing manufacturing

Number of Working Surfaces of a Company

Working surfaces usually have higher tolerance requirements than non-working surfaces. Because of that, it is assumed that with an increasing number of working surfaces the number of manufacturing steps for components also increase. So it can be deducted, that costs also increase. A declining process is assumed because, although complexity rises, efforts of additional manufacturing steps presumably decrease, cf. Fig. 4.6.

Number of Components of a Product

Additional assembly steps are necessary when more components are part of a product. According to Miese [25] the assembly costs increase progressively with rising number of components of a product, cf. Fig. 4.7. Furthermore additional components and additional assembly steps require additional tests. As the number of components and assembly steps increase progressive, the number of tests and so the costs increase progressively, too (cf. Fig. 4.8.)

Number of Components of a Company

As the number of components of a product, the number of components of a company has got the same influence on costs, cf. Fig. 4.9.

4.3 Determination of Modularity Costs of Properties

After introducing the dependence of properties and modularity, and costs and properties, in this chapter the relation of costs and modularity of each property will be identified using nomograms, a graphical calculating device.

Fig. 5 illustrates all identified relations with a positive financial impact of an increasing modularity.

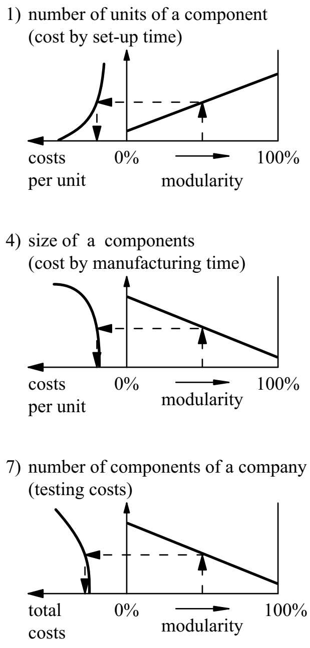

Fig. 5. Properties with positive financial impact on modularity

Following relations could be identified with a negative financial impact of an increasing modularity, see Fig. 6.

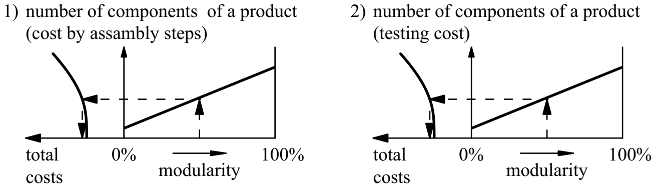

Fig. 6. Properties with negative financial impact on modularity costs

5 Summary and Further Steps

The engineer requires the knowledge about company specific cost factors to determine a cost-optimum product modularity. Therefore, the outcome of this paper is an approach to support modularization decisions of an engineer. With it, a structured procedure is introduced to identify factors which influence costs and which depend on product modularity.

Based on literature, the influence of modularity on manufacturing costs is presented in this paper as a case study.

Several limitations of this approach have to be mentioned. On the one hand the literature data just points out relative cost progressions. To use this data, company specific progressions needs to be quantified. On the other hand interactions of the properties were not considered in this approach, because company requirements will influence these interactions. So it is also necessary to identify and quantify the efforts of the interactions in a company.

In further research, the influence of modularity on the other departments (development, operations scheduling or procurement) should be analyzed. Additional to a literature research, several companies should be interviewed to identify these influences and cost-functions in detail.

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Proposal of a Research Methodology to Increase the Robustness of the Conjoint Trends Analysis Method through Its Formalization

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Abstract. Nowadays, the product user experience (UX) is essential in the design of innovative products. Several methods assist in defining this UX. Some help to define the aesthetic appearance of a product (which conveys the desired UX). They are very precise but are also complex and expensive to use. Others are easy and inexpensive to use but imprecise. The Conjoint Trends Analysis Method (CTAM) lies between these two extremes. However, several CTAM's instructions can be biased by the subjectivity of the CTAM user. Therefore, this research seeks to increase the CTAM robustness by formalizing instructions and making its concepts more explicit, aiming to increase its accuracy. Six experiments divided in four studies are proposed to respond to different research questions. Finally, there is a discussion on how the results can provide a basis from which to extract more robust guidelines for each step of the CTAM.

Keywords: Conjoint Trends Analysis Method, product aesthetics, user experience, product embodiment, product appearance.

1 Introduction

Some of the systematic product design engineering methods most commonly used today are Pahl et al. [1], Ulrich et al. [2] and Otto et al. [3]. However, none of these methods allow the definition of the product´s aesthetic appearance. Such aesthetic appearance here is understood as the set of values that must present the product in all properties that define its aesthetics [4]: psycho-physical, organizational, semantic, cultural-individual and universal. According to Cagan et al. [5] this aesthetic appearance conveys emotions and values necessary for the product to generate the desired user experience (UX). Hekkert et al. [4] defines UX as the self-awareness, subjective and affective, of what we feel when interacting with the product, at three levels: aesthetic-perceptual (given by the appearance of the product), emotional (emotions and feelings surrounding the product) and semantic (meaning and values of the product). Therefore depending on the interaction of these levels, in different proportions, and on the person, the product and the context, the UX if formed. Nowadays the UX can be fundamental to obtain innovative products, due to the high level of user

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satisfaction with the functionality of the products, including basic range products [5]. Among the authorities in ergonomics [6] and quality (KANO) [7] there is a consensus in this respect. Schifferstein et al. [4] argues that the aesthetic elements of the product must be coherent with the desired UX.

In general terms, the research problem of this project is how to directly link the UX with product-adapted aesthetic attributes and characteristics in a direct and structured manner. In order to define the aesthetic appearance of a product, the literature reports many methods. Following Pahl et al.[1], 11 of the most known methods can be classified into 4 categories: intuitive, analytical, evaluative and global (discursive). Below the methods of each category and their advantages and disadvantages are discussed [8]. Intuitive (Loewy's sixth sense, seeing magazines, Internet browsing): short and quick but not very precise; Analytic (Kansei Engineering 3 and 4): precise, respects UX's complexity but long, expensive and requires special statistics knowledge; Evaluative (laddering, semantic differential): relatively precise but a model or prototype is required, it is also expensive, long and risky; Global (Repertory Grid Technique, Moodboards, ZMET, Conjoint Trends Analysis Method): relatively precise but some of them need special knowledge in psychology and may be expensive. Most of the above methods do not adjust to the industrial context of SMEs, especially in emerging countries, such as Colombia, where 99% of companies are SMEs [9]. Usually in these companies resources are limited. However, the Conjoint Trends Analysis Method (CTAM) can adapt well to these contexts, as it does not require special knowledge, specialized professionals or expensive massive user studies for its implementation Moreover, CTAM can be used by product designers themselves [8].

CTAM is a semi-structured method that seeks to increase the accuracy in defining the product´s aesthetic attributes and in defining the UX desired for it [8]. Such a trend is considered a popular emergent style in product design in emerging countries [10]. CTAM has its origins in the fashion design industry. It has been developed, structured and used for over 10 years [10][11][12] in the car industry in France [11], among others. The result of applying the CTAM is a board (a composition of images) through which not only the desired aesthetic attributes of the product are conveyed (a style), but also the emotional and semantic attributes (values) desired for the UX [10][13] (see Figure 1). The CTAM then communicates the desired UX through the product. In addition to that, it is well known that visual aids encourage creativity in design [10][12]. The steps to build a TB are as follows (figure 1): 1) Establish the sectors of influence surrounding the designed product. An influence sector is any sector of human or natural activity that is related to the kind of product to be designed in any way and to the natural or artificial objects that exist in the sector. These objects have characteristic forms (geometry, colors, materials, textures, volumes) that can be integrated into the product to be designed and serve as a reference or inspiration for the product design embodiment phase. Magazines and websites that have images on these sectors must be collected. 2) Identify whether an image will be inspirational or not in the design process; inspirational ones should be selected until reaching a saturation point where no more inspirational images are found. 3) Classify images according to aesthetical, semantic or emotional criteria. 4) Debug the groups of images separating those that seem less coherent with the criteria. 5) Select only the most coherent and richer groups of images. A TB will be constructed from those groups. 6) Propose a harmonic composition of the images. Samples of colors and textures must be extracted in order to compose a palette to place alongside the composition. 7) Terms of the main features of the UX conveyed through the TB are identified and placed on the TB. The TB´s name must be defined as well. This name should be evocative so as to fulfill the inspiring function of the TB.

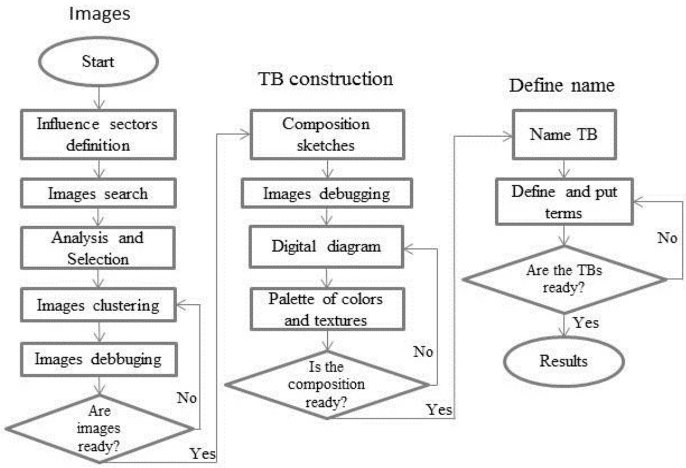

Fig. 1. Steps to follow to build a TB [10]

Castano et al. [8] assessed the use of CTAM in the design of a home plastic organizer and conclude that "this (evaluative) work reveals points where CTAM is less structured and where the subjectivity of those who conceived the TB can occur (for example, when deciding whether an image is inspiring or not)". This is due to the poor nature of some instructions. Castano et al. [8] concluded that CTAM is a promising method but can be improved in many areas. According to Castano et al. [8], the questions corresponding to the implementation and evaluation areas of the CTAM are: How to define influence sectors for a TB? These sectors have only been identified for the automotive sector. Which are the criteria for choosing an image as inspiring? Which criteria allows to group images and to debug groups of similar images? How to make the composition of a TB? How to assign the UX terms and name? Most of these steps are done intuitively. Other problems identified by Castano et al. [8], i.e. concerning construction and ecological validity will be addressed in an upcoming research. This publication is placed consequently within a broader study, which seeks to increase the robustness of CTAM by creating a better definition of its instructions and making its concepts more explicit. That study seeks a CTAM less sensitive to external disturbances (e.i. mood changes of the person doing the TB, or changes in the aesthetic training required). The final aim of the project is to consolidate the CTAM to increase the accuracy of its results. The remainder of the paper is organized as follows: Section 2 describes the set of experiments used to answer the research questions, Section 3 presents the results obtained until now and Sections 4 and 5 present the discussion and conclusions respectively.

2 Proposal of a Research Methodology

In order to achieve the research objective, four studies are proposed and can be observed in table 1: influence sectors, inspiration, composition and validation of CTAM with increased robustness. Each study consists of experiments that correspond to each research question. The following paragraphs then demonstrate the systematical development of different alternatives for each experiment, its choice, and the final development.

Table 1. Studies to increase the robustness of the CTAM

Study		Experiment	Questions	Objective
1	Influence sectors	1	How to define influence sectors for a TB?	Define the influence sector in different fields from automotive design
2	Inspiration	2	Which are the criteria for choosing an image as inspiring?	Define criteria for choosing an image as inspiring
		3		Understand the process of inspiration when designing a particular product
3	CTAM composition	4	Which criteria allow forming and debugging groups of similar images?	Define criteria to form and debug groups of images
		5	How to make the composition of a TB?	Define criteria to make the composition, to assign the terms and to name a TB
4	Validation. CTAM with increased robustness	6	How to verify an increase of CTAM robustness?	Verify an increase in the robustness of the CTAM

2.1 STUDY 1: Influence Sectors Experiment

Experiment 1 should contribute to defining the influence sectors for a TB. Two alternatives were proposed: a) Proposal of boards with visual stimuli from which participants (product designers) are asked to make a list of influence sectors, thus obtaining a general list. b) Make a general list of influence sectors from magazine images from the different design sectors. The list is delivered to some designers in order to select and rank the sectors that have influenced their designs. The selected alternative was the second because it allowed to cover different sectors of products frequently designed (i.e. furniture, tableware and home appliances), and would take less time than the first proposal.

In order to carry out the experiment an exhaustive and general list of influence sectors related to the type of products mentioned before should be made. This list is useful in building a TB to design common product categories. The initial list will begin with the sectors found in widely used design magazines. Within one image multiple objects are classified in different influence sectors. In this case, all the sectors found will be on the list. A saturation point must be reached, at which point the new sectors found are already part of the list and new sectors no longer appear. After this, a brainstorming of the possible influence sectors that influence the design of certain products is made (i.e. tableware, furniture and home appliances), in order to be exhaustive with the already created list. Then, the existence of characteristic objects for each sector is inquired, and whether there is general agreement on the characteristic objects pertaining to the sector (e.g. tableware sector´s characteristic objects: dishes, cutlery, etc...). This is done because TBs function visually. If the result of these two is positive, then the activity is defined as an influence sector, otherwise, it is not. From the general list of influence sectors, product designers from the industry are asked to choose and classify the sectors they considered for their last designed product, and rank them from the most influential to the least influential.

2.2 STUDY 2: Experiments about Inspiration

Experiment 2 should contribute in defining what the criteria for cataloguing an image as inspiring are. The alternatives proposed were: a) Ask participants (i.e. product designers) to leaf through a design magazine, and select inspiring images for a given simulated design situation. A protocol analysis method will be used to know the criteria for the selection of these kinds of images, and the process will be recorded. This method allows participants to verbalize their thoughts while performing a task, thus not altering the sequence nor the content of these (Cf.[14]). b) Select and place several groups of images of products, natural objects and people performing actions on sheets. Ask participants to select one of the images that they consider inspiring for a particular simulated design situation. During this activity the protocol analysis method will be used. The first proposal was selected because the magazine contains images of several influence sectors that provide richer data for the experiment. First, the images that are in a previously selected magazine are numerated, and a simulated product design task is proposed. Each participant is asked to leaf through the magazine and ask himself or herself in each image: is this image inspiring to me to design the task's product? So the individual images that are inspiring to a specific product design are identified. This activity is carried out until the end of the mag. This experiment consists of two groups of product designers: experienced and novice, a between subjects experiment [15]).

Experiment 3 should contribute to complement the results from experiment 2 with information obtained from interviewing product designers about their lives, experiences or situations as expressed in their own words [15]. It is considered that the inspiration process is continuous through life, and that the early stages of any creative process are individual [16]. According to the statements above, three in-depth interviews with expert designers are realized and the data is analyzed with the results of Experiment 2. Experts selected must fulfill the following criteria: first, they must have worked in product design and teaching; second, they must have designed constantly throughout their professional lives and third they have to be familiarized with the design language. The interview questions are first, to characterize the designers;

secondly, to allow them to recognize inspiration from their personal experiences; thirdly, to have insights on the sources of inspiration and fourth, to gain insights into the images as part of the inspiration. Each interview is recorded and transcribed. The results allow the recollection of data based on the criteria to choose an image as inspiring from the experience of experts.

2.3 STUDY 3: CTAM Composition Experiments

Experiment 4 should contribute to know which criteria allow to form and debug groups of similar images. The options considered were: a) Ask the participants (e.g. product designers) to form groups of similar images and discard the dissimilar ones. These groups belong to a larger set of images. In that set there are similar and dissimilar images defined a priori. A protocol analysis method is used to perform the task. b) Give a magazine to each participant and ask them to cut images to form groups of similar images. The first option was selected because it allowed the use of a limited number of pre-defined images chosen by the participants and consequently limited the number of images of similar criteria. During the activity the protocol analysis method is used [14] complemented with an eye tracker. This equipment allows to have information of exactly where and how long participants looked (and did not look) [17] when viewing the images. The subjects are then asked to form groups of similar images (according to a single criteria: emotional, semantic or aesthetical, according to the definition of UX [4]). Then the subjects are asked to remove the dissimilar images of each group (dissonant images), and ask themselves about each one: is this image highly similar with this group? If the answer is "more or less" or "little", the image must be discarded. Anyway, the discarded image can pass to another group of images. This is done to debug the groups and to obtain criteria used to do it.

Experiment 5 should contribute to the insights on how to compose a TB. The alternatives were: a) Show each participant (i.e. product designers) a TB already created themselves. Then ask them to remember how they made the composition. b) Ask the participants to make a TB for a simulated design situation, from a similar group of images, according to some formal-aesthetic, semantic or emotional elements they have in common (UX definition [4]). The protocol analysis method must be used in order to obtain insights of this process. Then a TB composition is done using image editing software. The second option was chosen because this experiment is to define criteria for the composition of a TB, which can be obtained from protocol analysis and would not be affected by haphazard memories as in a). The same set of images is given to each subject on a digital file. A laptop with sufficient graphical performance must be used. Each subject is asked to produce one TB from these images by diagramming the images in the software to form a harmonious and coherent composition. At the end of the layout, the subject is asked to write down emotions, meanings and values suggested by the TB, according to the UX desired to convey with the TB. Then the participant is asked to give an evocative name to the TB.

2.4 STUDY 4: More Robust CTAM Validation Experiment

Experiment 6 should verify whether there is an increase in the robustness of the new CTAM method based on the criteria defined from experiments 1 to 5. It should be defined as follows: two groups of people doing the same activity but, one with the CTAM already presented in the introduction of this paper, and the other with the new CTAM based on the new criteria found. A sample consisting of six Product Design Engineering Students from EAFIT University who have already taken the product aesthetics course and know the original CTAM could be proposed. They should be skilled in an image editing software. All other people variables are kept as homogeneous as possible. The six people are split into two equal groups: original and new CTAM. The original CTAM group receives the instructions given in the introduction, in figure 1. The magazines used to obtain the images could be the same used in experiment 2. As a result from 4 to 7 TBs are obtained. The "new CTAM " group must follow the same scheme described in Figure 1 for the same design situation with these changes: for influence sector definition, criteria defined from the experiments 1 must be used; for analysis and selection of images, the criteria defined from the experiments 2–3; for images clustering and debugging, the criteria defined from the experiment 4; for composition of a TB, name and terms, the criteria defined from the experiment 5. The quality of the TBs obtained by both groups, in terms of the UX conveyed by each TB, is evaluated through a semantic differential. This is a quantitative technique used to obtain the connotative meaning of an object. It analyzes to which extent product semantic oppositions directly concern the UX´s conveyed in each TB [8].

3 Results and Discussion

The first 5 experiments were performed as described above. Therefore the type of results obtained in each experiment and whether those results allow obtaining an answer to the research questions are described below. Experiment 6 has not been performed yet because it depends on the analysis of the results of experiments 1 to 5. Consequently, this last experiment will be discussed differently.

3.1 STUDY 1: Sectors of Influence

The initial list obtained began with the influence sectors found in the widely used magazine Domus (Italy), from February 2012 (latest volume available to the completion date of the activity): the magazine contains images of the influence sectors for tableware, furniture and electrical appliances design. As results of experiment 1, 2 lists of 15 influence sectors each one were obtained for design of home appliances and furniture. The first 5 influence sectors of furniture were in order of importance: architecture, furniture, fashion, work in office and construction. For electrical appliances the order was: electrical appliances, automotive design, technology, objects for the kitchen and objects for the table. Comparing the results from the three designers could evidence if there is a specific order in the list of influence sectors and consequently to propose a general list adaptable to any product design project. It is known that sectors of influence can be gradually distant from the target, based on the proportion of shared properties with the target object [18].

3.2 STUDY 2: Inspiration

In experiment 2 the same magazine “Domus” used in experiment 1 was used. The sample selected for this experiment consisted of groups a and b: a) One industrial designer (design chief) and two product design engineers (design manager 1 and 2), in charge of the embodiment in product design in a company of home appliances. Only one of the design managers knew the CTAM, the other persons do not. This group had people with more than 4 years of experience. b) Three students of third semester of the Product Design Engineering program at EAFIT University who were taking the Product Aesthetics course in which CTAM is taught. This group had novice designers. The results from experiment 2 were 6 transcripts of talk-aloud protocols, 3 from the home appliances designers (140 minutes, 43 pages) and 3 from the product design engineering students (101 minutes, 22 pages). First the transcripts of each participant will be analyzed, and then a comparison will be made between these two results to obtain information about the criteria for choosing a picture as inspirational. From the transcript results it is expected that experienced designers be “able to take advantage of various sources, semantically near or far from the target object, and to adopt and integrate different points of views about the suggested sources” [19]. In experiment 3 for the selection of images it is expected that designers use experience and knowledge gained before the project to conduct direct gathering of information [16]. The novel designers can consider an image inspiring when they find mainly functional similarities with the target object, whereas the experts also relate the images based on the structural aspects [19]. For experiment 3, three people were selected: first, two teachers from the EAFIT University Product Design Engineering program. They have worked the topic of inspiration and creativity and have a extensive experience in product design and in product design teaching (27 and 10 years respectively). Finally, a product design engineer with 3 years of experience (running his own product design company) was selected. The first two teachers knew the CTAM but they had not applied it; the latter did not know the CTAM. In this experiment 3 transcriptions of the experts’ interviews were obtained (116 minutes, 35 pages) to have insight about the inspiration process in product design to complement results from experiment 2. The analysis of these results would allow identifying what kind of images (domain sources) are most inspiring to experienced or novel designers. It would help to define criteria on how to know whether an image is inspiring or not, as well.

3.3 STUDY 3: TB Composition

The participants in experiment 5 were three students of third semester Engineering Product Design at EAFIT University, who were taking the Product Aesthetics course at the time of the realization of the experiment, and already knew the CTAM. They had the highest grades using CTAM in that course. 30 images were selected for the experiment, as follows: 25 similar and 5 dissimilar, similarity was defined according to colors and kinds of materials. The image selection was made by one of the researchers. The results for this experiment were 3 transcripts (15 pages) of talk-aloud protocol, one for each participant and 3 videos and data obtained from the eye tracker. Then, as a result of the experiment is expected that elements of the cognitive psychology categorization models [20] were used to define the criteria to form and debug the groups of images. For experiment 5, three students from Product Design Engineering (from EAFIT University) were chosen. They were from fifth semester (two female, 20 and 21, and a male, 19), and they had already studied and used the CTAM. They had medium level knowledge in image editing software. Although participants knew already the CTAM, it is initially explained to them and some TBs examples were shown. As results of experiment 5, 3 transcripts were obtained of the talk-aloud protocols (99 minutes, 16 pages) and 3 digital files (34.1 MB), each containing the TB realized by each participant. From the results of this experiment it would be possible to obtain clear criteria to, first make an organized and harmonious visual composition and second, to know the keywords and TB´s name, were chosen to complete the UX conveyed by the images.

3.4 STUDY 4: Validation

Experiment 6 has not been performed yet. It depends on the results obtained in all the above experiments. It is expected that when including the criteria defined in each one of the experiments 1-5 to the corresponding phase of the CTAM, the possibility of introducing subjective bias by participants in the decisions to be taken during the development of CTAM is reduced. With the criteria defined through the experiments, it would be possible to have TBs that allow designers to design products that convey more precisely the desired UX for the user.

4 Conclusion

Product design should be benefited with the results, in that it would allow defining the aesthetic appearance of a product with a qualitative method, in a relatively accurate manner. The design product activity is to formalize the CTAM´s instructions, 4 studies and 6 experiments were defined. For experiments 1 to 5 two options were proposed. The option that best met the research objectives was chosen. The results of the protocol analysis method data should help to reveal what the content of peoples' minds are while they are using CTAM. Eye tracking results should reveal the connection between the type of visual content and the amount of attention paid to that content. In summary all the results should prevent noise generation from external and subjective aspects in CTAM thus avoiding imprecise results. It should be considered that these experiments are qualitative: they allow to obtain criteria for guidance only, not to take crucial decisions in the design process. If even more robust CTAM´s instructions are required, quantitative experiments should be designed (i.e. quantitative correlational and significance analysis of this data) [21].

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Analyzing the Deviation of Product Value Judgment

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Abstract. Consumers perceive the value of durable goods at two points of time: first, they form their opinion about the value immediately before purchase determining their choice. Second, they form their opinion during the utilization phase, which determines their repurchase behavior. Both the expected pre-purchase value and perceived value during the utilization phase are affected by the product quality. Functionality and accuracy of production maintain no longer the only criteria for product differentiation. Ultimately, the perceived product quality, design and usability have a significant impact on the customer perceived product value. This paper presents the developed CPV construct and a three phased approach to provide the evidence that the pre-purchase differs significantly from the post-purchase value judgments. Empirical data of pre-studies are presented in this paper.

Keywords: perceived quality, product value judgment, perceived value.

1 Customer Perceived Value

The customer perceived value (CPV) [1] is defined as “personal perception of advantage arising out of a customer’s association with an organization’s offering, and can occur as reduction in sacrifice; presence of benefit (perceived as either attributes or outcomes); the resultant of any weighed combination of sacrifice and benefit; or an aggregation, over time, of any or all of these.” [2] The customer’s perception is the core issue, because CPV is not an objectively measurable value. Rather, the perception and attribution of value is different from individual to individual and from situation to situation (depending on time, place and environment). “Not only does each of us value the same things differently, we individually value different things, and at different times in different ways.” [2] In particular, the dependence of the value judgment on the time of assessment is essential to this paper.

The expected value of a product is determined by the consumer in a cognitive, subjective comparison process. He trades the expected benefits off against the expected costs and risks [3–6] .The result of this process is the value, which can be compared with the values of alternative products.

The pre-purchase phase describes the stage, in which the customer gathers first information and makes his choice about the product. The point of purchase is imminent.

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Pre-purchase product value determines the initial purchase. Whereas the post-purchase phase describes the stage, in which the customer uses the product in his everyday life and has an appropriate time to get used to it. Post-purchase product value has an impact on the probability of repurchase [7]. For both decisions, initial purchase and repurchase, the perceived product quality is essential. Especially in the higher price segment products are preferred acquired, whose quality is assessed by the customer as superior to competing products [8]. This impact can manifest itself both directly (product quality as a critical purchase reason) and indirectly (product quality increases satisfaction, which in turn leads to repurchase) [9]. For companies, the knowledge about the formation of the judgments about the expected and perceived product value is important. The customer lifetime value research shows, that regular customer are more profitable than new customers, which emphasizes the relevance of the post-purchase judgment. A high level of customer loyalty leads to repurchases of products, cross-buying and recommendation of the supplier. One Euro, which a durable goods producer spends to hold a regular customer, has a higher return than one Euro he spends to obtain a new customer [10]. The post-purchase value judgment will decide on the probability of repurchase and is based in most instances on the experience qualities of the product. The product perception changes over the consumption process. It is essential to see whether, where and how the perceived pre-purchase product value changes to the post-purchase value. The subconscious assessment and the changing review of priorities of customers are important aspects that must be considered when looking at the CPV over time. During the utilization phase, some elements of the CPV will appear more important – so the customer's judgment will be predicated on a different base. The hierarchical-model by Woodruff and Gardial also highlights the fact that customers estimate the product value at different times in varying contexts. Thus, the pre-purchase judgment is especially characterized by the desired product attributes. However, the consequences of the product utilization have a major impact on the CPV during and after the utilization phase [11]. Therefore, consumer perceived value is a dynamic construct [3], [12]. The focus of judgment shifts between the generating dimensions, depending on the time of observation [13–14]. Huber et al. postulate that the benefits and costs are defined in terms of consumer perceptions in the activities of acquisition, consumption, maintenance, as well as consumer expectations of personal value-satisfaction before purchase [15].

2 Justification of Need for Research

So far, most research is related to the declaration of the expected product value. It is often implicitly assumed, that the expected and perceived product value are determined by the same quality attributes. If this assumption is valid, companies might restrict their market research activities to the purchase situation. It would be sufficient to involve the voice of the customer at this point to develop customer-focused products and build up satisfaction and loyalty to the company.

However, evidences from several lines of research indicate that there are not the same quality attributes affecting the value judgment before the purchase and during the utilization phase:

- Pre-purchase value judgment is based rather on product attributes, whereas the post-purchase value judgment is based more on the consequences of the usage. Different levels of means-end-chains are dominant in these two phases. [14]
- Before purchase attributes are important, by which consumers can differentiate between alternatives. Customers frequently express rational considered thoughts. After purchase, attributes have a stronger impact on value judgment, which are relevant for satisfaction of need. Customers speak more often about emotions caused by product-usage. [14], [16–17]
- The approach of quality uncertainty from information economy distinguishes between search-, experience- and credence qualities of products. A product's quality that has mainly search qualities can be determined by inspection before purchase. For experience goods, this is only possible after purchase by using it. Therefore, pre-purchase value judgment can only be based on search qualities, experience with the product category and information taken from external sources, while information about experience qualities can be involved into post-purchase value judgment. [18–21]

So far, a detailed examination of the product value in two separate measurements does not occur in the current research approaches. The known publications are exclusively about surveys that attempt to measure product value at any time during the utilization phase. This is a serious methodological deficiency, as they imply an adjustment of pre-purchase and post-purchase value judgments in the perception of the subjects over time.

In summary, the literature seems to hold three gaps: First, in most publications either only pre-purchase or post-purchase product value is considered. Second, in the few cases, in which an attempt is made to collect both product values, there is no quantitative measure instrument to collect both values and thus to compare them with each other. Third, the measurement of the product values does not take place at two temporally separate times. For this purpose, it is essential to investigate on which level of abstraction and why the perceived pre-purchase product value differs significantly from the perceived post-purchase product value.

3 The CPV Construct

To understand and to be able to predict consumers' choices, it must be known, how they perceive products. One stated hypothesis is that consumers perceive products as bundles of quality attributes with connected attribute performances [3]. On the one hand, the benefits of an attribute result from the degree to which it is assessed as useful for the satisfaction of needs. On the other hand, whether the product-specific, perceived attribute performance has a perceptible difference in benefits compared to alternative products [22–24]. Therefore, from a business point of view, not the objective product quality is relevant. Instead, the perceived value created at the interface of the product and the user [25], compared to his expectations, affects the consumers' choice, deciding for or against the purchase [26]. The product value can be increased by two mechanisms: either by reducing the cost to the consumer or just by an increase in product deliverables, so the benefits [27]. However, it must be ensured that this value is also perceived as such by the consumer [27], which means, the manufacturer must have an idea of the product value from a customer's perspective.

Sanchez-Fernandez et al. suggest using a multidimensional construct for the conceptualization of the dimensions of the customer's perceived product value. According to this view, the product value is related to an aggregation of elements [28]. To design a general instrument for measuring the value of the product before and after the purchase, the trade-off between benefits and costs is the conceptual framework for the scale as shown in Figure 1 [4], [6], [29]. In accordance with the literature, this cognitive-rational approach should be extended to emotional, so-called hedonic dimensions [30–32].

Fig. 1. Trade-off between benefits and costs as the conceptual framework

Furthermore, it is necessary to specify the dimension of benefits and costs with corresponding elements. Treacy and Wiersema emphasize the key question, which must be taken into account for the creation of a measuring instrument: "What are the dimensions of value that customers care about?" [33]. The objective is to create a universally applicable item catalog. Consequently, a weighted additive combination of the elements seems suitable. This methodology ensures that no important aspects of the CPV will be ignored and follows the multidimensional view of the construct. Furthermore, the additive model takes into account the cognitive balancing trade-off between benefits and cost [34] and is preferred to a multiplicative model in the form of a ratio of benefits to costs [35]. First, all influencing benefit and cost elements must be examined and identified in order to deliver such an equation.

Sinha et al. point out: "Perceived Value is clearly a multidimensional construct derived from perceptions of price, quality, quantity, benefits, and sacrifice, and whose dimensionality must be investigated and established for a given product category." [36] If there is no certain product category, the elements of the construct should be investigated as comprehensive as possible including all items.

Furthermore, the aspect of consequences of the usage has to be added, because it is closely linked to perceived or desired characteristics of a product [3], [11]. The means-end-chain theory delivers statements to the question of how product characteristics establish benefits for the individual. Its central assumption is, that individuals aim for the achievement of valued states of being, also called ends, e.g. joy, security, the feeling of having a good performance [37]. Individuals choose those alternatives whose consequences contribute to achieving their goals. Hence, the consumption of the product equals the means to achieve the esteemed states of being (ends).

Therefore, the benefit of the product depends on the perceived contribution of the achievement [38].

In the following, item sets are developed that query the identified elements of the CPV individually [39]. The outcome is a multiple-item scale, which contains the CPV construct comprehensively. Thus, it is possible to determine the elements, in which the product value perceptions have changed, by comparing the results of the pre-purchase to the post-purchase judgment. Figure 2 shows the derived cost-benefit model, which sets the framework for this item generation.

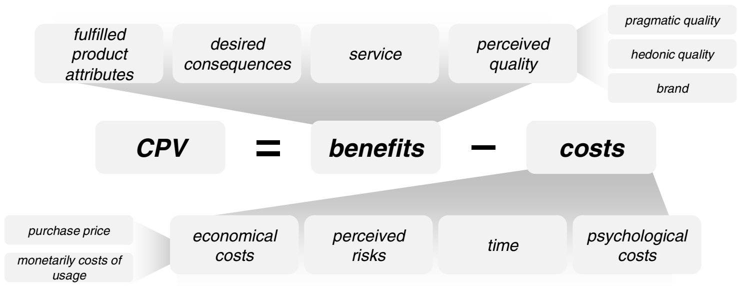

Fig. 2. The CPV construct with the abstraction levels as concept for the measuring instrument

The importance of individual product attributes for the overall value judgment changes after the purchase. The individual dimensions are considered unequally relevant and effect the final judgment unequally weighted, depending on the product category and individual. Interactions between the elements are considered as well. [39-40]

In most cases, the customer has difficulties to estimate the comprehensive product value prior to purchase. In accordance with the selected CPV model the described logic is used. Equation (1) is the calculation instruction, where n stands for the number of benefit elements and m represents the number of cost elements. The coefficient x is used to weight the corresponding element relating to the identified customer's relevance. According to the item rating scale, CPVs in the range between 6 and -6 are possible.

$$CPV = \frac{1}{n}\sum_{i=1}^{n} x_i * benefit\ element_i - \frac{1}{m}\sum_{j=1}^{m} x_j * cost\ element_j \quad (1)$$

The formation of the arithmetic average seems suitable to generate exemplary results from the questionnaire.

4 Approach to the Analysis of Deviation of Product Value Judgment

The objective is to provide the evidence that the pre-purchase value judgment differs systematically from the post-purchase value judgment. Based on that, the causes of the deviations have to be identified. First, it is necessary to investigate, in which way the CPV can be queried systematically based on its elements to determine deviations over the course of time. Subsequently, it must be specified at which two different measuring points the CPV can be evaluated. Finally, it must be investigated, how the results can be interrelated analytically. In terms of answering the research questions, it is necessary to go through three specific phases:

Phase 1: Scientific derivation and creation of a measuring instrument

It is pursued to investigate the pre-purchase and post-purchase product value with a measuring instrument. Based on the knowledge about the CPV construct, a measuring instrument (questionnaire) is developed. Afterwards, a durable good is selected to serve as a sample product in the following surveys. Initially, a list of criteria is developed for selection of this product based on literature on durable goods and practical considerations. The product should meet at least the following criteria: It should be known and used by many potential subjects, be applied in various usage situations and part of every day life to ensure usage. Subsequently, its relevant attributes have to be identified. Attributes are relevant, if the user derives any benefits through them. The identification of the attributes covers several steps. Considerations resulted in the following minimum activities: Test magazines, Internet forums and similar publications are investigated by comparing attributes within the *media research*. During the *dealer survey* the (specialty) retailer is interviewed about the attributes that customers care about. The *lead user survey* includes a half-day focus group conducted with 6-10 volunteers of the target group. Within this group interview, attributes and potential use situations are developed on the basis of existing physical exemplars of various brands. Based on determined attributes, the questionnaire is adjusted to the sample product and subject to a pre-test, which checks the different quality criteria.

The result of phase 1 is a validated questionnaire that measures the pre-purchase and post-purchase product value. It is adjusted with a set of customer-relevant attributes of the product sample.

Phase 2: Application of the questionnaire and inquiry of data at two measuring points

It requires a survey at two separate measuring points in order to determine the deviation of the CPV over time. The deviation of pre-purchase and post-purchase product value or during the utilization phase is of particular interest. At the beginning of the second phase, subjects are identified that are about to purchase a product in the relevant category. Therefore, they are in the first stage of the buying process (search for alternatives, selection of an alternative). The sample product is presented to the subjects, so that they have time to test it. Subsequently, the subjects fill out the questionnaire (survey of pre-purchase product value) and purchase the same product to ensure comparable data sets. The product is not delivered immediately as the purchase at the counter is an important part of the consumption process. Therefore, it should not be omitted in order to create a realistic situation.

After purchasing the product, the subjects use it during a specified period in their everyday lives. The period is set to three months, as it is long enough to use the product in different usage situations and get an idea of the product. After that period they fill out the questionnaire a second time (survey of post-purchase product value).

Phase 2 delivers answers about the pre-purchase and post-purchase product values through the questionnaires that can be transformed into analyzable data sets.

Phase 3: Analysis of the deviations

The evaluation of the collected data in phase 2 includes a preparation of the demographic data, re-examination of the quality criteria and inferential exploration for investigating the deviation of pre-purchase and post-purchase value judgments.

The different perspectives of the questionnaires allow a distinct analysis of the expected deviations at various abstraction levels (product value in general, benefit and cost dimensions of the product value, included elements). For example, it is possible to investigate whether deviations found in the evaluation of individual elements also affect the product value in general.

The design of the questionnaire allows to express the CPV using a concrete numerical value of each subject, both for the pre-purchase as well as the post-purchase survey. A numerical value is not only easier to compare, but also allows more precise statements about the perceived quality of a product. Furthermore, a measurable value of CPV allows the direct comparison of two time points of the survey, which is in terms of the present investigation, since the deviation of the CPV can be determined directly over time for each subject. For purpose of statistical analysis, values must be assigned corresponding to the response levels of the measuring instrument. The rating direction is set for each item. Based on the developed equation (1) to calculate the CPV, a graphical representation is provided in order to illustrate findings from the questionnaires. The radar chart shown in Figure 3 (a) is an appropriate compromise between a detailed level and an overall picture. Results of pre-purchase and post-purchase survey can be plotted in one diagram in order to allow direct comparison. Striking deviations between the perceptions at both times can be notified directly.

The objective is to identify the reasons for the deviation of pre-purchase and post-purchase value judgments. Results are both statistical statements about the deviation of pre-purchase and post-purchase value judgments and the results of the scale validation. Subsequently, a qualitative research approach is chosen to identify the reasons for the uncovered differences. Methodologically, the implementation of semi-structured interviews seems promising. Depending on whether significant deviations are found at all or only some abstraction levels, the configuration of the interviews changes. Subjects from phase 2, where deviations have occurred on the relevant abstraction levels, will be interviewed about the causes behind this alteration.

The result of phase 3 is a list of possible reasons for deviations from the pre-purchase to post-purchase product value.

Application and validation of the approach

A pre-study has been conducted to validate the generated CPV construct with the developed questionnaire containing 115 items. A tablet-PC has been chosen as sample product as it is matching the developed list of criteria of phase 1. With 19 subjects, individual and summarized CPVs have been evaluated. Figure 3 (a) shows exemplary the results of an evaluated individual pre-purchase CPV with an overall outcome of 2,01 and a possible fictive post-purchase CPV with an overall outcome of 2,31. It shows the deviation for each dimension over time. As shown in Figure 3 (b), it is also possible to evaluate a summarized CPV for all individuals with an overall outcome of 0,89 with the corresponding confidence intervals of all subjects for the product, to either compare different products of one category or different product categories with each other.

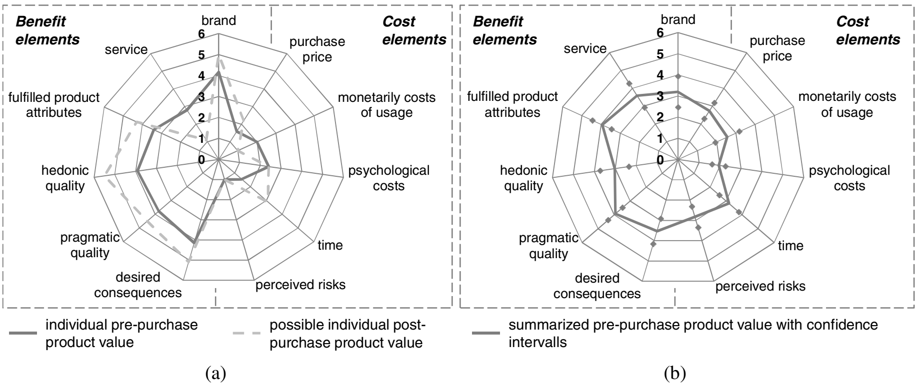

Fig. 3. Radar chart of the CPV elements and the deviation over time

5 Conclusion and Discussion

This paper discusses the need for research of analyzing the deviation of product pre-purchase and post-purchase value judgment. So far, the research was limited only to one point of time. In this approach, the research is extended to two separate measuring points to have comparable value judgments of each subject. Furthermore, this paper describes the suggested methodology to identify and discover both the deviation and the reasons for the different perception of the consumer. A measuring instrument was developed in form of a questionnaire, which makes it possible to analyze statistically data of the product value, both before the purchase and after the utilization phase and to compare the results. The approach to the evaluation has been applied in pre-studies with 19 individuals to assess each individual CPV and a summarized CPV. It must be pointed out, that the amount of subjects is not enough to make a valid statement. Therefore, more subjects have to be enlisted in further researches.

Subsequently, a qualitative research approach is proposed in order to uncover the causes for the deviations, so as to express recommendations to companies for future product development. Current literature provides various approaches to measure the product value. The CPV construct introduced in this paper was chosen to expose the different elements on a sufficiently detailed level in order to analyze the deviations over time. The quantification of the CPV at two separate measuring points will be conducted by means of the methodical approach. Within the context of this investigation, two measuring points are sufficient to analyze the causes for deviation of product value judgment over time. For further researches, it can be considered to extend the investigation to more than two measuring points. This allows identifying the developing customer product values through different stages of the product lifetime.

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Complexity Connectivity Metrics – Predicting Assembly Times with Low Fidelity Assembly CAD Models

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Abstract. Expanding on previous work to predict assembly times from detailed assembly models, low fidelity part models are used in a series of predictive performance experiments. Results reveal that this tool can predict the assembly time of a product to within 40% of the target "as built" time using a high fidelity neural network and a low fidelity CAD model. The tool is based on structural complexity, representing the assembly graph as complexity vector of 29 metrics. The graphs are automatically compiled from examining part proximity (interference checks) regardless of the choice of mating constraints used in the modeling. A neural network is then used to build a relationship between the complexity vector (input) and the assembly time (output). Low-fidelity models can be used to predict assembly times, thereby supporting earlier inclusion of design for assembly methods in the design process.

Keywords: Design for Assembly, Assembly Time Estimation, DFA.

1 Motivation for Time Estimation

Design for Assembly (DFA) is a design method used in industry to improve the assemblability of a product with the ultimate goal of reducing manufacturing costs. With increasing manufacturing costs, an interest in DFA has emerged due to the assembly phase in product development accounting for approximately 50% of the manufacturing time and 20% of the manufacturing cost [1–8]. Furthermore, approximately 70% of the total product cost is determined during the early stages of design, motivating the need for DFA tools that can support product development throughout the design process [9, 10].

Assembly time estimation tools, within the larger design for assembly method, have been developed for predicting the assembly time of a product [5, 8, 11]. Time estimate tools do not support assembly time estimation in the early stages of design as detailed information about the parts, assembly sequence, and assembly structure are required. This information is often not determined until the embodiment or detail design phase of the design process. The majority of these assembly time estimation tools are used primarily to estimate the assembly benefit of a design change to an existing product. This paper focuses on the development of an extended complexity

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connectivity assembly time estimation [12–14] method based on information retrieved from low fidelity CAD models in the conceptual design phase.

1.1 Connectivity Complexity Method

The term complexity is used in many disciplines all with different interpretations of the definition [15–17]. For this research, the term complexity will be used to describe amount of information required to describe a system comprised of more than one component [15, 18]. Previous research developed a set of complexity metrics to capture the connectedness of parts within a system [12, 14, 19]. The connectivity method uses the complexity metrics as the input vector to a historical-based prediction model to estimate assembly times of a product [12–14]. The complexity connectivity method uses 29 graph-based complexity metrics of an assembly[14, 19].

2 Low Fidelity CAD Model Assembly Time Estimate: The Experiment

Previous work has focused on estimating assembly times from detailed component and assembly models. This work evaluates the potential of using components represented at lower levels of detail (conceptual models or low-fidelity models). While the exact dimensions and features of the components are not know, the general system architecture and layout is captured [20]. The form of the individual components are developed throughout the design process to create a completed CAD model with working drawings in the detailed design stage [20]. For clarity, low-fidelity models are those that are found in conceptual design and high-fidelity models are found in detailed design phases.

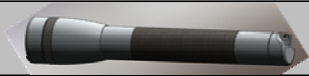
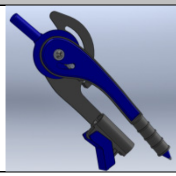
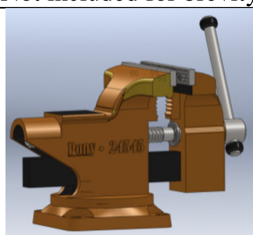
This experiment explores the use a modified complexity connectivity method to estimate the assembly time of models in the conceptual design phase. The estimated assembly time of the conceptual models is compared to the estimated assembly time of the complete models using the same modified complexity connectivity method. The following research questions are answered:

- What is the predictive power of ANN trained on detailed models to predict detailed models?
- What is the predictive power of ANN trained on detailed models to predict low fidelity models?
- What is the predictive power of ANN trained on low fidelity models to predict low fidelity models?
- What is the predictive power of ANN trained on low fidelity to predict high fidelity?

2.1 Set of Models

The experiment used a total of thirteen products (Table 1) to compare the estimated assembly time of high-fidelity models and low-fidelity models. The models were used in previous work and were created by multiple designers by physically reverse engineering existing products or downloading models from the public domain [13]. The last three models are withheld for testing purposes.

Table 1. Products Used in Training and Testingt

Common Name	Training/Testing	CAD Model Image
Stapler	Testing	Not included for brevity
Flash Light	Testing	
Ink Pen	Testing	Not included for brevity
Pencil Compass	Training	
Indoor Electric Grill	Training	See **Fig. 1**
Solar Yard Light	Training	Not included for brevity
Table Vise	Training	
Drill	Training	Not included for brevity
Shift Frame	Training	Not included for brevity
Vegetable Chopper	Training	Not included for brevity
Computer Mouse	Training	Not included for brevity
Piston Assembly	Training	Not included for brevity
3 Hole Punch	Training	Not included for brevity

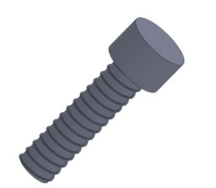
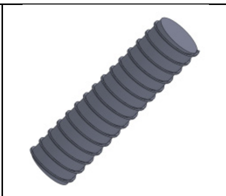
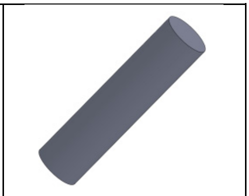
2.2 Reducing Model Fidelity

Low-fidelity CAD models are difficult to define and are often not distinctly saved by the designer before they are evolved to more detailed higher fidelity models. For this work, the high-fidelity models were reduced in fidelity to represent low-fidelity models in the conceptual design phase.

To do this, each part included in an assembly model was reduced to its lowest level feature. In SolidWorks the feature tree stores the features used to create a part and the order in which those features were created. To decrease bias in the reduction of fidelity of the parts, the feature tree was reduced to the top level feature for each part. It should be noted that if a multiple designers create the same part, a different conceptual model may result. This uncertainty is not the focus of this research and is reserved for future work.

As an example, the first feature used to create a bolt is an extruded shaft (Boss-Extrude1). Next, a swept extrusion (Sweep1) is used to create the threads around the shaft of the bolt. An additional extrude (Boss-Extrude2) is used to create the bolt head and then an extruded cut (Cut-Extrude1) is used to cut the hex in the top of the bolt head. Starting from the bottom of the feature design tree, the Cut-Extrude1 is deleted, followed by Boss-Extrude2 and Sweep1 leaving only the initial extrude as an example of a conceptual model for a bolt (see Table 2).

Table 2. Reduction of Fidelity of a Bolt Complete Model to Create a Low Fidelity Model

			
Cut-Extrude1	Boss-Extrude2	Sweep1	Boss-Extrude1

This removes detail from the parts in the CAD model, leaving a low-fidelity model of the product simulating a model created in the conceptual phase of the design process. The indoor electric grill (Fig. 1) is similarly reduced from a detailed model to an assembly of the low-fidelity part models. Mating relationships may be lost in this transformation, precluding the use of previous graph generation tools [21]. Therefore, a mate-independent method for generating the connectivity graphs is used based on interference checks.

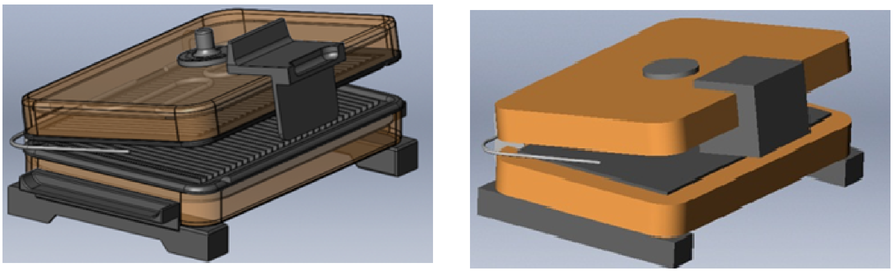


Fig. 1. Transformation of Electric Grill from High Fidelity Model to Low Fidelity Model

2.3 Artificial Neural Network Generation

The artificial neural network (ANN) used for this research is a supervised back propagation network [12, 13]. The ANN is trained by providing a set of input vectors and a set of target values. The ANN then creates a relationship between the input values and the target value. In this case, the complexity vector of 29 metrics is the input vector and the assembly time of the product will be used as the output. Once an ANN is trained, a new complexity metric is input and the ANN provides an assembly time.

2.4 Experimental Sets

Two separate neural networks are created and compared. The first ANN uses the complexity vector of the high-fidelity models as input and assembly times as the targets. The second ANN uses the complexity vectors of the low-fidelity models as the training inputs and the same assembly times as target times. This approach is used to test the ability to train a neural network to find a relationship between low-fidelity complexity vectors and product assembly times. Each ANN is used to predict the assembly time of a test data set (three products) using the high-fidelity and low-fidelity models. The experimental sets are summarized in Table 3.

Table 3. Experiment Design Sets

Set Number	ANN Trained on:	Test Set Type:
1	High Fidelity Models Vectors	High Fidelity Model Test Vector
2	High Fidelity Models Vectors	Low Fidelity Model Test Vectors
3	Low Fidelity Model Vectors	High Fidelity Model Test Vector
4	Low Fidelity Model Vectors	Low Fidelity Model Test Vectors

3 Conceptual Model Time Estimate Results

After the two ANN are trained, the input vectors are passed back in to the neural network to gain a qualitative assessment of ANN fit to the training set. One shortcoming with ANNs is the potential for overtraining, limiting the ability of the ANN to extrapolate to new data sets [22–24]. The percent error is calculated as the normalized difference from the target time (see Eqn. 1). A positive percent error indicates that the predicted time was greater than the target time, and a negative percent error indicates that the predicted time is less than the target time.

$$\text{Percent Error} = (\text{Predicted Time - Target Time})/\text{Target Time} \quad (1)$$

The ANNs are able to estimate the training set assembly times within 70% of the target time, but visually do not appear to be over fit to the training set data (see Fig. 2). Previous research offers techniques to prevent ANN over fit and improve performance of ANN by varying ANN parameters. As the focus of this paper is to demonstrate the potential to use ANN to predict assembly times of low-fidelity models, the improvement in design of the ANN itself is reserved for future work.

To test the performance of the two ANNs in predicting the assembly times, complexity vectors of three products (stapler, flash light, and ink pen) not used in the training are used for testing. For each of the test products the high fidelity and low fidelity graph complexity vectors were calculated and used as the input to both ANNs trained (high fidelity and low fidelity).

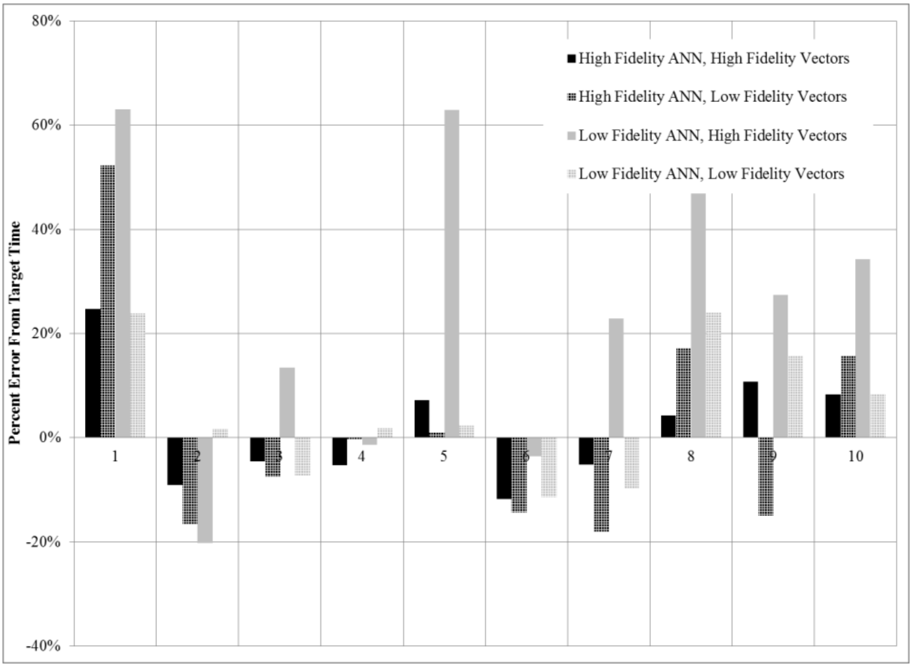


Fig. 2. Training Set Percent Error from Target Time

The target time, the predicted time, and the percent error for each of the three test cases are presented in Table 4. Each ANN predicted an assembly time greater than the target time for the test cases except for the high-fidelity ANN for the stapler. The test products varied in target assembly times from 34 seconds to 123 seconds. Additional test cases with a larger range of assembly times are needed to determine if the ANN time estimate accuracy is dependent on the assembly time or the complexity of the product being studied, but this is reserved for future work.

Table 4. Test Products Results Summary

Fidelity Levels		**Predicted Time [s] (Percent Error)**		
ANN	**Test Assembly**	**Stapler**	**Flash Light**	**Ink Pen**
High	**High**	115.84 (-6%)	107.65 (43%)	54.78 (59%)
High	**Low**	119.43 (-3%)	91.79 (22%)	46.41 (35%)
Low	**High**	157.19 (27%)	109.89 (46%)	72.36 (110%)
Low	**Low**	198.30 (61%)	95.19 (26%)	51.65 (50%)
	Target Time [s]	123.51	75.40	34.40

The percent error from the target time was calculated for each of the outcomes (see Fig. 3, Fig. 4, and Fig. 5).

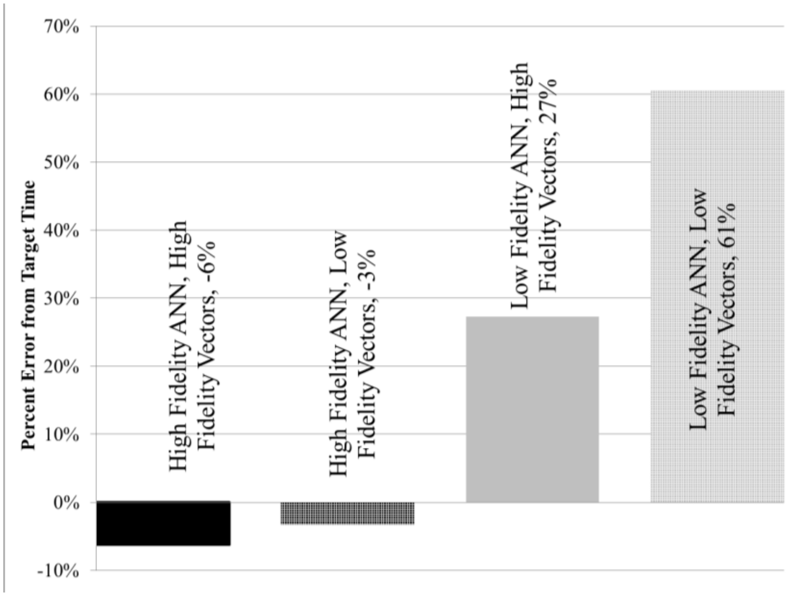


Fig. 3. Test Case Results for Stapler

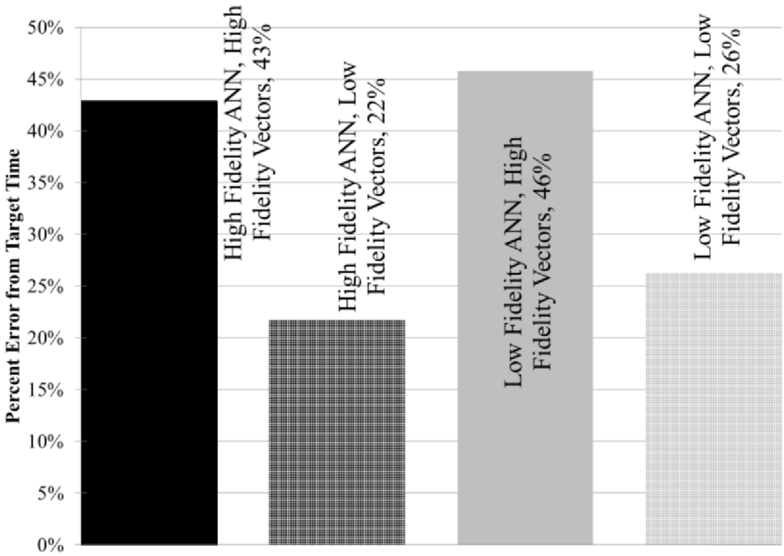


Fig. 4. Test Case Results for Flash Light

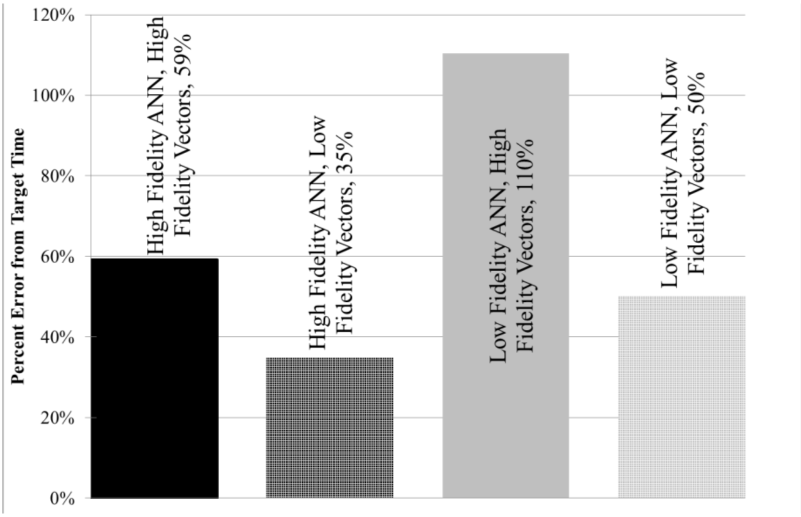


Fig. 5. Test Case Results for Ink Pen

The results from the analysis of the test cases indicate that both of the ANNs (high fidelity and low fidelity trained) can predict an assembly time to within 120% independent of the type of input vector used. However, the low fidelity ANN was the generally the worst at predicting assembly time when presented with a high fidelity input vector. The best combination of ANN and input vectors, based on the lowest percent error for all three test cases is the high fidelity ANN being provide low fidelity input vectors. The focus of this research is if an ANN can predict the assembly time of a low fidelity model. Both the high fidelity ANN and the low fidelity ANN were able to predict the assembly time of the conceptual model to within 120% of the target time. There was not sufficient evidence in this study to determine if there is a significant difference in assembly time estimation between the high fidelity and low fidelity ANN when using the low fidelity input vectors. The training sets and the test cases were limited in number and could potentially influence the results. The results of this study serve as motivation that there is potential to use an ANN to estimate the assembly time of models early in the design process.

4 Conclusions and Future Work

The ability of a neural network to create a relationship between input vectors and output vectors depends on the training set provided. The larger the training set (to a degree to avoid over fitting), the better the neural network is at predicting the output. While the input vectors used to train the neural network in this research are limited to ten training products, future work includes increasing the training set to determine if the assembly time estimation can be further improved. The number of test products will also be increased to ensure the trends in this limited population are valid. This paper presents the preliminary findings that must be extended with more validation.

The findings of this study suggest that the high fidelity assembly model based neural networks provide good prediction tools for estimating assembly time for both high fidelity and low fidelity conceptual models. There was not significant evidence to suggest that the high fidelity neural network or the low fidelity neural network can better predict assembly time. It is clear however that a neural network trained on low fidelity models should not be used to predict the assembly time of high fidelity models. Ultimately, this tool shows promise for providing engineers in conceptual stages of product development with useful information about production costs early in the design process. The accuracy of these predicted times are sufficient to provide justification for alternative engineering selection decisions at early stages.

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The Virtual Reality Lab as a Synthetic Environment: From Strategic Approach to Practical Implement

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Abstract. The Virtual Reality laboratory (VR-Lab) at the University of Twente facilitates multi-stakeholder decision making processes. Using Synthetic Environments (SE) to facilitate collaboration and to visualize consequences and dependencies of choices, the lab stimulates optimal use of available expertise. The VR-lab embodies a flexible set of VR tools, software and working methods; therefore adequate facilitation of preparation and configuration of use is essential. For this purpose, a roadmap facilitates the attuning of the intents of (potential) user and the capabilities of the provider of the SE. This publication outlines the use of the VR-lab as a Synthetic Environment, as well as the preparations that a required to make that usage purposeful and efficient.

Keywords: synthetic environments, virtual reality, multi-stakeholder, decision making.

1 Introduction

Product development can be seen as a process of constantly making choices, often in consultation with multiple stakeholders from different fields of expertise. Within this team setting, developers have a need for support in communicating and for visualizing their problems and solutions, especially for gaining insight in the consequences and dependencies of choices.

This publication provides an overview of the approach, development, use and outlook of the Virtual Reality laboratory (VR-Lab) at the University of Twente [1]. This multi-stakeholder decision making laboratory facilitates the collaboration and decision making process in product development projects.

1.1 Scope

Within the field of product development, the need for support and facilitation of the various product development phases is obvious. In general, product developers also show enthusiasm for approaches that offer adequate support. Within the VR lab of the University of Twente, product developers are encouraged to address and optimize the development processes they employ in daily practice. The scope and emphasis is on supporting the decision-making processes that involve multiple stakeholders who aim

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to understand the implications of the many decisions that have to be made. Within these processes, many choices have to be made that involve multiple stakeholders. This immediately leads to complex dependencies between the choices made and the consequences thereof. These consequences are not always clear for every stakeholder involved. The VR-lab aims to give insight in the relations between and dependencies of all decisions, and to present them in the most purposeful and adequate manner. Furthermore, for the design process, it is important that such support can be delivered quickly, with minimal adjustment to the development process, the project planning and schedule. This implies that the configuration of support should be flexible and easy to adapt to different situations.

The VR-lab gives designers the ability to rely on support in the design process when it comes to cooperation (figure 1). Such support is available from the earliest stages of the development process. In these stages, it is desirable for the various stakeholders to define a common vision and understanding of the (explicit and implicit) problems that together constitute the basis of the development project. During the solution generation phase, the lab offers the possibility to clarify ideas for future scenarios using many types of visualisations and interactions. This also gives direct insight into the consequences of possible choices in areas such as safety, construction, use situation and composition. The lab adds the most added value to a process when a (large) group of stakeholders is interacting with one and the same set of information, and when they approach and handle this set in a way that best suits their own personal expertise. In this manner, the interactions and adjustments of other stakeholders to the data are immediately relevant and can be made visible. It is therefore possible to assess the collaboratively composed solution (path) based on individual expertise. In this, it is essential that every stakeholder perceives the information that is meaningful for him; therefore it must be possible to omit redundant information and information that cannot be processed. In other words, the working methods, together with the capabilities of the VR-lab should enable individual stakeholders in effectively and efficiently addressing information that is relevant for his perspective, in the context of the overall solution (path).

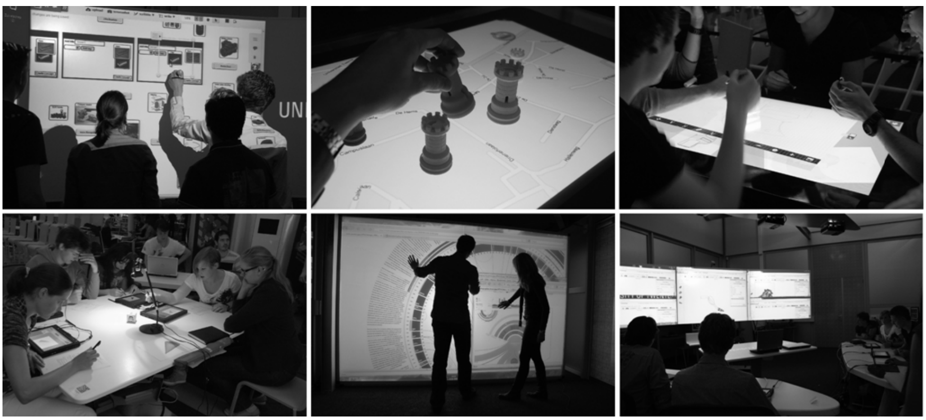

Fig. 1. Impression of projects in the VR-lab

2 Methodology

A product development process can be considered to be a constant trade-off between problems and solutions. To support and facilitate this trade-off, it is important that all stakeholders share an aligned vision on both. This starts with the definition of the actual design problem, rendering a shared understanding between the various stakeholders. With this, everyone can assume that the defined problem is interpreted in the same way by all participants. This synchronized start creates a situation where different backgrounds and expertise of the various participants come together and where even end-user can be involved in the process. By providing each stakeholder with the possibility to directly and explicitly communicate in his or her preferred way, the risk of misinterpretations is minimized. Each stakeholder should be involved in the process by being provided with an optimized method to contribute. Based on the supplied input, the interests and bias of each stakeholder within each stage of the process can be depicted, in which this preference is strongly related to the actual circumstances. Based on all supplied input purposeful and continuous iteration between problem definition, solution generation and the assessment is feasible.

The methodology and working methods that constitute the basis for the VR-lab allow for structured, transparent and straightforward use of different tools during product development lifecycles. Usage of these tools ranges from scenario development and serious games to what-if design and information management. The VR-lab can be compared to a workshop, in which the available (VR) tools are exposed and can be addressed as utensils in a toolbox (figure 2). In order to make optimal use of the lab, the following aspects should be taken into account, and should also be reflected in the composite approach:

- Hardware
- Software
- User
- Environment
- Information
- Knowledge
- Methodology
- Resources
- Working methods

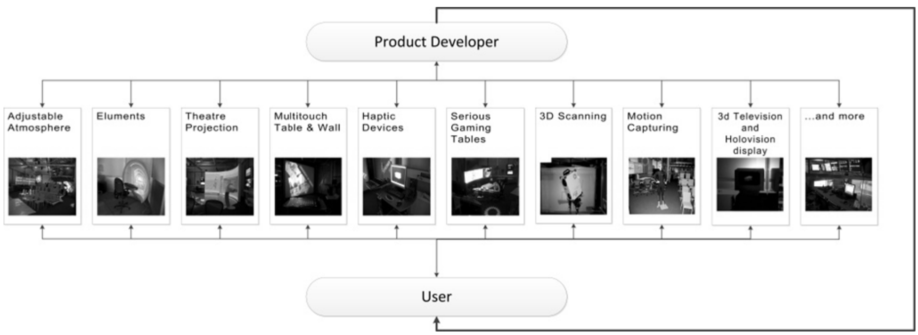

Fig. 2. Selection of multiple VR tools

The combination of the abovementioned methodology, the Virtual Reality lab and the set of stakeholders together constitute a so-called Synthetic Environment (SE). This artificial environment represents an alternative reality, which acts as commensurable to a real environment as required. To allow for natural behavior, enabling intuitive use, the interaction possibilities provided in the synthetic environment correspond to real world interactions as adequate as is appropriate. This alternative reality uses both virtual and augmented reality techniques to allow the various stakeholders to interact with it (e.g. make adjustments to it) in a way that is easier, more transparent, more purposeful and more controllable than in reality, while requiring less effort. This makes it possible to quickly evaluate multiple configurations, and also to review the consequences of possible choices. A SE can be adjusted while it is in use in real time and it therefore allows stakeholders to deal with design information in an interactive way. Therefore, it is easier to evaluate features and experiences under a wide variety of circumstances. As a result, the stakeholders become more conscious of their decisions and the related interdependencies. This is mainly because the information is presented to every stakeholder in an understandable format/way that is independent from the stakeholder's background or expertise.

These SE's prove their usefulness best in development processes of new or complex products, involving many stakeholders with various backgrounds. They can be used in nearly all phases of development processes; especially in the early stages SE's may well help to describe current and future scenarios.

The main characteristics and objectives of SE's are to ensure validity of decisions by using realistic interactions, to simulate effects in a familiar context in order to achieve a realistic image of the future environment, and to present corresponding images of future situations to facilitate negotiations about consequences of their characteristics [2].

In summary, Synthetic Environments can be depicted as well-considered compositions of possible future environments, used to give more insight into the consequences of the choices in such compositions. To enable stakeholders to experience this environment as veracious as possible, extensive use is made of virtual and augmented reality technologies. Bringing such tools to industrial practice becomes increasingly relevant, as the cost of hardware and software tend to decrease. Therefore, the ability to use SE's in smaller companies increases continually.

3 The VR-Lab as a Synthetic Environment

As with every workshop, the end result that can be achieved depends on the craftsmanship and expertise of the people using it; therefore, it is essential to adequately align the users' requirements, functional specifications and capabilities with the appropriate configuration of the lab and its tools. In other words, no fixed configuration can cater for all approaches, but a flexible and modular set of equipment can allow for quick creation of new settings.

The basic approach, as mentioned in the previous section, leads to an atmosphere in which initially a conjoint view of the problem, its setting as well as a better understanding of dependencies between all stakeholders is realized. From that systematic beginning, solution paths can be explored effectively and efficiently by employing working methods and tools in the lab. It is without doubt that the development and realization of a Synthetic Environment requires extensive preparation in order to effectively provide substantial and useful results. This preparation often is a cooperation between designers who want to use a SE, and the host of the facility that can provide the environment.

3.1 Approach

The flexible layout and composition of the VR-lab provides capabilities within a wide variety of projects. However, this flexibility of the configuration needs clear principles as concerns the composition of attributes. Given the comparison of the lab with a workshop, it is important to adequately address the preparation in the selection of elements that together will constitute an SE. In itself, the lab is not an automatic solution generator, but it can be a facilitator to make effective and efficient use of the expertise of all attendees. In this respect, it is important to distinguish between the three categories of aspects that together constitute the SE [3], as illustrated in figure 3:

- Techniques; new techniques allow for new possibilities to acquire or present data.
- Tools: techniques can be used and combined in virtual reality tools to make them applicable in a specific scenario.
- Solutions: in combining multiple tools, a virtual reality facility is created.

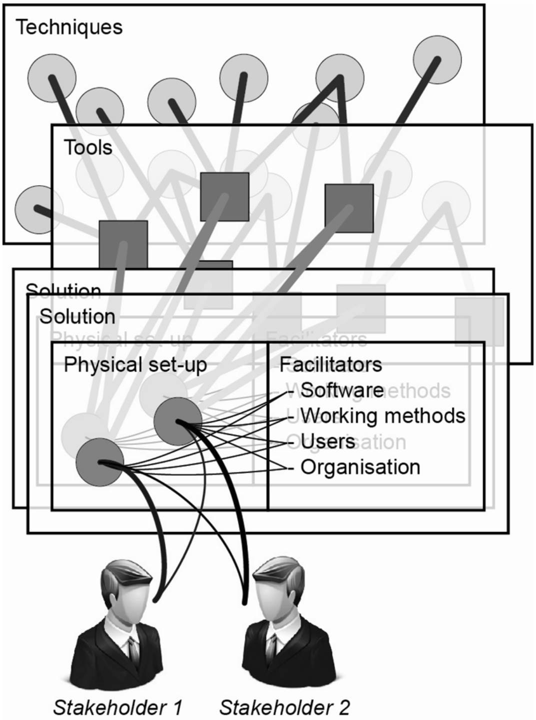

Fig. 3. Relation between techniques, tools and solutions

In order to properly prepare for the usage of a SE, it is necessary to determine on beforehand what the conditions are as concerns the desired goal, but also as concerns the technology used. Furthermore, the initiation of the desired use and the dependencies of the different stakeholders should be available on beforehand.

To be able to make optimal use of the VR-lab as a SE, it is essential to communicate the characteristics of such an environment with future users. From the perspective of the facilitator, it is important to get the right information from the future users, but that information can only be given by those users if they understand what added value a SE can have for them. This preparation should therefore be organized in such a way that the appropriate information is gathered from the prospective users in a structured way so that the data can directly be used by the facilitator to assemble the environment. This is essential to make it possible to combine the right tools based on the desired goal.

In order to prepare the assembly of a Synthetic Environment, and to communicate and explain the possibilities to potential future users, a roadmap is used as a communication and library tool [4], [5]. The roadmap is a guideline for the consulting process between the facilitator and the potential user; it guides both in determining what information is needed to execute the process and defines how the information is, or should be, interrelated (figure 4). Furthermore, the roadmap provides a blueprint on how to structure all the information generated in the start-up phase. Additionally, it provides an overview of the current state of preparation.

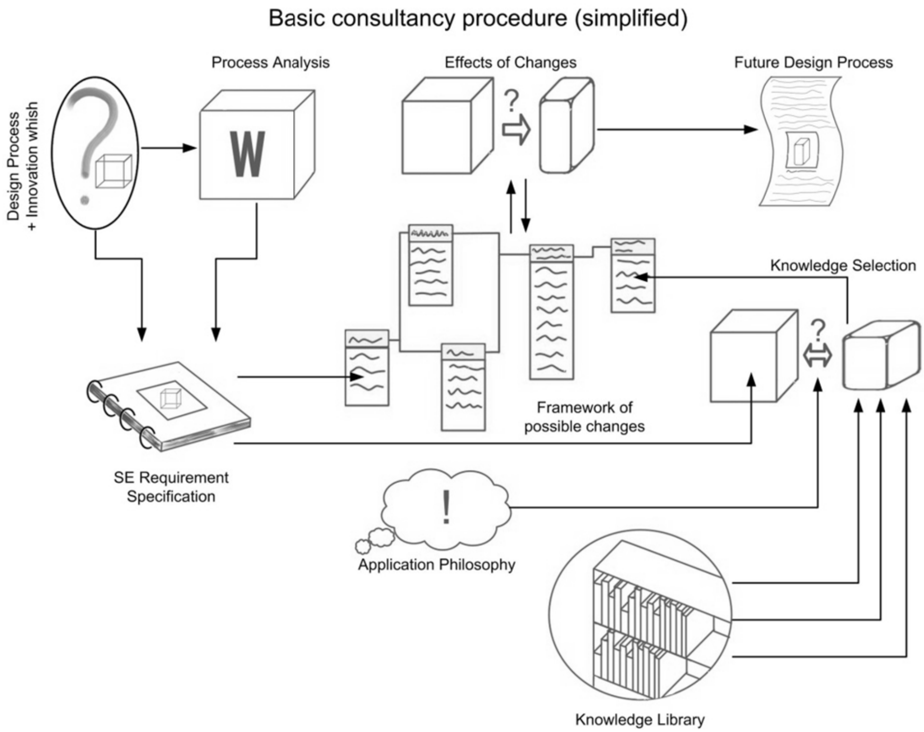

Fig. 4. Blueprint for developing and using a SE

4 Projects

Over the years, the VR lab has served as facilitator of Synthetic Environments for a large variety of projects in several phases of development. It is in the diversity of the projects that the flexibility of the use of the lab is evident. The diversification includes the number of stakeholders involved, the phase of the project, the equipment and the time required. But especially the content and objective of such projects is never the same, and does not allow for a one-to-one copy to other projects. Although the focus of the VR-lab is mainly on product development processes, it often shows that the methodology and approach is also applicable to decision-making processes in general. The core value mainly lies in the support of multiple stakeholders in creating and balancing multiple choices/decisions.

The researchers of the VR lab perceive clear similarities in the way of approach for the different projects. Because different devices and techniques are used in multiple ways, the VR-lab is a good example of a facilitator for SE's. Since the lab contains a selection of commercially available and custom made hardware and software, combinations of hardware and software that are frequently used together gradually emerge as a kind of higher-level building blocks. Every combination of VR-lab equipment and intended use in a SE allows the researchers to assess how successful the combination is or if the combination proposes any challenges. In any case, the gained experience provides input for use in future projects. In addition, during project execution, demands for adjustments and additions to the SE can be addressed. For example, additional support may be necessary in the process, which provides directions for new equipment or methods that need to be developed or purchased in the near future.

Not only the results of composing a SE often shows parallels for the researchers of the VR-lab, also the similarities in the underlying activities in establishing the SE provide ample guidance. To optimize stakeholder involvement in this, it is important to make good use of dedicated roadmaps. This makes it easier for each stakeholder to indicate and clarify the goal of the process, and makes it easier for the facilitator to come up with the most appropriate configuration of equipment, software and working methods. In addition, it gives all parties a sense of suitability and therefore brings more confidence in the choices of support and feedback methods in the environment. The roadmap simultaneously is the checklist and the guideline for the arrangement of a SE.

Future projects of the VR lab focus more on integrating different types of data/information sources. This not only results in increased integration of different types of documents, images and simulations, but mainly in using multiple types of 3D models in the environment. In addition to static virtual 3D models, the use of dynamic 3D models is explored and exploited, even in combination with e.g. tactile and haptic models. In addition, the possibilities of integrating multiple research disciplines during the exploitation of an SE are expanded. During the development and assessment of a product or environment, more information can be obtained about the potential risks, the expected maintenance costs, life cycle analysis or guidelines for suggested improvements.

In addition, the integration of 3D projected images, such as holograms, will be expanded further. The introduction of such new techniques that make it possible to view voluminous 3D models with multiple stakeholders at the same time from different angles provides easier understanding of future products and environments. As such, the transition from virtual to real, and vice versa, will gradually dissolve.

5 Conclusion

Using the VR-lab as a flexible toolbox has the inherent consequence that there is a continuous need and possibility to add new or improved tools. On the one hand this may seem to hamper the trouble-free employment of SE's in everyday practice, but more important, it also provides insight in what is expected in future tools. After every single project in the VR-lab, the design and implementation of the preparation roadmap is extended and improved, and is better aligned with the experience gained. Also, the range of available (VR) tools is constantly increasing, whereas the price of hardware and software is decreasing. This ensures that the use of Synthetic Environments for smaller project groups increasingly comes within reach. Simultaneously, it allows the VR-lab to be applicable and useful for a wider audience. The experiences of previous projects in the VR-lab also challenge the researchers to define more general implementable tools; at the same time it offers more opportunities to customize and personalize them before or even during use.

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A Tool Proposition to Support Multidisciplinary Convergence in Immersive Virtual Environment: Virtusketches

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Abstract. Companies need to improve product use value thanks to ergonomics integration into product design process. This could be achieved by collaboration between ergonomists and mechanical designers. However, these actors have different methods, representations and tools making difficult to carry out the convergence between them. Thus, the aim of this paper is to introduce a new tool, Virtusketches, to improve communication between ergonomists and mechanical designers during convergence phases of a human-centered design process. Virtusketches is based on linking virtual reality (VR) technologies with 2D sketching and annotation as a tool that could be used by all the actors involved in design process regardless of their specificity. A case study is presented to test the tool during a convergence step of an automotive design project.

Keywords: Product Design Process, Collaborative Engineering, Ergonomics Integration, Intermediary Objects, Virtual Reality, 2D Sketching.

1 Introduction

Nowadays, innovation is a key driver to improve competitiveness and business performance in industrial companies. This innovation could be achieved by considering use value into product design process [1]. Indeed, use value is a component of the product global value. Recently, it became a product differentiation factor in the market.

Ergonomics is one science dealing with use value. It applies information about the human behavior, skills and limitations in the product design. Hence, ergonomics integration into product design process is one way to improve product's use value and consequently product's competitiveness [2]. In this context, Broberg has defined three approaches to integrate ergonomics into product design process [3]. In the first approach, ergonomics integration could be done by transferring ergonomics knowledge and skills to engineers. To this end, several solutions could be found such as the ergonomics experts systems [4]. The second approach focuses on organizational factors.

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For instance, in this approach, the role of the ergonomist as a member of the design team during design process can be enhanced; an ergonomist can take the role of an expert, a facilitator [5], a political agent [6] or a political reflective navigator [7]. The third approach focuses on the extra-organizational factors. These are factors outside the organization as the regulatory aspects (e.g. European Union's directive on machines).

In accordance with the second approach of Broberg, we focus our work on the collaboration between ergonomists and mechanical designers for integrating ergonomics into product design process. This collaborative work is mainly achieved during successive iterative convergent phases of the design process. Indeed, convergence is considered as an activity that relies on exchanges between different actors concerning several design alternatives. However, ergonomists and mechanical designers have different intentions, backgrounds and circumstances making it difficult to carry out the convergence between them [8].

Thus, the aim of this paper is to introduce a new tool, Virtusketches, to improve communication between ergonomists and mechanical designers during convergence phases of a human-centered design process. This tool is based in the fact of linking VR technologies with 2D sketching and annotation as a tool that could be used by all the actors involved in design process regardless of their specificity.

2 Multidisciplinary Convergence

The overall design process is convergent, but it contains phases of both divergence and convergence [9]. While the objective of divergent phases is to generate several ideas and solutions to solve the design problem, the objective of convergent phases is to reduce the number of proposed solutions and to lead to one detailed solution.

Convergent phases are considered as phases of exchanges and argumentation between different actors concerning several design alternatives in order to reach a satisfying joint decision. During these phases, the actors transmit, communicate, propose, criticize and share ideas like they are in a kind of debate. Each actor has his/her own viewpoint based on his constraints, objectives and experience. These viewpoints have a dynamic nature. They evolve during convergence phases through social interactions and communications between actors who are trying to reach a joint decision [10]. Three levels of convergence can be defined. The first level is the convergence about the objectives. In this level, formulating the problem of the design is necessary to subsequent ideas generation into design process. A well-defined problem is half solved. A good strategy to define a problem is to consider it from multiple viewpoints that may reflect the interests of different actors [11]. The second level is the convergence about design alternatives. The different alternatives need to converge on one choice of design that satisfies the different actors. Additionally, we propose a third level of convergence which concerns the evaluation of the design. It is clear that convergence in the higher levels is more important and has more impact on the product design than lower levels (fig.1).

This paper focuses more precisely on convergence between ergonomists and mechanical designers. However, these actors have different methods, representations and tools making difficult to carry out the convergence between them [8]. Moreover, everyone is attached to specific profession and, consequently, attached to a specific lexical field and vocabulary. One word could be very precise and have a specific and one meaning for one expert but will be totally confuse and imprecise for another expert working in another field [12]. This fact sometimes leads to a lack of information and to language barrier between these actors. It can also lead to some bad decisions and mistakes during design process.

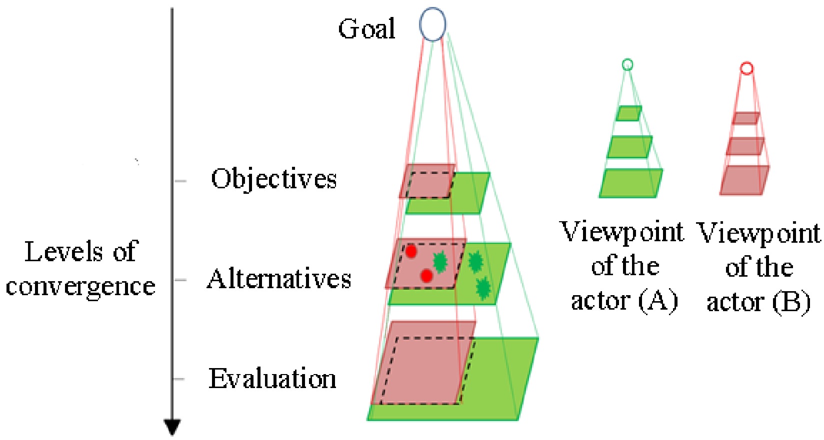

Fig. 1. Three levels of the convergence into product design process adapted from [10]

Thus, ergonomists and mechanical designers need to support the communication and, consequently, convergence between them. In this context, a lot of researches highlight the importance of Intermediary Objects (IOs) into product design process and more specifically in the development of collaborative work.

3 Intermediary Objects (IOs)

A key dimension of collaborative design is the use of IOs. They include all artifacts, whether physical (mock-ups, sketches, etc.) or virtual (CAD models, calculation results, etc.) produced by the actors during design process. In other words, they cover all kinds of externalization and they circulate between actors involved in the product design process [8]. These artifacts represent a part or the whole characteristics of product's identity (functions, form, materials, constraints, etc.). Furthermore, they constitute the traces of design activities carried out by the actors. IOs contribute to the construction of a compromise and the sharing of common knowledge between the actors. Moreover, they ease shifting their viewpoints during convergence phases. That is to say, IOs act as mediators into product design [13].

More interestingly, Star and Griesemer [14] introduce the notion of Boundary Objects (BOs). These objects are located at the intersection between different heterogeneous social worlds. They maintain coherence across these worlds. In the context of participatory ergonomics, Broberg identifies eight characteristics of boundary objects [15]. For example, they have to be objects- in-the making and built-in affordances as will explained later.

However, the notion of IOs is often confused with the notion of BOs. Vinck [13] indicates that IOs don't necessarily have the characteristics of BOs. In some cases, IOs contribute to the articulation between heterogeneous social worlds. In fact, IOs becomes BOs when they are equipped with a common structure between these different worlds [14]. This structure can be found by integrating BOs' characteristics proposed by Broberg in the development of IOs into product design process.

4 Virtusketches: A Tool to Support Multidisciplinary Convergence

4.1 Problematic and Objective

Virtual reality (VR) is a recent technology which is used into product design process. It allows immersion in virtual environment (VE) [16]. So, actors can visualize and manipulate VR mock-up in relief and in an intuitive way. Moreover, VR allows actors to interact with VR mock-up in real time. Actors can also test some scenarios of using the product. Considering all these advantages of VR, this paper focuses on the fact of using VR mock-up as BO to support collaboration between ergonomists and mechanical designers during convergence phases of product design process. In this context, project reviews are conducted around VR mock-up in VE throughout convergence phases [2]. The primary objective is typically to ensure the design is in conformance with its requirements with a secondary objective of highlighting potential deficiencies in the design as viewed by the various actors [17]. Face to face communication between actors is conducted during this virtual design review to reach a compromise and joint decision concerning some alternatives of design. However, despite all the possibilities of immersion and interaction offered by VR mock-up, collaboration and communication between actors, especially between ergonomists and mechanical designers, remains difficult. More precisely, these actors need an intuitive support of action on VR mock-up to express their intentions and to explain their ideas and argumentations to other actors [18]. Furthermore, the need to obtain traces of actors' activities during project review is highlighted to support the next design phases. These needs could theoretically be justified by BO's characteristics proposed by Broberg [15]. Indeed, Broberg indicates that BOs are objects- in-the making and built-in affordances. They are not ready; they need to be created by the actions of the actors during the project review. In other words, all actors should have the possibility to act on the BOs. This clearly is linked to the notions of open objects and closed objects [19]. Closed objects only transfer some information from one actor to another actor. For example, CAD drawing may transfer some information from the designer to the ergonomist; but the ergonomist is not able to modify it. On the opposite, open objects offer the possibility of action to all actors. This possibility will help to increase the power of their ideas and make them clearly understandable by everyone involved in the design process.

Thus, our objective is to offer to actors the possibility of action on VR mock-up during design review in VE. This should improve the communication and hopefully the collaboration between these actors.

4.2 Linking VR Technology and 2D Sketching

Sketching is a powerful means of interpersonal communication [20]. It consists of the production of quick and messy intuitive drawing of actors' idea. It provides not only a mean for representing mental images of actor's ideas but also a way to facilitate the actual generation of such mental images [21]. That is to say, the activity of sketching stimulates creativity in design thinking. Moreover, self-made sketches also support the limited human memory capacity and mental processing for a detailed problem analysis [22]. In addition, annotations play a major role in design coordination and knowledge elicitation in asynchronous phases, and an important cognitive synchronization role during synchronous phases [23]. They can foster knowledge creation and participate to the development of shared understanding among the design team [24].

Virtusketches is a tool based on the fact of linking VR technology to 2D sketching and annotations. More precisely, we propose to complete VR techniques with 2D sketching and annotations as a tool that could be used by all the actors involved in the design process regardless of their specificity. This will transform the VR mock-up into open object on which every actor can act.

4.3 Tool Description

As already mentioned, the objective of this work is to provide the actors with a design supporting tool which can be used in VE during convergence phases into product design process. The goal is to integrate the benefits of 2D sketching and annotations into the benefits of VR technology. The conjoint use of Virtusketches should enable the actors 1) to act on the product design and 2) to ease ideas confrontation. This tool should ease exchange ideas between actors through sketches over recently captured photos of the VR mock-up during project review in VE.

To implement Virtusketches, we use a virtual reality platform composed of 3 active stereoscopic screens (2.10m * 2.80m) (fig.2-a). To manipulate VR mock-up and to capture actor's viewpoint in VE during project review, Wii (Nintendo®) Remote Controller is used. An Ethernet network is implemented between virtual reality system and a sketching pen tablet (fig.2-b). A remote monoscopic screen of the immersed actor's viewpoints is used. This remote view allows non-immersed actors who are out of the VR platform to obtain a non-distorted view of the immersed actor's viewpoint (Fig.2-c). VR software (Virtools) is used to develop VR application on the VR platform. To sketch on the captured photos by the pen tablet, Autodesk SketchBook Designer software is used as user interface.

One typical use case of our tool would take place during project reviews. In this scenario, one of the actors visualizes, manipulates and interacts with the virtual mock-up in VE. If this actor finds improvements, faults or ideas to express and communicate with other actors, he or she can capture his or her VE viewpoint like a snapshot which will be directly transferred on the sketching pen tablet. After that, this actor can express and communicate his/her own intention to the other actors by sketching and annotating his/her captured viewpoint thanks to the pen tablet. The other actors may also participate in sketching and annotating the captured viewpoints. Then, the sketched and annotated captured viewpoints can be displayed and hidden on VR platform during the project review. This process is iterative until reaching convergence between the actors.

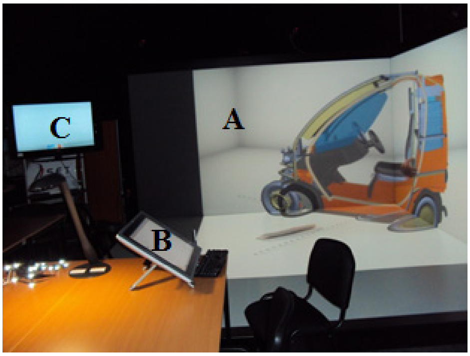

Fig. 2. Virtusketches a support tool of collaborative work: (A) VR platform. (B) Sketching pen tablet. (C) Monoscopic screen.

5 Case Study: Ergonomics-Mechanical Design Convergence

5.1 Context of the Study

In order to test Virtusketches as a tool that supports the convergence, it was used during a convergence phase of an automotive design project. MobyPost is an ongoing project that aims at developing a whole system combining a carbon neutral vehicle with a novel technology based on a solar hydrogen fuel cell system. In this context, a hydrogen vehicle for postmen is being designed. The project is conducted by nine partners; one of them is the SeT laboratory (laboratoire Système et Transport). The objective of SeT laboratory is to develop a vehicle adapted to some specific needs of the postmen (i.e. considering ergonomics aspects) with the respect to technical functions of the vehicle (i.e. considering mechanical aspects).

This paper presents a project review which was conducted using Virtusketches in VE. The actors who participate in this project review were one ergonomist, 2 mechanical designers and one industrial designer. The objective of this project review was to achieve a consensus about powertrain accessibility for maintenance and the design of the vehicle's cockpit. Indeed, ergonomics constraints play a critical role in the current vehicle design. For instance, one of the major constraints concerns the fact that postmen get in and get out of their vehicle about 350 times per day. Ergonomics, thus, want to consider this in the design of the vehicle's cockpit.

5.2 Procedure

Some actors involved in this study had no previous experience with the VR project review and the manipulation of the VR mock-up. So, a familiarization phase was conducted. By the end of this phase every actor has to know how to: 1) turn the VR mock-up and change its scale to check some details; 2) turn around the VR mock-up and even enter it; 3) use a ray to indicate or to select some parts of the vehicle; 4) hide and display a previous mock-up of the vehicle to compare it with the new mock-up. 5) Hide and display a virtual human in the vehicle, the reach zones and the vision zones; 6) take a photo of their viewpoint in the VE; 7) sketching and annotating their captured viewpoint on the sketching pen tablet; 8) hide and display sketched and annotated viewpoint in the VE.

Each actor's contribution was colored differently (using a specific color on the pen tablet). This enabled to follow the traces done by every actor. Moreover, 2 roles were defined for actors in the VE:

- The first role is the role of immersed actor. In this role, the actor leads the interaction with VR mock-up in the VE and he can visualize VR mock-up in relief. He can also capture his own viewpoint in the VE and then sketch and annotate his/her intentions on the pen tablet.
- The second role is the role of non-immersed actor. In this role, the actor discusses and communicates with the immersed actor and with the other non-immersed actors. Sometimes, he can be near the immersed actor on VR platform (with quite distorted viewpoint) or he can also visualize the immersed actor's viewpoint on the monoscopic screen. He can participate in sketching and annotating the captured viewpoint.

The change between the roles of these actors has to take place in a dynamic way. Every actor can take the role of immersed actor when he wants. The documentation provided to actors was the PDS document (Product Design Specifications) which provide information such as functions and design constraints. However, the actors during this project review were focusing on the cockpit's specification and the powertrain's specifications. Actors were provided also with an assembly drawing that showed the principle dimensions of the vehicle. The project review was recorded by two video recorders; one was oriented towards the VR platform and the other was oriented towards the pen tablet. The participants in the study were then interviewed about the used tool after the project review.

5.3 Study Results

Following the project review, semi-structured interviews were conducted with the various actors who participate in the study. These interviews permitted to gather a qualitative feedback from the different actors concerning the use of Virtusketches during the project review. The experience feedback from using Virtusketches was generally positive. All the actors appreciated the possibility to act on vehicle design by sketching and annotating on their own captured viewpoint.

Virtusketches allowed the ergonomist to visualize the vehicle on the real scale. He had the possibility to validate the dimensions of the different parts of the cockpit by displaying the virtual human, the reach zones and the vision zones. He could also take the place of the driver on a physical seat in VE for testing the ease of ingress and egress out of the vehicle. It was possible to expect the use of the future vehicle by experiencing the gestures and postures of the driver on VR platform. Virtusketches enabled the ergonomist to express his ideas by sketching and annotating on his captured viewpoints. He felt more confident to suggest ideas and to express his intention without using technical terms normally used by mechanical designers. However, the sketches provided by ergonomist were simple and it was sometimes necessary to develop it by the industrial or mechanical designers who had experience in advanced sketching.

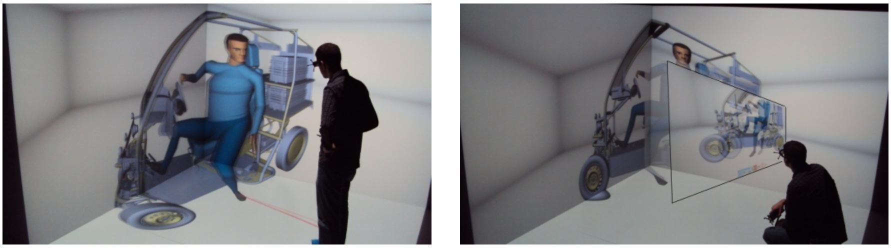

Fig. 3. The ergonomist visualizes the vehicle with the virtual human (left). The ergonomist takes a snapshot to his viewpoint (right).

Virtusketches allowed the mechanical designers to validate some mechanical specifications (e.g. the possibility of fabrication of some parts of the vehicle). It helped them to argue and to clarify their design choices to the other actors. By sketching and annotating the captured viewpoint, they could illustrate some ideas to other actors. However, mechanicals designers highlighted the need for some CAD functionalities in VE (e.g. the need to hide some parts to see the interior parts and the need to intersecting planes).

The industrial designer was very satisfied with the access to his traditional techniques which is 2D sketching. He also appreciated the possibility to capture his own viewpoint in VE. As the ergonomist, VR provided him the perception of the real dimensions of the vehicle.

The immersed actor could access to the sketched and annotated photos in the VE. All the actors think that Virtusketches tool helped them to facilitate the communication and consequentially convergence between them. However, due to some technical limits of VR platform, only one immersed actor could be on the VR platform. The actors wanted to discuss together on VR platform around the VR mock-up.

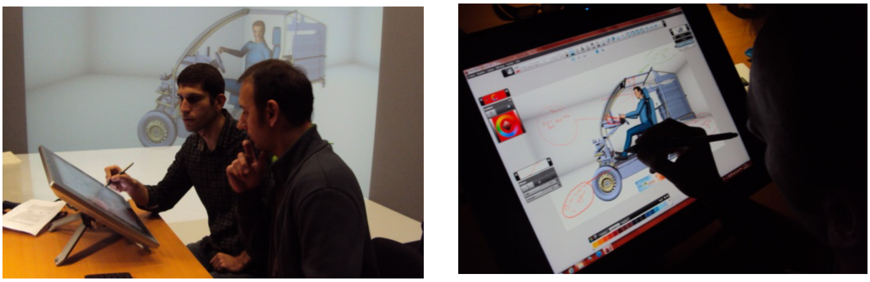

Fig. 4. The ergonomist explains his idea by sketching on the captured viewpoint on the pen tablet

6 Conclusion and Future Works

Collaboration between ergonomist and mechanical designers is one approach for ergonomics integration. In a collaborative work, it is necessary for these actors to communicate during convergence phases such as during project reviews. However, this communication is difficult due to the difference in their backgrounds, methods, and even in their vocabulary. Thus, relying on a literature review about Intermediary Objects (IOs) and Boundary Objects (BOs), this work presented Virtusketches as a support tool to ease communication between actors during convergence phases in VE. Virtusketches is based on linking VR technology with 2D sketching and annotating. It grants the actors the possibility to act on the product design turning VR mock-up into an open object. In order to test Virtusketches, a case study was presented during a project review of an automotive design project. Semi-structured interviews with the actors showed that the feedback concerning the use of Virtusketches was generally positive. The ergonomist was more confident and could more easily express his ideas to the other actors. Virtusketches also helped mechanical designers to clarify their design choices. The industrial designer was satisfied with the access to his traditional techniques of work which is 2D sketching.

These first results are essentially qualitative. Our future work will consist on conducting a quantitative evaluation of the proposed tool. Moreover, the impact of Virtusketches on the work of industrial designer will be more studied.

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A Visual Language for the Collaborative Visualization of Integrated Conceptual Models in Product Development Scenarios

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Abstract. In various industrial and scientific fields, conceptual models are derived from real world problem spaces to understand and communicate containing entities and coherencies. Abstracted models mirror the common understanding and information demand of engineers, who apply conceptual models for performing their daily tasks. However, most standardized models in Process Management, Product Lifecycle Management and Enterprise Resource Planning lack of a scientific foundation for their notation. In collaboration scenarios with stakeholders from several disciplines, tailored conceptual models complicate communication processes, as a common understanding is not shared or implemented in specific models. To support direct communication between experts from several disciplines, a visual language is developed which allows a common visualization of discipline-specific conceptual models. For visual discrimination and to overcome visual complexity issues, conceptual models are arranged in a three-dimensional space. The visual language introduced here follows and extends established principles of Visual Language science.

Keywords: Visual Languages, Product Lifecycle Management, Collaborative Engineering.

1 Introduction

With the division of work into specializations, collaborative scenarios have gained increased relevance in many disciplines and are indispensible in modern product manufacturing scenarios. Achieving consensus between local (inner domain issues) and global (cross domain coordination) are considered a major challenge [1].

Commonly, conceptual models (CM) are created to pervade and understand problem domains for analysis, optimization and communication tasks. This has led to standardized or de-facto standardized CMs for singular disciplines like BPM (BPMN, BPEL), ERP and product Construction (STEP) which are used to formalize and

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exchange information based on standardized definitions. Much effort has been conducted on the modeling process in order to derive a consistent and complete abstraction; however, less regard has been given to a sound visual representation of CMs. Most discipline-specific CMs do not provide a distinct, specified notation for entities and relationships. Those which provide designated notations like BPMN are criticized regarding their usability [2], [3]. Visual Language Theory proposes generic principles and guidelines for sound and understandable notations on the basis of information visualization and cognitive science.

Established models in science and industry are optimized for capturing knowledge of a singular discipline; however there is a trend to apply more holistic approaches in information management. Systems Engineering and Product Lifecycle Management address cross-cutting concerns with holistic information management strategies. Yet, notational aspects are not focused by these disciplines, although Systems Engineering provides a UML-derivative, namely SysML [4] for notation. Notably, Visual language science-based critiques of the notation paradigms in UML indicate that requirements for usability with UML are not fully met [5], [6].

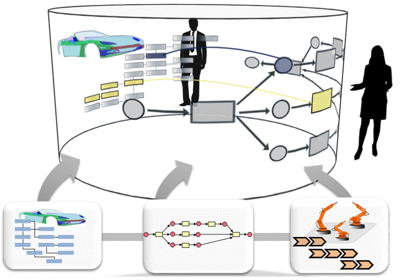
The targeted field of application of the work introduced here is a common visualization of conceptual models to support direct communication processes between experts from several domains. With a common and integrated visualization, overlapping concerns and dependencies between CMs should be made transparent for users. For this purpose, a visual language definition is developed to display integrated CMs from several disciplines within one common display. The definition follows rules and principles from the discipline of visual language theory. To overcome the visual complexity arising from the number of discipline-specific CMs displayed together, we introduce space as a visual variable to display relationships between CMs.

This paper is structured as follows: firstly, the context and proposed application of this concept is introduced by presenting concrete use-cases. On this basis, related scientific and industrial concepts for CM integration and Visual Language development are analyzed and explained. In the following a visual language definition is introduced which is capable to support a common visualization of discipline-specific models.

The work introduced here is developed in scope of a research framework of the Institute for Information Management in Engineering at Karlsruhe Institute of Technology.

Context and Environment of Application Scenario

The application scenario of this research is characterized by decision making processes which impact several disciplines. Various tasks in product development require participation and coordination of several disciplines. Product design decisions would most certainly influence related manufacturing processes and related resource management. Alternations of a manufacturing process might require adaptations of the product design. Following these examples, coordination and collaboration issues between disciplines must be resolved to achieve optimal design solutions with reference to all related fields. In direct communication, processes experts in their respective fields have to negotiate agreements to cross-discipline issues. Therefore they must communicate their discipline-specific knowledge, formalized in their conceptual models to colleagues with a different background. The differing backgrounds of stakeholders, manifested in nomenclature and semantic constructs of their models, has to be resolved during the communication process. In order to support and expedite communication, a common visualization of the conceptual models is proposed. With a visualization of the major elements from each discipline and a link to corresponding entities in other disciplines, communication should be eased as dependencies are visually transparent. In addition, the work presented further develops a conceptual framework addressing collaborative scenarios for manufacturing process optimization [7], [8].



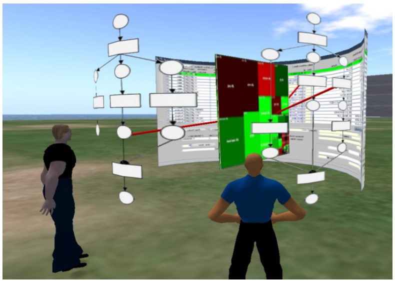


Fig. 1. (left) Vision of common visualization of conceptual models, showing an immersive cylindrical visualization of multiple models; (right) Mock-up of a Petri-net based Process visualization within the framework.

Common use-cases for the targeted platform are characterized as decision making with impact on several disciplines. Typical examples are Make-or-Buy decisions during manufacturing process planning. Action alternatives for procurement or in-house production would impact on product design and construction, the manufacturing process as well as resource management. The procurement of components might require alternation of the product structure and design for integrating purchased components. The manufacturing process would require adoptions for assembling the components. This would further on impact resource application.

A concrete example considers a decision making process in the branch of solar manufacturing devices. The decision considers procurement or self manufacturing of the mounting. The decision alternatives influence the product design as the connector between solar panel and mounting device might need adaption. The manufacturing process is influenced by varying process sequences for the manufacturing and consequently a different application of resources.

To identify an overall optimal solution, communication and compliance between all concerned disciplines is required. A common visualization of integrated conceptual models could support the communication process, because the dependencies and impacts of each alternative would be transparent. Each discipline expert would have a specialized model for conducting the issue in his CM, whereas the dependencies to the other disciplines are visible. This should avoid misunderstandings as participants have visual support about the artifacts in the models affected by the decision.

2 State of the Art und Related Work

The activity of conceptual modeling results in a formalization of the aspects of a problem domain with an explicit description of entities of interest, their properties and relationships with the purpose of communication support and to provide a thorough understanding of the problem domain [9].

Referring to General Model Theory by Stachoviak [10], Conceptual Models (CMs) are derived from reality following the paradigms of “Reduction” (consider relevant entities and properties), “Pragmatism” (specific purpose of the model, factor for the selection of entities) and “Projection” (mapping of real world concepts and relations to the model). In industrial production scenarios there are standardized and de facto-standard conceptual models for capturing and exchanging knowledge of disciplines. A common standard on which most proprietary and open PLM systems are oriented is STEP, catalogued as ISO norm 10303 [11]. Process Management applies a conceptual model for activities and arrangements of activities. Standardized models in process management differ in executability, power of expression and visual representation. Enterprise Resource Management (ERP) is a concept for effectively managing human, financial and production related resources of an enterprise. In opposite to standardization of BPM and PLM, ERP information is formalized in de facto-standard models, commonly following major system developers. The awareness of a need for discipline-spanning approaches is evident in implemented methods and systems in PLM and ERP to support cross domain collaboration with holistic information management strategies; however integral visualization is not proposed by neither of them. Visualization of product data and process information is implemented in separate windows of an application or within a sectioned common diagram. Approaches lack of visual means for showing interconnection properties.

A widely followed approach in Visual Languages (VL) design research is to create an analogy to spoken or theoretical languages. Visual syntax and sentences function as generic elements from which Visual Languages are composed. Graphic primitives are considered as language terminals which are used to form visual sentences. Language terminals or variables are the most primitive visual means used to express and distinguish semantic entities in the underlying model. A catalog of basic notations, enumerated as visual variables is described by Bertin [12].

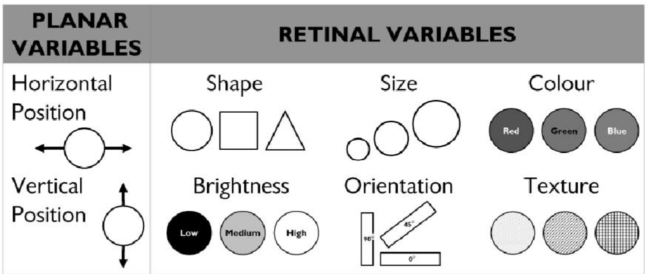


Fig. 2. Visual Syntax elements defined by [12], [13]

A general but very detailed description of notation concepts is presented as the "Physics of Notation" by Daniel Moody [13], [2]. Cited approximately 140[1] times within the last three years it continues to receive increasing recognition. The "Physics of Notation" (PoN) summarizes and integrates criteria and principles for developing visual languages representing conceptual models. In his research, he critically engages with current notations in technical areas like software engineering or process management and points out the demand for a scientifically rigorous analysis of VLs. In VL research, there are a number of approaches to define criteria for CM visualization focusing mainly on cognitive aspects of perception and understanding. Although the PoN principles are not empirically validated, they are scientifically and theoretically well constituted. The basis of the principles in line with acknowledged approaches of visual language research [2], [14], explicitly the Cognitive Dimensions Framework [15], [16]. The principles are introduced based on standardized visual languages like UML [5] and BPMN [3]. For the visual language proposed here, the PoN principles are applied because of their scientific and theoretical validity. There is no distinct method for measuring the extent to which the criteria are fulfilled. The principles are formulated to be both principles and evaluation guidelines and should not be interpreted as absolute laws but guideline to the VL definition process. The principles consider both visual (perceptual) and cognitive aspects regarding understanding.

PoN principles are applied to the interconnections between entities of different CMs and are not fundamentally different as the general demand for understandability and distinctness is of great importance in the cross-domain representation, too. The aggregation of CMs does not introduce fundamentally different constructs, except for the higher complexity. This demands a more thorough and balanced application of PoN principles to both CM specific visualizations and CM-spanning elements.

3 A Visual Language for Integrated Conceptual Models

In order to develop a visual language definition to display a set of related conceptual models, methods must be applied to establish the connections between the concepts. The general issue of information integration is widely extensively researched and although not yet fully solved, there are numerous promising industrial and scientific approaches to solve this issue [17], [18]. Scientific approaches differ in structural and semantic information model heterogeneity. In order to provide sound and correct integrated models for the use case of decision making, the semantic integration as the highest level of information integration is pursued [19]. Therefore established approaches from the field of knowledge management namely ontological based approaches are applied, namely an ontology based integration based on Bunge-Wand- Weber ontologies [20]. In scope of this work, a semantic based integration between entities of regarded information models is assumed. This results in direct interconnections between entities of several conceptual models. The relationships are assigned a type which expresses the characteristics of the connection.

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[1] According to Google Scholar, `http://scholar.google.de/`

3.1 Visual Language Principles

Previously described Physics of Notation principles are proposed for notations of singular CMs. The principals are applied to the common visualization of related conceptual models. This demands an extension of the visual variable set used for singular models. The repertoire of visual variables is used in singular models. Although not all variables are commonly applied, there are no reserved variables, as the regarded models do not provide a distinct notation though their notation is (de-facto standardized). Therefore it must be assumed that the full set of visual might be applied in any of the models regarded. The semantic concepts which are displayed with the visual variables used in the individual models demand however an obvious distinction for users.

To stick to the common notation and support with familiar notation, the visual syntax element "Shape" should not be used for distinguishing CMs, as this would result in a *"symbol overload"* [2] as the same visual discriminator would be used to distinct inner CM concepts and CM as a whole. Constraints for VL development are summarized as follows:

- The discipline identity must be retained and visually transparent
- A high recognition capability for discipline specific models must be given
- The visual complexity must be balanced against the need for completeness of visualization.
- Discrimination of discipline-specific models

Visual discrimination of differing discipline models is essential for users. The assignment of concepts to their CM has to be distinct and visual. In given constraints (reserved visual variables) the discipline models are be color-coded. Colors are not applied in standardized notations and can therefore be used for discriminating models. Furthermore color coding for distinction is a powerful visual means [21]. Each discipline is assigned a designated color to be used for all other visual variables of the model. The principle of *Semiotic Clarity* with a distinct mapping between color and discipline is thus fulfilled by a single discipline color allocation. In the aggregated overall visualization, the CMs are arranged, visually separated, without overlapping, for distinction and recognition value. The combination of the visual variables follows the PoN principle of *Dual Coding* [2], which recommends applying several visual variables for the same semantic concept to improve distinction.

3.2 Discipline-Specific Encoding

Orientation-related visual variables are used expressing hierarchical (vertical arrangement) and sequential (horizontal arrangement) properties of the structures to support recognition value. The distinction between different types of concepts is commonly implemented with geometric shapes (eg. BPMN) or pictorial icons. To support the recognition value for singular CMs, both 2D shape and orientation are considered reserved and will not be applied for indicating cross-domain disciplines.

Applying the orientation and shape variables to inner CM artifacts fulfills the principle of *Cognitive Fit* in PoN. When sticking to native and common notations in the CMs, the most commonly used shape would be a box. To provide *Semiotic Clarity*, the geometry would have to be altered which would contradict with *Cognitive Fit* principles. To avoid confusion, the color coding is complemented with a spatial distribution of individual models. The models are spatially separated in the visualization; there is no overlap of concepts from several conceptual models. When showing models in isolated areas of the visualization canvas, the affiliation of concepts to their models is transparent. A distinction by shapes is not essential for discipline specific CM discrimination.

3.3 Instance Descriptions

Common discipline-specific CM notations widely apply textual annotations to encode artifact properties and information. Especially in CMs with a comprehensible number of different concepts, textual information is of high relevance in order to discriminate singular entities. Text is commonly used to identify and mark individuals (instances) of the concepts. This paradigm is followed in the VL introduced here. Textual representations are reserved for instance discrimination. Textual instance discrimination is used for all discipline-specific CMs and follows a standardized notation and nomenclature to support *Cognitive Fit*. Instances are both concrete concepts and relationships.

3.4 Cross Discipline Relationship Visualization

Relationships between concepts of several disciplines have different characteristics compared to the inner discipline relationships. They are not integral components of the CMs, like relationships between concepts in a discipline. Inner discipline relationships express the structure of model artifacts in a discipline, whereas cross discipline relationships indicate how discipline-specific CMs are connected. These fundamentally different characteristics must be regarded in visualization for avoiding confusion and misleading users.

The visual variable applied should not visually emphasize the cross-domain relationships, as they are not introduced to be in focus of the consideration. The introduction of the cross-discipline relationships is a major difference to common approaches both in conceptual modeling and visual language development. This demands a distinct and unique visual syntax to indicate the special character of the relationship to users. To provide a unique visual variable for cross discipline relationships, a spatial arrangement of CMs in the third dimension is introduced to visualize the cross discipline relationships in depth. The discipline-specific CMs remain in a 2D planar diagram; while the collection of diagrams as a whole are arranged in the volumetric space. The spatial visualization is only applied to discriminate conceptual models and relationships.

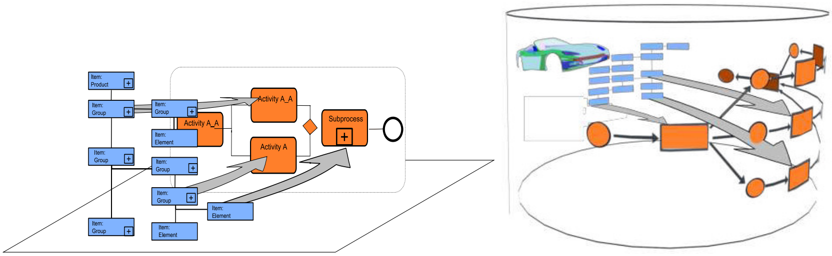

Fig. 3. Schema of spatially arranged conceptual models in layers and cylindrical arrangement

This visualization approach demands consideration of the position and orientation of users. Depending on the point of view, singular CMs are visible in the foreground when looking straight on a CM diagram. When moving in the information space, established from arranged and linked CMs, cross-discipline relationships become visible. The orientation and viewport of users are means of interaction and navigation with the visualization. With including users' perspective to navigation, new means for visual complexity management are introduced: The pruning technique for handling visual complexity with reduction of entities displayed is implemented with navigation paradigms [22], [2]. Perceptive complexity is addressed with interaction paradigms. With reference to modeling theory the abstraction and mapping process results in a specific view on the real problem domain. With this metaphor, the contradiction between visual complexity [29] and a holistic view (showing multiple CM diagrams in one view) is overcome with means of interaction.

This 3D approach makes the different kinds of relationships visually distinguishable by separating the dimensions of the visualization. This reduces the visual complexity, as elements which are not of primary interest are put to background without losing a view on the big picture. The spatial arrangement is consistent with principles for complexity management. Parts of the CM complex which are not the focus of consideration are kept in the background, which follows pruning principles of non-relevant information for complexity management [2]. As the entire artifact of linked CMs is available the pruning mechanism is implanted with visualization and interaction metaphors.

4 Conclusion

Discipline specific conceptual models are commonly visualized with the set of visual variables described in [5]. In a common visualization of several CMs the arising visual complexity is addressed by introducing the visual variable of "spatial distribution". Considering CMs as images of the real world created from the point of view (formal *"Pragmatism"* [10]) of a spatial arrangement of CMs is self-evident as the viewpoint of disciplines is just mapped to the information visualization artifact. With the third dimension used for the introduced relationships, a visual distance is established to the inner discipline relationships. This results in handling the issue of complexity not only with visual language elements but additionally with interaction metaphors like position and point of view of users. Depending on the point of view of users, only fragments of the CM complex are visible, either singular CMs or relationships between a few CMs. However, the relationships to relevant CMs are visible in the same display and therefore part of the scenery. This bridges the gap between a task-based application of the platform and a visualization of the context of the task within the problem domain.

Complexity is reduced, as non-relevant CMs are taken out of primary focus of the user within performing a task. Empirical studies with 3D visualization have shown that the visual complexity can be reduced by using a combination of stereoscopic visualization and movement tracking, with the complexity reduced by a factor of three [14]. The possibility of visualizing the context of tasks without changing the visualization environment indicates benefits in the understanding of cross discipline issues without visually overburden users.

The concept of a spatial visualization of CMs following the principles of PoN is currently in development. The target platform is an immersive Virtual Reality environment at the Lifecycle Engineering Solutions Center in Karlsruhe, Germany. The facility offers a passive stereoscopic 3-side projection system with head-tracking. An empirical evaluation of a use-case for business process planning scenarios is expected in late 2012.

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The Right Knowledge Management Strategy for Engineering Analysis SME: A Case Study

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Abstract. The aims were firstly to identify major problems within a calculation and analysis SME and then to determine the adequate Knowledge Management Strategy. A participant observation was performed for a tem month period within an engineering analysis SME, making a census of usual and unusual problems met by engineers during their daily activities. A keyword characterization grid for engineer's problems was performed. Through census prioritization and anecdote characterization three families of problems were identified: perpetual training, electronic-paper-document-mail classification and engineering activities support. The results justify a Knowledge Management implementation, highlight the importance of the turnover factor, and lead to recommending a codification strategy.

Keywords: Knowledge Management Strategy, Codification, Personalization, High Turnover, SME, Characterization, Engineer Problems.

1 Introduction

Computational mechanics generally includes Finite-Element Analysis specificities and complexity. Intensive knowledge acquisition occurs through the highly cognitive tasks involved in the analysis process. Such engineering analysis activity is often outsourced to small specialized companies. These SMEs have to manage projects of various sizes from different industrial sectors with a wide range of problems. There are knowledge intensive companies, where the knowledge management could be a way to improve the efficiency and the reliability of process.

Still from nowadays, a few works have been done describing how Small and Medium Enterprises (SME) manage their competitive performance through a well chosen Knowledge Management System [1]. The managers and the companies have perfectly seen the potential benefits of managing the knowledge of their employees. This management must be done at all levels and particularly in technical departments. The improvement of the knowledge transfer within a team contributes significantly in increasing the final product quality; it can be also timesaving on the long term and

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could leverage the satisfaction of employee through a feeling of efficacy and performance. But the implementing cost of such a KM system is a severe issue for SME especially since the implementation and maintenance are costly, and the success is unsure with a failure rate about 70% [2]. The question of the necessity of the knowledge management is a great issue and the right Knowledge Management that suits to the SME is not obvious.

Through a case study, in this paper we investigate on the relevance of a knowledge management in engineering analysis SMEs, and on the choice of an appropriate strategy in the deployment of the KM approach. The following section exposes the state of art and the research question. The third section describes the Case Study approach, and the research method to address the question. The fourth section explains how the samples were collected and characterized. These samples are then analysed in section 5 in order to answer the research question. The sixth part concludes the paper.

2 Literature Review

As summarized by Wong and Aspinwall [3], businesses that can efficiently capture the knowledge embedded in their organization and deploy it into their operations, productions and services will have an edge over their competitors. And it is obvious that SME have to always keep an edge over multinationals in order to survive. Moreover, as Zanjani rightly states "Besides large organizations, the success of small business or an SME can be linked to how well they manage their knowledge" [4]. Our research team shares the knowledge definition of Wilson [5], which clearly distinguishes the information from the knowledge. He defines the particularity of the knowledge by existing only in the human cerebral activity within his experience and his interaction with his environment. On the contrary, the information is only an association of several data that could make sense in the context, like a message, a schema, or a graph. But in spite of the inexistence of knowledge outside of our mind, we accept the human capability to create highly organized information from his personal knowledge, through adequate "knowledge transfer spaces" called by Nonaka as "Ba"[6]. These "Ba" are supporting knowledge transfers.

Referring to engineering analysis activity, a knowledge support typology was proposed by Baizet [7] in order to characterize the knowledge created and handled by professionals. Knowledge supports for analysis teams is broken down into four categories: References, Tools, Methodology, and Modeling. *References* refer to actors' knowledge about the localization of know-how, information or knowledge: like expert person, seek document/norm/procedure or right server/computer. *Tools* refer to actors' knowledge about the potentials of his analysis tools, including its functionalities and limitations like known bugs, modeling limitations or machine capacity exceeding. *Methodology* refers to actors' knowledge of internal procedures which organized the enterprise and the processing of affairs, including the process of construction and validation of a new knowledge. *Modeling* refers to all technical know-how, like modeling tricks, modeling simplifications and equivalences of real system behavior.

Beylier et al. consider each piece of technical knowledge as linked with specific information that they call Support Data [8].

We have widened our vision with the awareness of crucial knowledge identification [9], as it is obvious that all knowledge within an organization do not have the same weight and the same criticality. The company needs to support the creation, storage and spread of the highly organized information generated. That's why the knowledge management could be a solution if well aligned with the enterprise policy and working employee needs.

According to Hansen [10], it is necessary to have a clear strategy to implement a functional and sustainable knowledge management. Currently there are two major strategies widely accepted: the codification strategy (system oriented strategy) and the personalization strategy (human oriented strategy); both shall be present, but the whole system will be long-lasting only if one of them is chosen as the major strategy.

The choice depends on several factors like the company size, its core business, its employee culture, its geographic dispersion, its policy) called by Wong [3] as Critical Success Factors (CSF). As reported by Wong, many companies that are attempting to initiate KM are unsure of the best approach to adopt.

In the same objective, Gourova [11] has summed up not less than 9 papers on KM strategies and practices, augmented by 5 other papers intending to help SME (including Wong's one) to choose the most appropriate strategy for them. The challenge results are based on a huge study of 199 SMEs from 7 countries of EU. The major challenge found is the lack of a KM Champion to lead the KM implementation; in second position are cultural and organizational barriers; followed by management resistance, the lack of experience in the senior management and lack of financial resources. Among the barriers for KM introduction, the most relevant to the SMEs are as followed: Time and Priority of managers, Lack of management commitment, Fear to share the knowledge, Apathy of sharing knowledge, Lack of confidence and trust in consultant companies of KM expertise. Not included in Gourova's paper, in 2004, Meroño et al. [2] made an interesting experiment to test their theory of a relationship between KM strategy and business strategy. They proposed an alignment of a personalization KM strategy with a differentiation business strategy versus an alignment of a codification KM strategy with a cost business strategy. The experiment over 4 differently aligned SMEs, two supposed as good and two supposed as bad, has proved this relationship but has also shown the consequent influence of the CSF which seems to assure the success of a SME not well aligned strategically. More recently and partially based on the alignment work of Meroño, Zanjani [4] has proposed an alignment taking into account three binary levels. The choice of the KM approach could be driven by the SME specific characteristics leading to choose successively the KM strategy, the KM tactic and the KM tool. The decisional tree leads to eight classes of KM approach. Recently, Hussain has made a census in developing countries of SME characteristics and has proposed several recommendations. One of these states the personalization strategy as the unique possible strategy for SME [12].

Hence, in the light of this literature review, it comes that due to the specific nature of knowledge, managing it could be costly and the result is often uncertain. In addition, SMEs have specific characteristics which highlight some critical success factors.

The engineering analysis activity proved to hardly rely on different categories of knowledge, which could be worth being managed. In this paper we address the following questions: is it sensible to deploy a Knowledge Management approach to support engineer activities in an engineering analysis SME, and if so, which KM strategy best fits the context of such accompanies. A case study approach was used to investigate on these questions.

3 Our Case Study Approach

The study was conducted within a mechanical engineering SME that provides its customers with engineering analysis services. Within this 28 people company, 15 engineers are in provision and 7-8 engineers are part of a parent house team dedicated to this activity. The customers can be either principal contactors or other SMEs, working in various industrial sectors (transportation, energy, leisure…). Projects ordered are spread out over half a day to 4 months. The work is generally done by a single analysis engineer but several knowledge exchanges are done within the team to boost, help or check the evolution of the project. Projects can be either totally new with an occasional customer or at the contrary very recurrent with a regular customer and it is not rare to have recurrent affairs spaced out of three years like dam gates analysis. Engineers in charge are encouraged to ask to the reference, for instance the expert.

The research method used to answer our research questions consists in five steps.

Firstly, a participant observation has been performed for a year within the SME. The aim was to make a census of the usual and unusual problems met by engineers in their daily activity. As problems generally occurred in a set of successive events, the problems set was collected as descriptive anecdotes. In a second step, the anecdotes have been prioritized and characterized. The aim was to identify the major problems of the SME to focus on, and to define common descriptors for all the anecdotes. In the third step of our research method, the most critical anecdotes have been analyzed in order to determine whether or not deploying a Knowledge Management solution could be relevant for the SME (our first research question). The forth step is using the previous literature revue to identify the recommended Knowledge Management strategy and options in our specific case. Finally, the aim of the last step is to test the recommended strategy from the literature to the most critical anecdotes, in order to check if such a strategy could solve these major problems regarding the specific SME context.

4 Sample Creation and Characterization

Identification and recording of the daily problems

Problems were detected through several indicators:

- an allocated hours exceeding for the affair
- an unconformity detected at the validation procedure
- a client return at the After Sales Service

- an unwilling infringement of the internal procedures of an affair process
- an informal discussion between engineers
- a problem directly confronted to, as an engineer of the company.

Once detected, the anecdotes were formalized thanks to informal interviews with the stakeholders involved in the anecdote. Over a ten months period, a total of 51 anecdotes were captured.

Prioritization. A meeting involving a former expert of the enterprise helped the prioritization. Severe anecdotes were selected based on impact analysis while others have been eliminated. The impact was assessed according to three criteria: the lost time, the extra cost and the customer satisfaction decline. The impact has been classified according to three levels of anecdote treatment priority: Critical, Priority and Comfort. This prioritization had two aims. The first one was to purify the census by eliminating the anecdotes which were not an issue. The second one was to prioritize the critical set of problems that have a major negative impact on the enterprise business. It should be noticed that the prioritization have considered the gravity of the consequences taking into account the occurrences. Therefore it is no longer necessary to treat the occurrences of anecdotes; it is included in the priority level. By prioritization of the 51 anecdotes, 12 were classified as critical, 14 as priority, 14 as comfort and 11 were eliminated, or 22% of the anecdotes, like sum up in Table 1.

Table 1. Prioritization of the anecdotes

Priority	Number of Anecdote		Total
Critical	12	40 (78%)	51 (100%)
Priority	14		
Comfort	14		
Eliminated	11	11 (22%)	

Characterization grid. The selected anecdotes were characterized according to the actors' experience and seniority, and to the nature of the problem.

Table 2. Characterization grid for job experience and seniority levels

Job Experience levels	Expert	Confirmed	Initiate	Beginner
Seniority levels	Former (+3 years)	Intermediate (1 to 3 years)	Recruit (- 1yearr)	

Table 2 shows the characterization grid related to the job experience level, and to the seniority level. We considered 4 levels of experience: the beginner, who has never used a Finite Element Software; the initiate, who is a worker seeking a lot of knowledge; the confirmed, who is an experienced and nearly knowledge independent worker; the expert, who is a reference. Regarding the seniority, 3 levels were defined.

Table 3 shows the different categories (first row) and sub-categories (last four rows) of the nature characterization. The description of this classification is out of the scope of the paper, but the four main categories are intended to make it possible to distinguish between the truly knowledge related anecdotes and some possible interferences. *Document* refers to a misused/a misunderstanding of a document or an unfound document. *Tool* refers to a material failure, an unwanted crash, an expert file break or an obsolete method; and *Processes* refers to the willingly infringement of a known procedure or a lack/a flaw in a procedure. The Knowledge category is adapted from the literature [7-8] in order to have a more precise identification of the knowledge related with each of the anecdotes.

Table 3. Characterization grid for the nature of the anecdotes

DOCUMENT	TOOL	PROCESSES	KNOWLEDGE
Creation	Software	Commercial Offer	Practice
Retrieval	Material	Realize	Project
Modification	Method	Verify	Customer
Reused		Validate	Activity Communication

The 40 anecdotes selected by the prioritization have been subdivided into 113 elementary anecdotes prioritized by inheritance. Among them, the rest of the paper is focused on the 27 anecdotes (88 elementary one) concerning engineering analysts' activities.

5 Anecdotes Analysis

Relevance of a KM approach

The keyword characterization grid is used to identify major problems met by our engineering analysis SME, with a special focus on knowledge transfers.

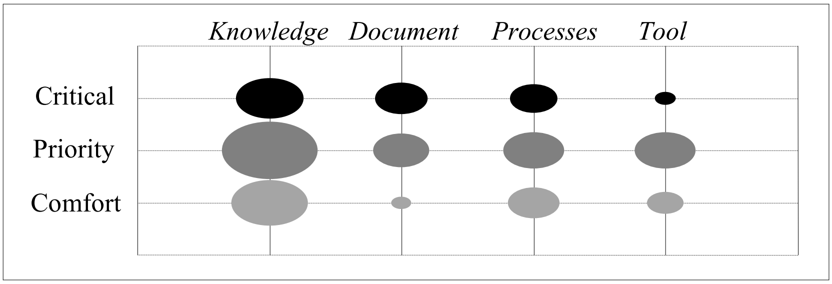

Fig. 1. Number of elementary anecdotes according to each category and priority

Figure 1 shows a representation of the number of elementary anecdotes by categories and by priorities. A large dot denotes a high number of anecdotes. It comes from this figure that half of the anecdotes are concentrated in the *Knowledge* category, making of this category the most important point to focus on, whatever the considered priority level.

This observation is strengthened by Figure 2 and Figure 3, which show the relative level of each of the previous categories in relation with job experience (figure 2) and seniority (figure 3).

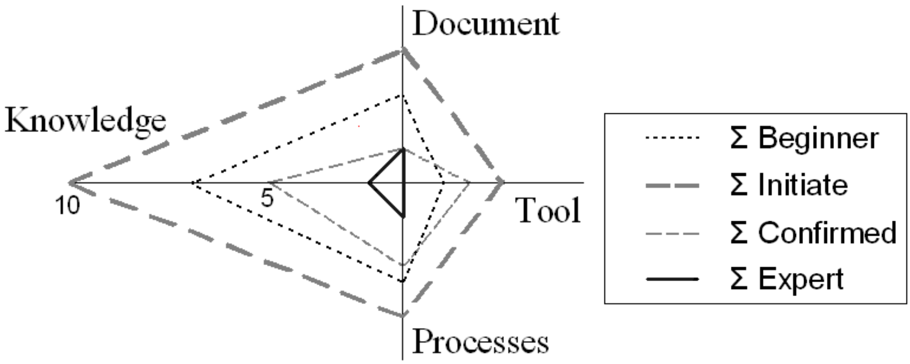

Fig. 2. Number of elementary anecdotes per calculators according to experience

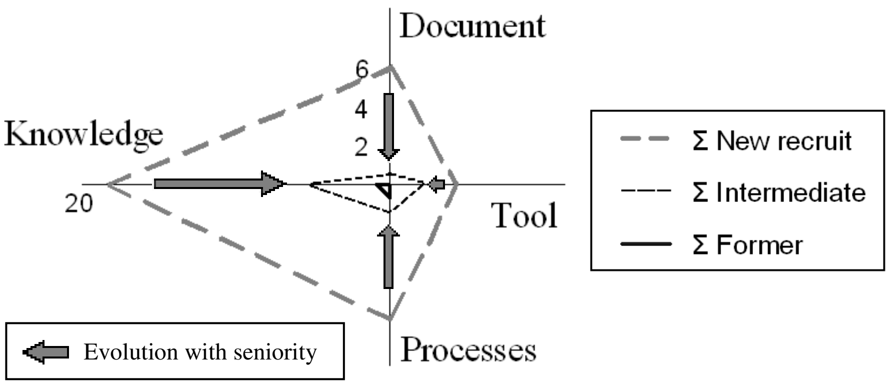

Fig. 3. Number of elementary anecdotes per calculators according to seniority

It is to be noticed that both graphs display the number of elementary anecdotes per employee of the same job experience or seniority category. According to job experience, statistics show there are three times more anecdotes for beginners, as there are many of them, but as shown in figure 2, the job experience per employee has no significant problem decrease. According to seniority, statistics show clearly there is a sharp decrease of the number of anecdotes per employee between a new recruit and an intermediate. It means that the 2 first years are the worst for project quality and SME profitability.

In addition, it comes from a more detailed analysis of the content of the anecdotes that a high number of anecdotes prioritized as Critical or Priority are linked to a particular know-how seeking left unsatisfied, (knowledge, document, and even process categories). Among others, the following elementary anecdotes: the time wasted trying to use a specific macro, the difficulty of understanding a too complex macro, the absence of a expert file notice, the vacation or departure of a norm expert to clarify parameters or analysis steps, show the lack of expert people. Analyzing the human resource information of the company shows that the parent house team is nearly completely renewed each 3 to 5 years. The matter is not only the tediousness of recurrent affairs, the analysis job has no possibility neither of evolution nor of promotion excepting becoming a project manager and managing, therefore analysis engineers rarely stay in their profession and a specialized SME cannot keep them in another department or promote everyone.

Hence, the knowledge nature of most of the anecdotes, the large amount of anecdotes involving recruits, and the high level of turnover, inherent to the engineering analysis profession, show the relevance a knowledge management intention for engineering analysis SMEs. More in detail, the critical anecdotes combined with a high turnover effect may lead to a continuous training waste and a perpetual low quality fatal for the SME. The observation backs this conclusion because new recruits and beginners disturb continually former and more experienced workers who form them knowing they won't stay, as direct consequence, the motivation of formers can only go down by usury until they left too.

The Document criticality shows a major problem related to classification, because of huge occurrence of the "retrieval" keywords. It means a key issue about knowing where the information is. Accordingly, the observation has shown the systematic emergence of a personal electronic library of useful information built by each engineer. This personal document is often be used and transferred instead of official ones; but when the owner leaves the enterprise, the personal library stops being dynamic because it can no longer be known, referenced and spread by the "librarian". The knowledge linked to this unstructured and rarely well tidy information is lost. The Processes occurrences show a consequent carelessness of employees to respect procedures. The combination of the "not respected" sub-keyword from Processes category and the "not aware" sub-keyword from Reference Knowledge category about organization procedures shows the urge of well integrate employees relatively to internal organization described by procedures. The recruit autodidact or the practice integration is not enough; as the turnover is severe, there is a quick degeneration of the integration by personalization. The association of: the lack of document management; the number of keywords in Tool (tool awareness) from Practice Knowledge category; with the need of spreading procedures, shows that in spite of a law number of anecdotes in the Tools category (tool failures) a job supporting tool is needed.

Choice of an appropriate KM strategy
If KM is a potential solution then according to Hussain the personalization strategy is the right strategy for SME. Logically this conclusion should be back by the decisional tree of Zanjani. The foreseen approach according to this decisional tree of Zanjani is:

- a KM strategy of Personalization: The SME has as mainly innovative and knowledge intensive tasks in spite of a lot of routine and very specific knowledge tasks.
- a KM tactic of Individualization: The SME is clearly a small company.
- a KM tool should not be an IT-based tool: The SME is geographically oriented because engineer in provision does not participate to knowledge transfers.

The literature seems coherent and recommends a Personalization Strategy in the case of our SME. Nevertheless, regarding the turnover characteristic previously identified, this recommendation is worth to be questioned. Indeed, anecdotes could hardly be solved sustainably by personalization as the majority of actors are no longer present and current intermediaries have had short overlap with formers. When testing the principle of a personalization strategy against the anecdotes, it comes that only nine of them may be solved. The personalization approach requires direct interactions between people which are often quite impossible in such a turnover context, and being inherent to the engineering analysis activity, even a radical change in the management strategy would not have a significant effect.

Moreover the presence of tedious recurrent tasks to be long term supported and well transmitted to new recruits tend to the choice of a codification approach for at least supporting these tasks. The observation in the company has shown that each engineer has built a personal useful electronic data library, for recurrent and more innovative affairs, knowing perfectly where personal information is. It means unstructured information are already written and in use for all kind of affairs. This is more especially true for intermediate and former engineers, which could partially explain the observations form figure 3. The analysis of complete anecdotes shows that 25 anecdotes have good prospects to be sustainably solved by an adapted codification strategy. The turnover, factor generally ignored in literature, is here a heavy decisional factor and led to consider the turnover as a Critical Success Factor which influences the choice of the KM strategy. So, as a conclusion of the results, in spite of several coherent recommendations, the codification strategy looks a better choice for an engineering analysis SME with a high turnover.

6 Conclusion

A participant observation within an engineering analysis SME has permitted to determine some major problems met by the engineers in their daily activities, particularly in knowledge transfers. 88 elementary anecdotes characterized for the study have been analyzed in order to answer to 2 research questions about the necessity of a KM approach and, if necessary, the right KM strategy.

The analysis of the anecdotes has permitted to justify a KM solution targeting on new recruits, independently of their experience. In addition, the necessity of clear procedures of data storage for certain document has emerged.

Even if, according to the actual academic theories and results, a personalization strategy should be recommended, it has been shown that a codification strategy seems to better suit this engineering analysis SME. The main reason is the high turnover in this kind of SME that particularly affects knowledge sharing, or even document sharing and retrieval due to time constraints and lack of former employees. The turnover implies also that a lot of energy is wasted in perpetual training even on highly recurrent projects. The heavy financial implementation cost of a codification strategy could be profitable as it mainly supports recurrent affairs.

Limitations of this work may be related the few number of elementary anecdotes, the restriction to a department of the SME, and the cloud of the minimal turnover justifying a codification strategy. Further investigations will focus on deploying this strategy while taking care to diminish the cost and ensuring compatibility with high turnover.

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An Ontological Approach to Integrated Product and Process Knowledge Modeling for Intelligent Design Repositories

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Abstract. Formal representation of design and manufacturing knowledge in distributed design repositories is a key enabler of autonomous design-to-fabrication. This paper presents an ontological approach to formal representation of product and process knowledge in order to enhance the intelligence of design repositories. The product and process ontology developed in this work is based on the Web Ontology Language (OWL). A methodology is proposed for part characterization, clustering, and similarity measurement based on the asserted and inferred properties of the part instances in the ontology. Part families are formed according their semantic similarities from the perspective of geometric and non-geometric attributes. Ontology population is conducted semi-automatically assisted by automated feature recognition techniques.

Keywords: Product ontology, part family, design repository, similarity measurement, semantic web.

1 Introduction

Engineering design process oftentimes involves alteration of the existing designs in order to arrive at design variants based on the new requirements. About 80% of design artifacts created in a typical manufacturing firm are modifications of the designs already available either internally or externally [1]. *Design repositories* are among the key components of the decision-support systems that enable the designers to efficiently reuse the existing design knowledge in the form of design artifacts or engineering best practices. A design repository archives design artifact and design processes knowledge and typically provides some means of knowledge search and navigation. Despite significant advances in development of design information models and search and retrieval tools and technologies such as commercial PDM and PLM solutions, the existing design repositories still lack the required level of intelligence for enabling effective knowledge reuse. Designers in average spend 60% of their time searching for the right information or verifying the validity and relevance of the retrieved information in a given context [2]. To effectively support knowledge management

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throughout product life cycle, design repositories need to move beyond serving as passive and static data silos and enhance their intelligence such that they can dynamically provide every design task with the relevant design knowledge. Also, an intelligent design repository lends itself better to semantic search and retrieval.

To create more intelligent design repositories, it is first necessary to enrich their underlying information models in terms of formal semantics. In presence of formal semantics, machine agents can actively participate in design retrieval and synthesis process. Given the fact that design practice has increasingly become collaborative conducted by virtual teams distributed globally, a unifying semantic model is essential for eliminating or reducing the semantic ambiguities that are typically present in heterogeneous environments. For more than three decades, researchers have been working on developing better ways of capturing, representing, exchanging, and reusing engineering design knowledge in a robust and flexible fashion. Numerous knowledge representations schemas have been developed based on different formalisms including pictorial, symbolic, linguistic, virtual, and algorithmic [1]. With the advent of Semantic Web technologies, symbolic knowledge representation through development of formal ontologies has gained a new momentum and researchers started adopting the new knowledge representation standards provided by the Semantic Web technology suite, such as the Web Ontology Language [1] (OWL), for modeling different types of knowledge with varying levels of formality and rigor. OWL is recommended by World Wide Web Consortium (W3C) as the ontology language of the Semantic Web. It uses XML/RDF as the syntax, hence it has enough portability, flexibility, and extensibility for web-scale applications. Description Logic [3] (DL) is the knowledge representation formalism used in OWL-based ontologies. DL provides formal syntax and semantics for developing knowledge models within a domain of interest in terms of concepts, relationships between concepts, and logical constraints that concepts must satisfy. Additionally, it enables automated reasoning services such as concept classification and consistency checking. Therefore, due to its formality, expressive power, and its web-native format, OWL provides a suitable framework for knowledge representation in distributed design repositories.

This paper presents an integrated ontology for product and process knowledge modeling. The presented ontology is axiomatic and uses logical restrictions for formal definition of the concepts used in the ontology. One notable aspect of the proposed ontology is providing a direct connection between product knowledge and manufacturing process knowledge. This connection is built through relating the manufacturing features of the parts to the manufacturing services that can fulfill the requirements of each feature. The proposed ontology not only encodes the asserted properties of the design artifacts available in the CAD models, but also accounts for the inferred properties that can be extracted from the asserted ones. In this way, design knowledge can be expanded and enriched systematically, thus improving the performance of the search engines that operate based on the ontological content. To demonstrate how the proposed ontology can support intelligent design retrieval, a methodology for part characterization, classification and clustering is proposed in this paper.

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[1] `http://www.w3.org/TR/owl2-overview/`

2 Related Work

Several ontologies have been developed in engineering design with the objective of providing a richer conceptualization of a complex domain and providing a shared vocabulary for information exchange among product stakeholders [1]. Core Product Model (CPM) [4] is one of the earliest ontologies developed for design representation that supports form, function, and behavioral aspects of the product based on the model developed by Gorti et al. [5]. Two key concepts in CPM are *Artifact* (i.e., a distinct entity such as part or assembly) and *Feature* (i.e., a portion of artifact's form). The Open Assembly Model (OSM) is an extension of CPM that provides the standard means for representing assembly and tolerance propagation models [6]. Both CPM and OSM use object-oriented formalism and do not provide adequate formal semantics. Some researchers have used the core concepts of CPM and developed more formal ontologies accordingly such as the work reported in [7]. In the area of product family knowledge molding, Nanda et al. [8] proposed a methodology for capturing component design information through adopting a graph-based formalism represented in OWL. There are also multiple information models and ontologies that are specifically developed for knowledge representation in design repositories [9].

The literature review revealed that most of the existing ontologies for design representation do not provide sufficient formality for concept definition. In other words, the axiomatic aspect of knowledge modeling and representation are not adequately addressed in the existing models. Also, a clear disconnect between design knowledge and manufacturing knowledge in the existing models undermines their ability in creating a cohesive body of knowledge that supports various phases of product realization process.

3 Product and Process Ontology

Products can be described from different viewpoints including structure, function, and behavior. The proposed ontology mainly describes the structural aspects of a product. The functional aspects are addressed indirectly through referring to the category to which the products belongs. Fig. 1 shows the concept diagram for the three core classes that describe a design artifact, namely, `Product`, `Assembly`, and `Part`. `Product` class has a set of data-type properties that describe the physical attributes of the product such as the dimensions of the bounding box and the weight of the product. Also, through a set of Boolean properties, it can be specified whether the product belongs to the mechanical, electrical, or electromechanical categories. A more detailed categorization is provided through assigning the Central Product Classification[2] (CPC) code to each instance of the product class. CPC is a comprehensive classification of products based on the physical characteristics of products and is aimed at providing a framework for standardization of product classifications and promoting harmonization of various types of statistics dealing with goods and services. Since taxonomies provide useful semantics by virtue of representing parent-child relationships, CPC and

[2] http://unstats.un.org/unsd/cr/registry/cpc-2.asp

other similar taxonomies are used extensively in the product ontology. Also, the industries related to a given product instance can be specified through `hasRelatedIndustry` property which has the Industry class in its range. The instances of the `Industry` class are categorized based on North American Industry Classification System (NAICS) taxonomy.

The BOM-related information is described through the relationships between Product, Assembly, and Part classes. An instance of the product class can have one or more parts or sub-assemblies. A product can also be a single part such as a gear or shaft. In this situation, the physical attributes of the product such as material and dimensions are directly derived from the properties of the single part connected to the product through `hasComponent` property. The properties of the Assembly class are very much similar to those of the Product class. However, an instance of the Assembly class should have at least two assemblies or parts attached to it in order to be regarded as a valid instance of the Assembly class. This condition is formally specified in the ontology through a constraint, or axiom, as shown in Fig. 1.

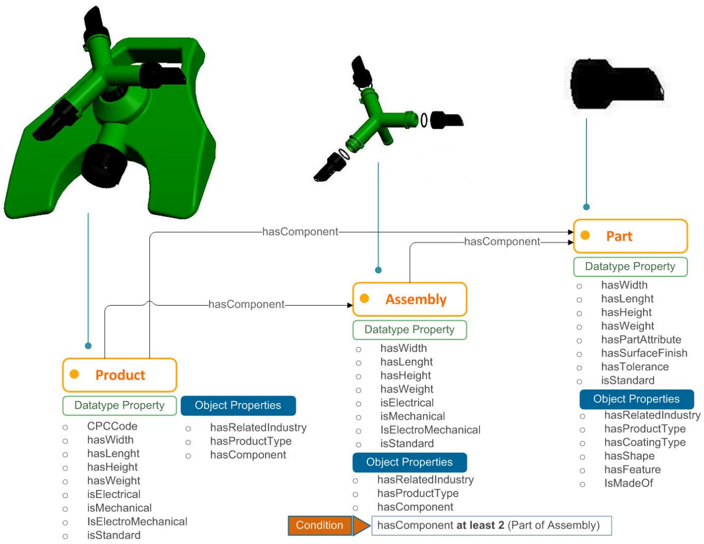

Fig. 1. The concept diagram of the product class

The Part class has more detailed generic attributes that specify the overall shape, manufacturing features, tolerances, surface finish, material, and coating type of the part along with the dimensions of the bounding box. These properties can be used for inferring the manufacturing requirements of the parts and their upper-level assemblies. Furthermore, each part can have a set of specific attributes pertaining to the particular category the part belongs to. For instance, an *ejection pin* can be further described through some attributes such as shoulder length, head diameter, and head thickness. These attributes are classified as sub-classes of the `hasPartAttribute` property. All the properties discussed so far are categorized as *asserted properties*, the properties that are directly specified by the user or available in the CAD model. However, capitalizing on the reasoning services enabled by a formal DL-based ontology, one can infer new properties not explicitly specified by the user or the geometric model. These properties are referred to as *inferred properties*. Some examples of inferred properties are complexity level, machinability, and fixturing difficulty. The inferred properties are not part of the core properties of the product ontology and the intention is to allow users to introduce their own desirable properties depending on their particular search scenario. More details on how to infer part properties are provided in the next section.

4 Part Clustering and Characterization

This section describes a methodology for part clustering and characterization based on the product ontology presented in this work. The objective of part clustering and characterization is to provide a unified framework for quantitative comparison of different parts based on their asserted and inferred properties. The scope of this methodology is limited to individual *machined parts* with varying levels of geometric complexities. Fig. 2 shows a representative set of parts that are included in the scope of the part characterization methodology. However, the underlying techniques presented here can be applied to other processes as well. The ability to effectively quantify the similarities of parts within a design repository is one of the key requirements for accurate formation of part families. A methodology for measuring part similarity is proposed Mun et al. [10] which mainly focuses on numeric and textual properties of the attributes part instances but it does not take into account the information contained in the taxonomic structure of the ontology.

Fig. 2. Sample parts that are included in the part clustering methodology

The proposed methodology combines schema-based approach (by utilizing the taxonomic structure and axiomatic definition of the concepts) and instance-based approaches (by utilizing the property values given for product instances) for part classification and similarity analysis. The main steps of part clustering and characterization process are described below.

Step 1: Part Classification

In the first step of the proposed methodology, parts are classified based on a given array of geometric and non-geometric criteria such as part material, required processes, types of machining features, overall shape and dimensions, main function, and the associated industry. The purpose of part classification step is to construct an initial set (S) of parts (p) that have enough commonalities to render a meaningful comparison among them. The output of this step is the set $S = \{p_1, p_2, \ldots p_n\}$ with size n whose members are instances of the `Part` class. The set S narrows down the search space into a smaller set of similar parts. The part instances in the set S are selected either explicitly through picking one or more existing named part classes from the ontology, such as `PumpPart` or `AerospacePart`, or implicitly through building a temporary class of parts that possess a set of desired properties. The former class specification approach is referred to as *schema-based approach*, whereas the latter is called *instance-based approach* in this work.

Schema-based Classification: For schema-based classification, DL reasoners such as Pellet [3] or HermiT[4] are employed to automatically classify the available sub-classes of the `Part` class represented as named classes in the ontology. These classes are defined formally through a set of logical constraints, thus lending themselves to automated classification. If a certain class is selected by the user for similarity analysis, then the instances of the selected class, along with the instances of the associated sub-classes, will be added to the set *S* for further analysis.

Instance-based Classification: Semantic Web Rule Language (SWRL) rules are used in order to create temporary classes that define the search space *S*. The following SWRL rule, for example, represents a class of parts, called `DesiredPart`, that are made of aluminum, belong to the hardware manufacturing industry, and have a cylindrical shape with a diameter less than 2 inches. The class, `DesiredPart` will be temporary added to the ontology by the reasoner on the fly and then all instances available in the ABox, that conform to the specified requirements, are retuned as instances of the `DesiredPart` to be included in the comparison set *S*.

```
Part(?p) ^ isMadeOf(?p,?m) ^ Aluminum(?m) ^ hasRelatedIndustry
(?p,?i) ^ HardwareManufacturing(?i) ^ hasShape(?p,?s) ^ Cylind-
er(?s) ^ hasDiameter(?p, ?d) ^ swrlb:LessThan(?d, 2)
→ DesiredPart(?p)
```

Step 2: Comparison Factor Selection

In this step, the factors (*F*) for part characterization and clustering are identified. Some examples for comparison factors are level of precision, level of complexity, machine setup difficulty, and manufacturability. A pairwise arrangement of the factors results in creation of one or more two-dimensional *comparison planes*. It should be noted that the value of a comparison factor for a given part might not be directly obtainable from the ontology and extra reasoning and inference processes might become necessary to arrive at the factor value or level for each part. For example, the *level of complexity*, as a possible comparison factor, has no explicit definition mandated by the ontology and it can be interpreted differently for different part families. The factor pair (F_x, F_y) represents the axes of the 2D comparison plane. Each part instance serves as a data point to be positioned in the comparison plane based on its coordinates along each axis.

Step 3: Normalization

Depending on the choice of comparison factor, each axis of comparison might have different scales and units. Therefore, in order to provide unified metrics for comparison,

[3] http://clarkparsia.com/pellet/
[4] http://hermit-reasoner.com/

it is first necessary to normalize the min and max values on each axis on a [0,1] scale. To this end, each comparison factor undergoes a normalization process based on the minimum and maximum values available in the entire population.

$$S'^{p_i}_{F_j} = \frac{S^{p_i}_{F_j} - Min(F_j)}{Max(F_j) - Min(F_j)} \quad (1)$$

Where $S^{p_i}_{F_j}$ is the score of the *i*th part along the *j*th factor, $Min(F_j)$ and $Max(F_j)$ are the minimum and maximum value respectively for the *j*th factor based on the given set S, and $S'^{p_i}_{F_j}$ is the normalized score of the *i*th part in the set along the *j*th factor. For example, if the machinability rating is selected as the *j*th factor of comparison, and given the min and max values of machinability to be 75 and 124 respectively across the entire comparison set, then the normalized score of the *i*th part with the machinability rating of 95 is calculated as:

$$S'^{p_i}_{F_j} = (95-75)/(124-75) = 0.4 \quad (2)$$

The normalized score, in itself, does not convey much information and it should always be treated as a *relative* measure.

Step 4: Clustering

Once the data points (i.e., part instances) are positioned in the comparison plane, they can be clustered for characterization and similarly analysis. Different approaches can be adopted for part clustering:

Four-Quadrant approach (Fig. 3-a): In this approach, the comparison plane is divided into four identical quadrants through splitting each axis. This approach is devised when the attributes represented by both axes are more qualitative or discrete in nature and a high-low scale can sufficiently describe the attribute without significant lose of information. The count of manufacturing features on a part or the number of machined faces are examples of such attributes. Also, one may choose to treat more quantitative and continuous attributes such as size or weight as high-low attributes just to perform a rough comparison based on these attributes.

Rule-based approach (Fig. 3-b): In this approach, SWRL rules are used to create part clusters or bubbles that satisfy the requirements set by the rules. For example, a rule can be generated for identifying all part instances that belong to automotive industry and need 5-axis machining. In fact, both instance-based technique and schema-based techniques used for creating the initial set of part instances in step 1 can be applied here to create more specific sub-sets for a more refined comparison.

k-nearest neighbor approach (Fig. 3-c): In this approach, part groups are formed based on their Euclidian distance form a given reference part. The objective is to identify the top k parts that are closer to the reference part in the two-dimensional comparison space.

Closeness radius approach (Fig. 3-d): In this approach, the part instances that are within a given proximity threshold from the reference part form a cluster.

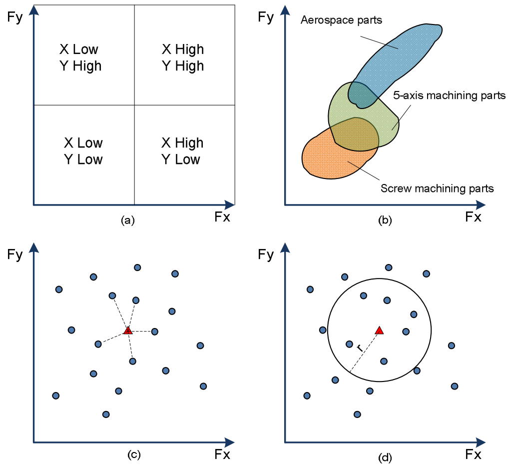

Fig. 3. Different approaches for creating part clusters (a) four-quadrant approach (b) rule-based approach (c) k-nearest neighbor approach (d) closeness radius approach

5 Implementation

This section describes a proof-of-concept implementation of the proposed methodology. There are two main implementation areas is this work, namely, the ontology and the part characterization and clustering programs. The ontology is developed in Protégé 4.1 and ontology manipulation is conducted using OWL API for OWL 2.0. Ontology population is carried on semi-automatically; meaning that the property values are partially extracted from the CAD file in an automated fashion. The information items that are obtained from the CAD file are mainly geometric in nature and include values such as the overall dimensions, removal volume, mass, and type of manufacturing features and their corresponding attributes. Also, the required manufacturing services, such as milling, turning, and drilling are automatically identified through using a pre-defined feature-to-process mapping incorporated in the system. More detailed information on automated feature recognition and service identification techniques used in this work can be found in [11]. Other non-geometric information such as material, coating type, product type, and related industries are entered manually through the Java interface shown in Fig. 4. Using this interface, all the *asserted properties* of the parts are collected and saved as an OWL/XMLfile. The OWL/XML files are used as the input for the part characterization and clustering programs. The lower right corner of Fig. 4 shows the user interface of the part characterization program that infers various characteristics, or *inferred properties*, of the individual parts based on their asserted properties. Some of the inferred properties of the parts that are used in this implementation include complexity, machinability, and fixturing requirements. Both asserted and inferred properties can be used for the purpose of part characterization and clustering. However, the inferred properties usually provide more in-depth understanding of various part features and characteristics.

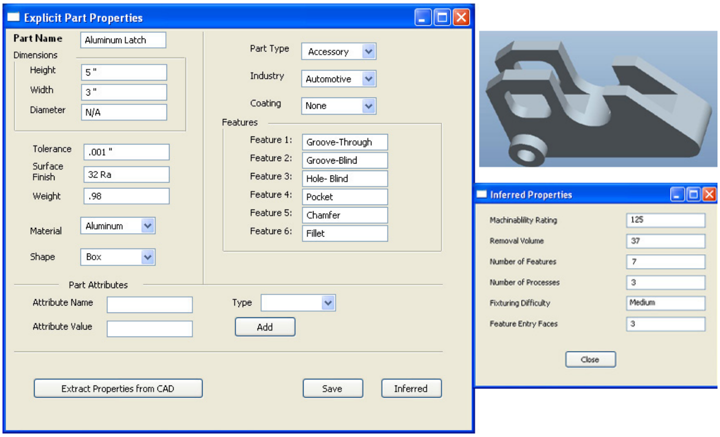

Fig. 4. The user interface for entering the explicit properties of the part directly and indirectly (through the CAD file)

Fig. 5 depicts an example scenario for comparison of three parts based on *fixturing difficulty* and *machinability* factors. In this example, Part B is closer to Part A compared to part C with respect to the Euclidian distance in a 2D plane built by fixturing complexity and machinability as the comparison factors.

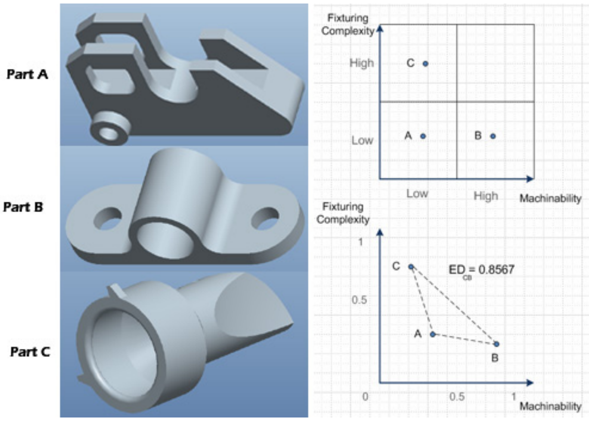

Fig. 5. Three sample parts compared based on their machinability and fixturing complexity

6 Conclusion

This paper introduced an ontology for integrated representation of process and product knowledge. The proposed ontology uses OWL as the ontology language. The purpose of the product and process ontology in this work is to enhance the intelligence of the design repositories through annotating their contents with formal semantics. A part clustering and characterization methodology was introduced to support semantic search and retrieval process in engineering design. The proposed methodology adopts both schema-based and instance-based approaches. Future work in this area include validation of the ontology and the clustering methodology based on a larger sample of parts through comparison with human expert judgment and also enhancement of the axiomatic definitions of product categories. Additionally, automated ontological learning and cognition in design repositories is another promising research avenue that calls for further investigation.

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Know-How Identification, Scoring, and Classifying in Product Development Processes

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Abstract. The following paper describes the development of a method for identifying, scoring and classifying captive process know-how in German enterprises of the automobile industry. Object of study will be the product development process. An initial point is described, in order to illustrate the results of an empirical analysis that lead to the necessity of protecting captive process know-how methodology.

After decomposing the selected product development processes (PDP) into rea-sonable steps, a special scoring system is used. Subsequently, the process de-pendencies between each other are being analyzed using multidimensional scal-ing. Within these steps the criticality of each process part concerning know-how protection is being scored. Using the method of scenario planning it is feasible to draw different possibilities of global cooperative partnerships in the future. These scenarios are the basis for classifying the identified process know-how for utilization in future cooperations.

Keywords: know-how protection, international cooperation, product development process.

1 Introduction

The German automobile industry is facing new big challenges. The continuous deterioration of the global economy and the persistent importance of the Asian market for the international automobile industry conspicuously illustrate that situation [5]. The changing preferences of German-Chinese cooperation towards increasing of corporate development projects lead to the necessity of reconsidering the cooperation models of German original equipment manufacturers (OEM).

Furthermore the Chinese Government imposes strict conditions on western enterprises, which try to join the Chinese market. This attitude, also commonly known as Chinese protectionism, has the purpose to selectively open their market and, also, protect it from unwanted outer impact [17]. Especially key branches, like the

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automobile industry, are rigorously controlled. For instance, the market entry for foreign enterprises is bound on acquiring in a Joint Venture (JV) with a Chinese OEM [4] [8] [22] [23].

Within these collaborations, Chinese OEM effectively learn how to produce high quality and their aspirations concerning collaborative job splits has changed. The evolution of the collaboration processes between German and Chinese OEMs has being observed the past few years. At the beginning these collaborations where characterized by developing the products in Germany and locating the production in China. Today a large percentage of product development is now placed in China [9] [24]. Against this background, an empirical analysis had been conducted in order to point out the necessity of reconsidering German OEMs collaboration processes with Chinese JVs. The results of that analysis constitute the initial point of developing the methodology, which is presented in this paper.

2 Results of an Analysis

As already mentioned above, it was the analysis' intention to point out the necessity of reconsidering the collaboration processes in German-Chinese corporation projects. Furthermore optimization potential should be exposed. Therefore, a representative German-Chinese cooperation project was selected for analysis. Using a semi-structured questionnaire, eighty interview partners were questioned. Each interview was recorded and evaluated based on Mayrings procedures of interpreting content analysis [15].

The implications of this research are manifold. The results of the evaluation point out the necessity not only of reconsidering the collaboration models in German-Chinese cooperation projects, but also of reconstructing them.

The data would seem to suggest, that one topic is of great importance. One of the main differences between the German and Chinese interviewees is the understanding of the contractual based know-how transfer. Whereas the Chinese members claim to need more transfer of process know-how than given by the German partners, German members are afraid of losing core competence while rendering its captive process know-how. In consequence of this an unrestricted sharing of captive process know-how by the German partners could indeed entail losses of core competence. Otherwise a strict rejection of the Chinese requirements could disrupt the collaborative projects progressing [13].

Finally, the results lead to the conclusion that only the accurate knowledge about their own captive process know-how could protect the German OEM from losing its core competence. Therefore the captive process know-how ensconced in the various processes need to be identified. To sum up, it is necessary to find a method which allows identification, scoring, and classifying of the enterprises captive process know-how, in order to handle it properly in cooperation with a potential competitor.

3 Methodology for Identifying, Scoring and Classifying Process Know-How

Before starting to develop the above named method, a literature research exposed that there are numerous amounts of approaches for scoring know-how in enterprises. For example the know-how protection portfolio [25], the Knowledge-Asset-Management-System [18] [19] [20], the APUD-model [21] [26], or the Competitive Advantage Valuation Method [21] [3] can be named. Unfortunately, most of these approaches deal with the focused topic on a very abstract level. Although giving valid theoretical background, the implementation into practice mostly fails [1]. Thus, the necessity of a method to be developed, which is of practical suitability, is implicated.

The following executions explain a practically suitable method for identification, scoring, and classifying of captive process know-how in automobile planning processes.

3.1 Decomposing Assigned Processes

Decomposing the advertised processes into reasonable parts is the first step of the method. Therefore, the different sub-processes of the product development process (PDP) are divided into process-parts, which are subdivided again into process-steps. This differentiation has to be realized by an expert, which at the best is located in a section where the example sub-process is situated primarily. Figure 1 shows the differentiation using the layout planning process as example.

3.2 Scoring Single Processes

The second step of the method, which is characterized by scoring the sub-processes individually, is divided into two parts. Using disqualification criteria, the process-parts have to be rated concerning know-how protection criticality. Following [10] [11] [25] and based on patent system principles, five questions were defined which label each process-part into high, middle, or low criticality of losing captive know-how. Following is the list of the mentioned questions:

1. Is the respective process a key process for the whole project, or for any other enterprises project?
2. Does the process require the necessity to unfold captive know-how or techniques from other processes?
3. Is the achievement of the project objectives essential for the project's success in general?
4. Is the process highly responsible for projects return on investment?
5. Is there a high risk of copying the process by competitors?

If these questions can be answered positively, a high criticality of losing captive process know-how is given. As a consequence that process should hardly be shared with a potential competitor. If these questions can be answered negatively, there is no risk to share the process know-how with any partner. But if these questions cannot be answered either with yes or no, the second part of the step comes into play.

Within that step, twelve criteria have to be scored for every process-step in the respective process-part. Every criterion, also based on patent system principles and according to [14] [26] [16], has to be appraised in a Likert-related scale. Following the twelve criteria are listed:

1. The respective process-step is innovative.
2. The process-step contains a lot of the enterprises captive innovations.
3. The process-step is unique compared with other branch competitors.
4. A fast modification of the processes functionality could not yet be foreseen.
5. The necessary level of education for this process is high and expensive.
6. The process-step allows synergies with other processes of the enterprise.
7. Time expenditure and financial effort for creating the process-step techniques are high.
8. The process-step generates a great cost advantage towards branch competitors
9. The process-step generates a great profit advantage towards branch competitors
10. The costs for external creation of the process-steps outputs would be high.
11. Outsourcing of that process-step means loss of image.
12. It is impossible to keep the process-bound know-how or techniques secret.

The results of appraising the questions are cumulated percentages for every process-step, which are the base for classifying the process-parts and, finally, the whole sub-process at a later stage. Firstly, the process dependencies have to be analyzed in step three. Figure 1 shows an example for single scoring using layout planning as sub-process.

3.3 Scoring Process Dependencies

After scoring single sub-processes it is necessary to analyze process dependencies. Step one ensures that a lowly rated single sub-process, according to know-how protection, does not have any exchange of captive process know-how with a highly scored single sub-process. If this is the case, the scoring of the low rated sub-process has to be reconsidered. Otherwise loss of captive process know-how is highly probable.

To achieve a valid result the use of multidimensional scaling has been proven as a reasonable method. On account of the fact that there are different techniques of multidimensional scaling, it should be specified the selected technique for each step in accordance to [2]. Initially, a process-structure matrix, to be completed by an expert, is needed. This matrix contains the pairwise assessment of each sub-process with any other sub-process it is cross-linked to. It would be advisable to analyze both the quantity and the quality of the process-dependencies. The connection between the advised sub-processes are based on input and output of information. The information that is to be rated as captive process know-how are bound on different know-how-owners, which can be of personal, material or quasi-material source [12]. For rating the process dependencies, it is necessary to consider the amount and quality of the know-how owners bound information, which are to be transferred.

sub-process	timeline in month	process-part rating	process-steps		scoring
layout planning ◐ M3	0-5	concept layout ◐	1	process-step 1: examine the tenders	63%
			2	process-step 2: …	58%
			3	…	…
			…	…	…
	…	layout workshop ●	1	process-step 1: presenting the premises	K.O.
			2	process-step 2: …	K.O.
			3	…	K.O.
			…	…	K.O.
	…	… ○	1	process-step 1: …	32%
			2	process-step 2: …	41%
			3	…	…
			4	…	…
	…	… ◐	1	process-step 1: …	…
			2	process-step 2: …	…
			3	…	…
			…	…	…

● high criticallity of losing captive know-how ◐ middle criticallity of losing captive know-how ○ low criticallity of losing captive know-how

Fig. 1. Example of single scored sub-process

Figure 2 shows an example of a quality-related process-structure matrix on the basis of a pairwise comparison combined with a 9-point Likert scale.

	Sub-Process	1	2	3	4	5	6	7	8	9	10	11	…
1	Layout Planning												
2	Materials Handling	3											
3	Logistic Planning	3	2										
4	…	1	8	8									
5	…	2	8	3	9								
6	…	2	8	4	8	9							
7	…	2	8	1	9	9	8						
8	…	6	1	3	9	3	2	2					
9	…	9	4	8	5	8	9	8	4				
10	…	9	4	8	5	8	9	8	4	2			
11	…	9	6	6	6	8	9	9	4	7	9		
…	…	9	4	8	5	8	9	8	4	2	5	3	

Fig. 2. Example of a quality-related process-structure matrix

To ensure a useful interpretation the process-structure matrix data has to be transformed into an easily comprehensible presentation. Using the method of multidimensional scaling, it is possible to transparently decrypt the data. Figure 3 illustrates an example that is based on the Euclidean Distance Model. The advantage of this model is its simple indication of the sub-processes connections. The distance between each point represents the strength of the researched subject. In the present example it is the quality of the know-how related process-dependencies. A short distance means that there is critical mass of captive process know-how exchange. A long distance, on the other hand, stands for less exchange.

After single scoring of every sub-process the PEP includes, it is possible to mark every process in the design-structure matrix with its individual scoring result. Thus the possibility of elucidating highly critical process-dependencies in the matrix is given.

In Figure 3 an example for the layout planning process is presented. Obviously there are great dependencies to process 6 and 11. The matrix also shows that these processes have a high criticality concerning loss of captive process know-how. Hence a sharing of the layout planning process with a potential competitor could mean to loose captive process know-how hidden in process 6 and 11 as well.

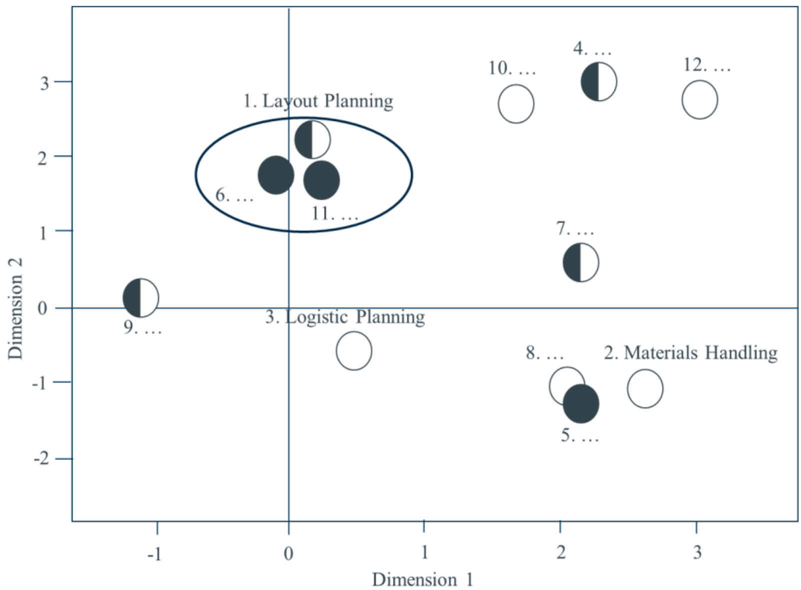

Fig. 3. Example of design-structure matrix using the rating method

As a conclusion the single scored criticality should be reconsidered. Every single scored sub-process that appears negatively in the process-dependency scoring is marked relating to a 3-point marking-system, listed below:

1. M1: quantity and quality of process-dependency is low
2. M2: high quantity and low quality of process-dependency
3. M3: quantity and quality of process-dependency is high

For example in Figure 1 the layout planning process is marked with M3. It should be pointed out, that using the process structure matrix is not the only possibility to measure process-dependencies. Another option would be the use of the correlation-matrix that is based on Quality Function Development (QFD), created by Shigeru Mizuno [27]. The QFD-matrix is used to sum up the results by showing the House of Quality (HoQ) in which the matrix represents the house's roof.

3.4 Classifying Processes Based on Scenario Planning

The foundation for classifying each sub-process is laid out. Up to this point one is enabled to score every sub-process, process-part, and process-step of the PEP singly. Also the process-dependencies can be considered. Last step of the method is to classify the identified processes, which have a high criticality concerning loss of captive process know-how.

Because the criticality of losing know-how is dependent on future collaboration models, it is necessary to consider different models that are possible in the future. Therefore a useful method for prognostication is the scenario planning method [6] [7]. Without going into detail, the scenario planning method for this example gives the opportunity to develop different future scenarios for collaboration with Chinese OEMs. Normally a worst case, a best case, and a trend scenario are developed within using the scenario planning method. Furthermore, every scenario has a unique impact on loss of captive process know-how.

	process can be shared	individual decision	process should be kept secret
scenario 1 (low risc of know-how loss)	≤ ○ ≤ M1, ≤ 20%	intermediate	≥ ◐ ≥ M2, ≥ 60%
scenario 2 (middle risk of know-how loss)	< ◐ ≤ M1, ≤ 30%	intermediate	> ● ≥ M2, ≥ 70%
scenario 3 (high risk of know-how loss)	≤ ◐ < M2, < 45%	intermediate	≥ ● > M3, > 80%

Fig. 4. Example of scenario-based classification system

On account of the fact that every process has its own characteristics concerning know-how handling, only an experienced expert should accomplish the classification system, as it is illustrated in Figure 4.

The expert has to estimate the scenario-related circumstances impact onto the risk of know-how loss. Within that estimation, the expert sets the limits for criticality, marks and percentages of every single scored sub-process, process-part, or process-step.

For its appearance as a decision-making assistant tool the presented method can only give guidance for handling captive process know-how in collaboration projects with potential competitors.

The application of the presented method shall be explained at the example of scenario 1 of Figure 4 in which the risk of know-how loss is lowly rated.

It starts with considering the scored criticality for the proposed sub-process. If this is rated middle or lower, or the process-dependency is marked with M3 or lower, there is no need to go into detail. The whole sub-process can be shared with any partner. If the criticality is rated high, or the process-dependency is marked with M2 or higher, the whole sub-process should be kept secret and not be shared with any partner. Every result that can be spaced between these extreme values needs to be individually considered. Next step would be to take a look upon the process-parts, where only the scored criticality of know-how loss is determined. A middle or lower scored criticality leads to the decision to share the whole process-part with any partner. A high rated criticality entails the denying of process-part access for every partner. Intermediate rating again has to be considered individually by precisely looking onto the process-steps. Now the percentages found in step 2, by single scoring the process-steps, come into play. A scoring of 25% or lower enables the process-step for being shared with a partner. A scoring of 80% or higher blocks any partners access. The sharing or access-denying of an intermediate rated process-step needs to be individually decided by an expert.

4 Conclusion

Although it is very complex and elaborative, the method presented enables the user to identify, score and classify any sub-process of an automotive product development process concerning captive process know-how. Certainly the method contains some deficiencies concerning the continuously understanding of scoring. Thus it does not seem to be possible to ensure an absolutely unique consistency in the overall scoring, because of the high diversity of individual rating influences. In order to keep the deficiencies to a minimum, one department should control the implementation of this methodology, and an expert team should moderate all data-collection. It could be useful to establish a standardized business process, which will enable consistent use of the above procedures.

As a reminder, this method is to be understood as a decision-making assistant tool for handling captive process know-how in collaboration projects with potential competitors.

In addition, this methodology offers the possibility not only to understand it as a tool for protecting captive know-how, but also to use it in order to identify qualification weaknesses in the project partner's processes, in order to give advice on where and how to optimize their qualification skills. The identified processes, which contain enterprises core competences in the form of captive process know-how, are unique. Potentially, this knowledge could improve every project partner's process efficiency.

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How the Integration of Environmental Concerns Modifies the Integrated Design Process

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Abstract. Regarding the economical and environmental pressure from consumers, legislation, and competitors companies need to be proactive and to propose new products in shorter times. For this, they need to change and adapt their design methods. To be effective, the design process must now address the entire life cycle of a product, from its definition to its end of life. Thus, integrated design is one solution to better design a product while considering and integrating all its aspects all along its life cycle. However, the environmental aspect is not so easy to integrate than another technical constraint. This paper aims at showing the changes induced by the integration of environmental concerns into the integrated design process. It involves notably new data, new tools, new actors or still new strategies.

Keywords: ecodesign, integrated design, environmental concerns, design process, design team.

1 Introduction

Regarding the economical and environmental pressure from consumers, legislation, and competitors, companies need to be proactive and to propose new products in shorter times. For this, they need to change and adapt their design methods. The design phase is an important phase of the product life because it determines the success or failure of the commercial offer.

The design process should not only be considered as an activity to solve problems, but as a complex activity to answer technical, social, strategic and economic concerns. Tools supporting the plurality of the domains and parameters to consider in a design process exist. Design for X tools is an example of this evolution. Those tools, issued from design for X methods, recommend a very early consideration of parameters that are usually considered very late in the design process (and so, often too constrained to be well considered). The « X » represents the Assembly (Design For Assembly), the Manufacturing (Design For Manufacturing, Design for Machining), the Recycling (Design For Recyclability), etc. They introduce a new point of view during the design process to describe not only the technological requirements but also all the future life cycle aspects of the product.

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With these new approaches considering the product life cycle, the way the organization supports design also has to be reconsidered. Concurrent engineering and then integrated design and simultaneous design are used to answer the common goal: to better design a product while considering all its aspects all along its life cycle. However, the environmental aspect is not so easy to integrate than another aspect or technical constraint. So, design approaches have to be developed to consider environmental constraints early during the design process. This paper aims at showing the changes induced by the integration of environmental concerns into the integrated design process. It involves notably new data, new tools, new actors and moreover new strategies. Necessary elements and their relationships are identified for a good environment integration.

Section 2 presents a brief review of research background. The changes induced by ecodesign in companies are presented in Section 3. Section 4 described the required elements to support the integration of ecodesign in a context of integrated design. Section 5 draws the conclusions.

2 Background

This section aims at presenting on one hand ecodesign and on the other hand concurrent engineering. The review of these two concepts is required because they are the founding principles for the issue of this paper.

2.1 Environmental Concerns in the Product Development

Currently, mechanical designers provide technical solutions to meet companies' and customers' needs as the function to perform, the cost of the product, or its ability to be mass produced. However, increasing importance of the environmental issues forces product designers to consider certain environmental criteria in the design process [1]. Thus, ecodesign focuses on the integration of environmental considerations into product development [2].

Ecodesign covers any design activity which aims at improving the environmental performance of a product [3]. According to Bovea and Pérez-Belis [4], three key factors are required to optimize the design process in term of environmental performance:

- The integration of the environmental aspects in the early stages of the product design process.
- The consideration of a life cycle approach.
- The consideration of a multi-criteria approach.

Thus ecodesign, through these three features, helps the design team to improve the product environmental performance minimizing its environmental impacts during its whole life cycle. Different motivations lead a company to ecodesign. Gurauskiene and Varzinskas [5] present some drivers for eco-design: legislative pressure, cost savings, and emerging green markets. Van Hemel and Cramer [6] summarize the most influential external and internal stimuli (table 1).

Table 1. The most influential external and internal stimuli for ecodesign [6]

The most influential external stimuli	*The most influential internal stimuli*
Customer demands	Innovational opportunities
Government regulation	Increase of product quality
Industrial sector initiatives	New market opportunities

These drivers enable to better understand the ecodesign choices of companies and their associated changes according to the priorities given for each driver.

2.2 Concurrent Engineering

In accordance with Poveda [7] we will present in this part the concurrent engineering. In order to develop a product a designer or more often a design team look for information to generate and assess solutions that satisfy both the requirements and the constraints [8]. The product design process consists in a set of actions realized by different actors. Each actor has his own tasks but the design team work together. To facilitate the works, companies are now working with new organizations "project oriented".

Those organizations do not modify the structure of companies that is still based on divisions that can be design office, production methods, purchasing department, etc. Nevertheless, those new "project oriented" approaches create a group of persons that have to meet together to discuss and to establish compromises and design choices on a particular project. This organization is necessary to avoid a viewpoint not to be considered or to be aware too late that the solution could be better.

In this organisation, the project manager is needed for conflict resolution. He manages the market study and defines the economical and technical objectives. He is a direct link between experts who have their own knowledge in their field of expertise. Those experts have the ability to assess the project with their viewpoints and to provide the information to the project manager and to the other experts.

Numerous propositions are done to model the design activity and to try to have this cooperation between the different actors that have to be considered during the life cycle. The simultaneous design concept is described as a design process where the design of the product, the design of the processes, the design of the manufacturing, the design of the assembly process, the distribution, the logistic for the use by users, and finally all the product life cycle characteristics are simultaneously considered. This can be done with two approaches described in the two following paragraphs.

A Design Can Be Parallel. One speaks about parallel design when the tasks are shared among designers and that those design tasks are realised in parallel with the others. This parallelism is necessary to decrease development time.

A Design Can Be Integrated. The integrated design aims at integrating early during the design process the constraints from different expertises to allow CAD tools to help the design and not only to assess too late the proposed solutions.

The objective is to integrate the life cycle actors during the design process and to provide them all the necessary data to think about the solution and to allow them to act on the product definition. It is not only a problem of knowledge formalisation. The problem is to create new tools to favour cooperation between the different actors having different viewpoints on the product during its definition.

From the Willingness to Integrate to the Need for Cooperation. The integrated design aims at allowing all disciplines, all experts concerned by the product under development to intervene on its design, and take into account the different experts viewpoints to make decisions all along the design process. But, either if those objectives are clear, it is not easy to implement the approach. A real difficulty consists in the translation of those recommendations and constraints into product requirements. And a more difficult question is how the different viewpoints can coexist for different steps of the product life cycle. There are often antagonisms (i.e. manufacturing constraint and aesthetics).

So, in this process starting from the expert viewpoint to a translation of the requirements, is there any general rule to assume those translations? Is there any priority between the different viewpoints? How to establish the best compromise for a product optimise regarding all the viewpoints?

That is the issue for integrated design and those questions are addressed to all the actors of the design process and new relations between them have to be established. During a project, they construct specific knowledge and know-how related to their own expertise. To really cooperate, they need to change the way they were used to work, considering only their field of expertise. They have to go toward cooperative works. In that case, they have to modify a little bit their goals and usual references. This modifies radically the design process. The goal is not only to share data but to share and modify in-depth their own expert logic.

3 Changes Induced by Ecodesign in Companies

The integration of environmental concerns induces changes in the company to be effective. Indeed, to integrate environmental goals into a design process is not like the integration of another technical constraint and organizational aspects have to be considered. In accordance with Le Pochat [9], we will show how this new viewpoint, considering a multi criteria approach during the assessment and the improvement of the product involves important changes in a company.

3.1 Data Fluxes

Numerous data need to be compiled to be able to realize environmental assessment and environmental improvement of the products. The data can be technical, organizational but also sociological. Moreover, those data have to be identified inside and outside the boundaries of the company, from the raw material extraction phase to the end-of life phase. This inventory shows that beyond the classical designers' teams, eco-design projects need the involvement of all the divisions of the company. Bertoluci et al. [10] showed on an industrial example that the informational fluxes were transformed and that a real transverse approach is necessary inside and outside the company. Sarkis [11] showed that when strategic decisions have to be made at the strategic level of the company, they have to modify their internal organization and the relations with the customers and the supply chain.

As mentioned by Gondran [12], environmental data are necessary to manage environmental impacts for a company and the network of data is really important to integrate environmental aspects during the design process. The more a company constructs relations with others, the better environmental aspects are integrated.

Two points have to be underlined:

- On one side, the necessary environmental data are outside the boundaries of the company and are spread on numerous suppliers, subcontractors, customers, recyclers, etc.
- On the other side, those data are not directly available. Indeed, the need for those data appears gradually with the eco design emergence in companies. Those needs were not relevant before, so the data were not collected.

This show the necessity to create those environmental data fluxes to complete the existing data fluxes. Many companies are now working on those questions. Indeed, this modification is not trivial for the company, because:

- The data networks are not usual. This leads the company to modify the habits and relations with the life cycle partners.
- The data are rare and spread, that generate difficulties in the collection inducing time consuming processes and additional costs.

3.2 Partnerships

One of the barriers for the eco-design approach in companies is the separation between the « environment division » and the classical structures (the « green wall »). And yet the representation of the fluxes linked to environmental concerns in the company and toward external partners shows that all the actors of the company are concerned by eco-design. Beyond the actors of the company, industrial partners from the supply chain have to be implicated in the eco-design processes. This implies a network involving internal and external partners and changes in their works.

3.3 The Design Process

Sherwin and Bhamra [13] state that ecodesign implies a concurrent engineering process. But the integration of environmental aspect during the design process is also depending on the use of new tools, on new design process and new knowledge [14]. Tonnelier [15] also underlines that technical aspects have to be considered for eco-design, but also management aspects.

So, the new organisation for eco-design, based on concurrent engineering, should consider the following transformations during the design process:

- The use of new tools (eco-design tools).
- The creation of new indicators to be able to assess the product under design from an environmental point of view.
- The use of new data.
- The implementation of new procedures to allow the definition and validation to take into account environmental constraints into the product requirements.

3.4 Companies Strategies

Integrating eco-design involves changes within the corporate strategy [11]:

- At the level of its policy.
- At the level of the strategic approach of the product development, i.e. for the definition of the specifications.

Policy: The Environment as a Value. The company has to define the environment as a value in order to explain its involvement among the workforce of the company. This involvement is necessary [15] to ensure the success of the integration.

Thus, the integration of this environmental constraint changes the hierarchy of usual values of the company (performance, quality, cost, etc.). This hierarchy has then to be redefined. Millet [14] mentioned a paradigm shift in the business.

This change in the corporate strategy will contribute to modify the communication system of the company, both internally (information, involvement and motivation of staff) and externally (marketing, CSR, etc.).

Definition of the Specifications. Defining the product specifications is difficult in the evolving context of the company. The integration of eco-design, changing the influence of each constraint to each other, will force the company to change its business strategy to enable the team to prioritize constraints, and define the specifications.

3.5 Knowledge and Skills

The eco-design integration, through the integration of a new and complex constraint, modifies necessarily the required knowledge. All the modifications within the company presented in this section require knowledge and skills which need to be created because they do not culturally exist in the company. They will enable to define the strategy, use the eco-design tools and manage the environmental data of the product.

Jacqueson [17] declares that this environmental knowledge is the driver of the eco-design integration.

4 Elements to Support Changes

To support these changes, we propose different elements to facilitate the integration of ecodesign in an integrated design. This section describes these different elements and their connections.

4.1 Actors

As described in a previous part, a design team in constituted to develop a product. This team consists obviously of designers from the design office but it also includes other actors from different departments, like research and development, methods, production, purchasing department, etc. The design team is managed by a steering team, usually by an only person called the project manager. In a context of integrated design, this project manager has a multidisciplinary role. He ensures the coordination between the different actors and their points of view in order to meet all the constraints.

Moreover, considering ecodesign, an environment expert is strongly required in order to manage eco-design and the environmental issues in the product design process. This expert is called in this paper the environmental supervisor. Indeed, the project manager needs to be assisted by this environmental expert because he usually does not have the skills to understand the environmental data, the environmental indicators and thus he cannot take informed decisions. The environment supervisor can be an environment expert of the company or if there is no environmental expert, it can be a consultant. In the same way, an environmental expertise can be required occasionally within the design process to manage environmental issue in a particular field. The project manager can learn the environmental skills through experience over time. Thus the environmental supervisor is no longer necessary.

Environmental data coming from the suppliers are required to ecodesign a product. The suppliers are therefore requested to share information about their products, components, materials, factories or other. The shared data will be useful to realize the environmental and cost analysis of the designed product. These close relationships between the supplier and the design team are quite new.

4.2 Different Requirements

This part is dedicated to the description of elements that should be required to carry out the development of an eco-product in integrated design. These elements should help all the actors to communicate, to share their work and to have a global view of the design process. The objective of these elements is to help the project manager in the decision-making process.

The Sustainability Calculation Module. The sustainability calculation module consists of three modules: a simplified life cycle assessment (S-LCA), a life cycle cost module (LCC) and a specific calculation module for ad-hoc indicators. This module is managed by the environmental supervisor and returns indicators. Data to carry out the calculations come from the suppliers and from the designer tools.

Indicators. Indicators are useful to represent the product and guide the design. Different types of indicators can be used: environmental indicators coming directly or indirectly from a life cycle analysis (LCA), cost indicators, indicators usually used by the designers, e.g. the energy efficiency of electrical motors, and other ad hoc indicators, e.g. recyclability rate.

Dashboard. The dash board consists of a panel of suitable indicators to represent the product and then guide the design towards the objectives. The project manager in collaboration with the environmental supervisor chooses indicators which meet the main objectives. Thus the project manager has to prioritize because it is not possible to manage all indicators. This set of relevant indicators changes according to the company but also according to the project. These indicators will be visible by all the actors involved in the design process. Most indicators are generated in the sustainability calculation module but some of them come directly from the designer tools. This dashboard enables to have an overview of the most relevant indicators and thus make easier the decision-making.

Reports. Two kinds of reports are generated from the calculation model with the assistance of the environmental supervisor towards different goals. The first kind of reports is dedicated to the project manager and consists of an environmental report and a cost report. These reports associated to the dashboard aim at having a comprehensive vision of the product and its weaknesses. The second type of reports is dedicated to the designers. It could be report from different viewpoints: component viewpoint, product point of view (assembly, etc.) or other viewpoints, such as material, distribution, etc.

According to the results described in the report, specific rules and guidelines are suggested to the designers in order to improve the critical points of the product highlighted by the reports.

Rules/Guidelines. Rules and guidelines for ecodesign are used to help designers to improve the environmental performance of the product.

4.3 Interaction between the Different Elements

Fig. 1 represents the main elements described in this section and their relationships. To sum up, the project manager is in charge on one hand of the product model and on the other hand of the dashboard including indicators. The environmental supervisor works on the sustainability calculation module to get indicators and reports. Obviously, the project manager and the environmental supervisor work together to manage the project and to make the decisions. The designers use their tools to realize their tasks and satisfy the requirements and the constraints

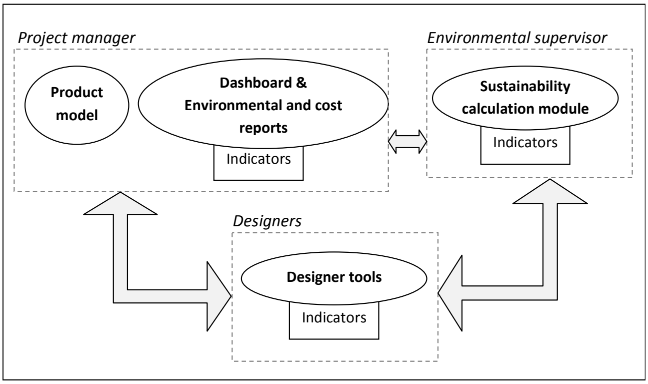

Fig. 1. Elements described in this section and their relations

The different tools and indicators are already developed but what is important is the elements dynamics and in particular the relationships between tools managed by the environmental supervisor and classical design tools managed by designers. The good choice of tools and methods is also essential and it must be done depending on the activity fields, the design process and the eco-design objectives of the company.

5 Conclusion

This paper showed the consequence of integrating environmental concerns into a design process and more precisely in the context of integrating design. Some characteristic stay constant whereas others have to evolve.

This integration of environment does not modify the functioning of the design process organization. The objective stays as in classical integrated design to integrate the life cycle actors and their different viewpoints during the design process. Moreover the need of cooperation between the different expert and also with the project manager is not changing.

However the integration of environmental issues involves changes and evolutions for a number of things. Thus, we show the needs to create environmental data fluxes, to extend the relationships with the suppliers, to have an environmental expert, to develop rules, guidelines and indicators for ecodesign, or still the need of involvement from the company. All these criteria contribute to the success of integration.

Different required elements were identified in order to support these changes into the design process. Then, these elements will be useful to describe an ecodesign methodology developed within the G.EN.ESI project. The methodology will enable to help designers in their environmental design choices.

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Towards Integrating Sustainability in the Development of Product/Packaging Combinations

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Abstract. An auspicious approach to increase sustainability of a product/packaging cycle is to investigate the dependencies between the different life cycle phases and corresponding actors. For any actor, the perspective on the global cycle initiates from his own position; therefore, it is required to make the entire life cycle more transparent by showing and interpreting the dependencies as well as the correlations and sensitivities of the different phases in the life cycle. The emerging actor network can serve as a fundament for an approach that allows for the meaningful comparison of various aspects of sustainability during the development life cycles of product/packaging combinations.

Keywords: packaging, life cycle assessment, integration, development cycle.

1 Introduction

Sustainability is an important topic in the field of packaging, which is reflected by the embodiment of the topic in mission statements of many of the large organizations in the field. Economic plans are complemented with specific ecologic goals and social protocols, adhering to Brundtland's original definition of sustainable development. Within development trajectories organizations are also more aware of the need and use for sustainability, doing justice to people, planet and profit. However, external influences put these developments under pressure. For instance, the rapid growth of economies and accompanying increase in prosperityseverely threatens the availability and accessibility of resources. Together with an ever-increasing population it is a challenge for organizations to develop product/packaging combinations that advocate a livable world for next generations.

Packaging, especially those used for fast moving consumer goods (FMCG) have an indirect but essential role in fulfilling the concept of sustainability, as its contribution to health is indispensable; without packaging it would be impossible to conserve and transport FMCG in the existing supply chain. Yet, these important aspects sometimes seem to be used as a permit for the use of scarce resources, over-specified packaging, or using the package as billboard. However, in adhering to sustainable development, it is inevitable for organizations to take ecologic responsibility for their activities. Simultaneously, economics are the driver of current society and aspects as profitability and solvability are indispensable for organizations. Thus while social aspects form the

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underlying ratio, the balance between economic and ecologic aspects is decisive in integrating sustainable development in the field of packaging for FMCG.

While the need for sustainable development is recognized by the industry and moves towards a standard prerequisite in development trajectories, the translation of mission statements, goals and protocols in adequate working methods for everyday practice is not obvious. Many tools and techniques for assessing sustainability exist, yet none is tailored to the development of product/packaging combinations; usually they do not account for the importance and particularities of the conjoint (development) life cycles of the product and the packaging.

This publication describes an approach that allows for the purposeful comparison of analysis methods for development life cycles of product/packaging combinations. In this, the corresponding working methods are elaborated on as well. Moreover, first insights on integrating LCA methodology and sensitivity analyses in earlier phases of product/packaging development cycles are depicted.

2 Sustainable Packaging

For fast moving consumer goods, the packaging often is an inherent and indispensable prerequisite to be able to transport, sell and use the product. Consequently, the life span of FMCG packaging generally depends on the life span of the content. Given the resources and energy spent in producing, transporting and using both the product and the packaging, the influence of the packaging on the 'degree of sustainability' of the combination becomes significant.

In fulfilling its functions the packaging is mostly subservient to the content. This is all the more true for FMCGs in which packaging have a larger influence on the entirety. Without its packaging, sprinkles for instance would be well-nigh impossible to transport or use. In serving its intended purpose, the product is thus largely dependent on the packaging. Moreover, the packaging becomes an intrinsic part of the product. Therefore the definition for packaging that is used in this research is: 'Packaging is a (set of) physical artifact(s) that temporarily or unremittingly assumes the functions preserving, protecting, enabling use & handling and conveying formal & informal information of the related product.'

The relation of packaging with sustainability is two-sided. By containing, protecting and preserving its content, packaging contributes to important social aspects of sustainability like health and need for food. Especially for FMCG, packaging foster the transport and use of food and drinks. On the other hand, packaging often only partly fulfill the intrinsic expectations that are embedded in the concept of sustainability. For instance, packaging materials are often made from scarce resources that are disposed when the packaging has fulfilled its functions. Furthermore, the energy needed to produce the packaging is not always in balance with its relative short life span. Therefore, it is obvious that mission statements of large organizations in the field aim at reducing use of packaging materials. However, important prerequisites such as fulfilling the packaging functions and preventing product failure, are lacking.

These preconditions are important because in many cases, the product or content has a higher environmental impact than the packaging [1]. If the packaging fulfills its functions it has a role of leverage; its potential impact on the environment is less than the potential impact of the content. The packaging can make the entirety more sustainable. In other words, an investment in packaging can prevent a product from having an environmental impact that exceeds the investment in the packaging by far.

3 Existing Tools and Techniques

For applying sustainability in the various development processes of product/packaging combinations, it is important to investigate the existing tools involved in developing product/packaging combinations. Presumably, in many cases, the degree of sustainability is determined in hindsight. Consequently, sustainability is often applied as an a posteriori check, instead of as an aspect that is inherently integrated in the development cycle. It would obviously be beneficial to use a life cycle assessment for making decisions based on environmental impact during the development phase. However, this is often unfeasible, as such an assessment requires much and detailed data that is simply uncertain or not available during the (earlier phases of the) development cycle.

3.1 Tools Evaluated

Numerous tools have been developed for assessing sustainability in the development processes of products and packaging [2, 3]. When these tools are grouped on both the required maturity of the project and a global/ specific axis, three main groups can be distinguished: principles, guidelines, checklists and scorecards; quality function deployment (QFD); and analytical tools (figure 1).

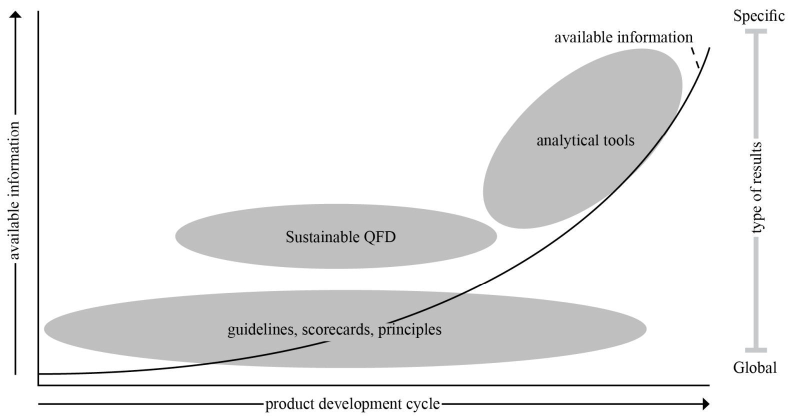

Fig. 1. Overview of tools and their applicability

Principles, Guidelines, Scorecards and Checklists. These tools offer a qualitative way of evaluating different concepts or aspects of sustainability and are amongst the most applied tools in industry. Within these tools, a huge amount of potential useful knowledge is enclosed, usually via guidelines. However, in themselves guidelines cannot offer an indication of its own applicability or scope. This is all the more true when conflicting guidelines arise. Guidelines thus provide an easy to use tool, while in reality it requires huge amount of knowledge and experience to actually adequately utilize them. In the hands of less experienced users, the guidelines can thus be easily misinterpreted or misused.

Sustainable Quality Function Deployment. Several tools based on Quality Function Deployment (QFD) are specifically aimed at sustainable development. As with customer demands and wishes, these tools try to translate sustainable demands and wishes into requirements for a product or packaging. While the translation into more specific requirements is useful, the input is often largely dependent on existing guidelines and principles. This makes QFD aimed at sustainable development subjective to the same disadvantages. However, the technique does have a unique potential in anchoring the basic functions of packaging in a sound requirement specification and thus applying the sustainable principle described in paragraph 2.

Analytical Tools. Analytical tools are almost always based on the standardized LCA methodology, in which the product/packaging life cycles are modeled and the degree of sustainability is calculated using an impact assessment method. Life cycle assessments are a reliable and adequate technique for determining the degree of sustainability, provided they are executed in the appropriate and intended manner. However, reliable data is needed and the decisions that are made about for example used databases, impact assessment method and weighing factors, have to be transparent to appropriately interpret the results [4]. Tools based on LCA thus heavily rely on detailed information and data sheets, which are often simply not known or available yet in the earlier design phases. Furthermore, the proper use of a LCA methodology asks for expert knowledge and software, which is not an expertise that is embodied in normal businesses within the field.

3.2 Conclusion Available Tools

Existing tools offer a lot of guidance and support in evaluating the environmental impact. However, none of the available tools offers the quantitative and specific results while being applicable for all development phases. The research described in this paper is aimed at filling this gap by using the functional basis offered by tools based on QFD and incorporating life cycle thinking and best practices from the standardized LCA methodology as a basis. Making it applicable in the earlier development phases, the described problems with data and expertise are challenges to be faced.

4 Life Cycles of Product/Packaging Combinations

4.1 Global Life Cycle

A common way of depicting the global life cycle of a product is from cradle to grave, consisting of the following phases: raw material, production, distribution, use and disposal. Both product and packaging pass though such a life cycle. Because of their inherent dependencies, the life cycles of product/packaging combinations are more complex than the individual life cycles for products. Reason for this is the partial concurrence of the two life cycles. Figure 2 shows the overall product/packaging chain.

In the overlapping phases, the product and packaging form an interacting entity in which the packaging fulfills its functions. Since these functions are strongly related to the product, it is inevitable to take the product into account.

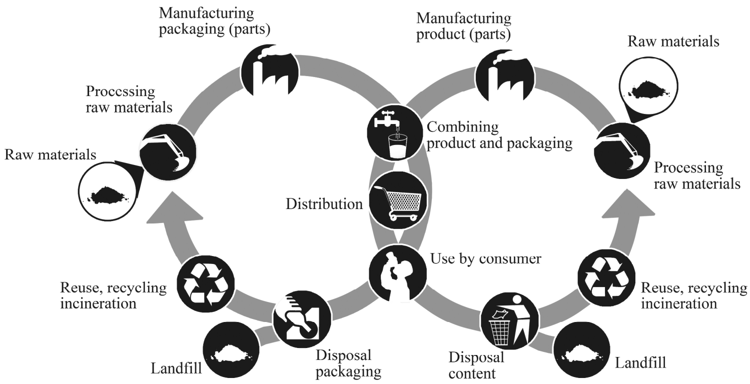

Fig. 2. Global product/packaging life cycle

4.2 Actor Network

For each product/packaging combination, the overall chain is more or less similar. While this depiction serves as a basis for understanding of the life cycles for e.g. legislation, the representation is not yet complete. In reality many more life cycles are incorporated in the product/packaging chain. Examples are life cycles from machinery, transport packaging, labels, ink, etc..

The life cycle of product/packaging combinations is thus more complex than shown in figure 2. Zoom in and the global life cycle transforms in an amalgamation of actors. For every actor, the local chain looks similar; inputs are coming from the preceding actors in the chain, the involved actors converge the inputs and the resulting output is sent to the next actors in the chain. Connecting all these links renders a network with all actors that are involved in the development of a product/packaging combination. An example of such an actor network is shown in figure 3.

In theory, an actor network is infinite, in using the network as visualization of the product/packaging life cycle, the network accommodates according to the focus point and case. This makes it possible to structure the network from every point of focus.

Using an actor network, the product/packaging life cycle becomes more clear and accurate for the various involved actors. It gives a more detailed insight into the actors that are involved in the life cycles of product/packaging combinations.

4.3 Influences and Dependencies

Mutual dependencies and influences can exists within the network, resulting in different types of relations between actors [5]. In determining these influences and their bandwidth, the so-called Customer Order Decoupling Point (CODP) can be used. This theory originated from the field of production engineering [6]. It defines the point(s)

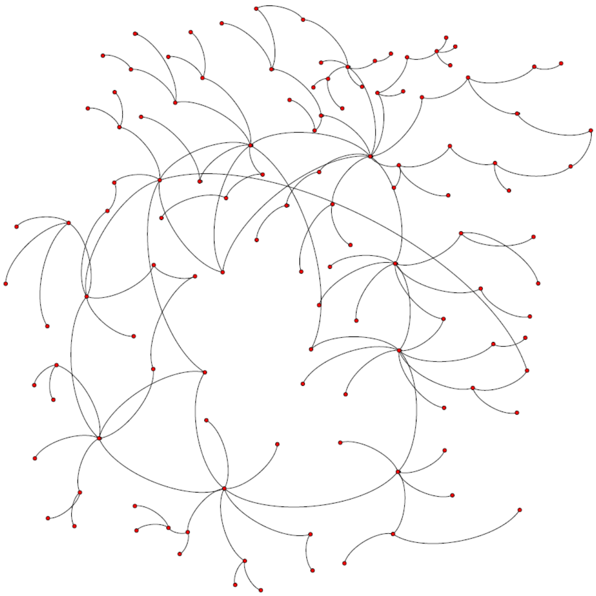

Fig. 3. Actor network

in a production process that separates the entire process in two parts: one outside the reach of external actors and a part that is organized to act and respond to the influence of these actors. In a similar manner the CODP can be used for determining the various relations that exist in the entire network. Making the points relative to the actor and changing the customer into subsequent actors, the theory renders a better assessment of the inherent dependencies as well as the influences of the various actors. Due to this influence and dependencies certain parts of the network can be considered variable or static depending on the perspective of the actor.

4.4 Conclusion Product/Packaging Life Cycles

The emerging actor network does justice to industrial practice and makes the underlying differences visible. It incorporates the daily practice of each stakeholder involved, while simultaneously focusing on the entire chain. It models the level of aggregation on which sustainable visions, missions and goals need to be incorporated in development cycles. The network forms a good foundation for a new approach which investigate different aspects like sustainability.

5 Envisaged Approach

5.1 Aim

The network described in section 4 provides insight in the various relations between the stakeholders involved and the information about stakeholders and their products.

This network, and the information it contains, can underpin the analysis of different aspects - like sustainability - throughout the entire development life cycle of product/packaging combinations. In order to facilitate developers of product/packaging combinations to adequately employ such analyses, a structured and transparent approach is required that allows for the effective and efficient manipulation of the information in the network. To make this approach instrumental in product/packaging development, the development of a facilitating tool is the appropriate way. The resulting tool can be used to make deliberate and well-considered decisions and allows for unequivocal communication between stakeholders and external parties.

The communication that is enabled between the stakeholders does not only depend on the quantitative data that substantiates life cycle analyses. Especially the different perspectives of the different stakeholders render the ability to provide stakeholder-specific decision support based on the network and corresponding, available and evolving information. In this, stakeholders can address their own focus and selection of aspects and environment, while simultaneously mapping out the overlaps and interfaces in the network. In doing this, the relative importance of individual aspects can be balanced against the context of the overall development cycle.

5.2 Scope

The tool will be developed to analyze product/packaging combinations. In this field of expertise, it is not uncommon for stakeholders to have overview of just a specific section of the entire network involved. As a consequence, probably not all stakeholders know each other. Even more, in theory the stakeholder network is infinite, having many unexpected, implicit connections and links stemming from different contexts. It is therefore impossible to take all the processes into account when analyzing the network. The goal definition and the stakeholders that are involved determine which processes are in scope during the assessment.

The advantage of the network is that it renders a dynamic structure that can transform depending on the point of view. As mentioned, the network and corresponding information are addressed differently by every stakeholder that is involved. With the tool , for example, the material processor can use the network to investigate the consequences on the network regarding to for example the environmental impact. Simultaneously, for the waste processor it is possible to determine the consequences on the life cycle when changing for example the location of waste processing. Even the concurrent attention for varying levels of aggregation is possible.

5.3 Scenarios of Use

Different scenarios from an industrial background are described to demonstrate the relevance of using an actor network for analyzing a variety of aspects such as sustainability and implementing it into different phases of development trajectories. The three scenarios prospect the achievements made possible by the network principle and outline the high-level requirements for the tool based on the stakeholder network and the accompanying working methods.

Scenario 1. With goals addressing recycling percentages achieved while reaching the limitations of material reduction, a large manufacturer decides to shift its focus towards the entire network of the product/packaging combination. As the environmental impact of the product is significantly higher than the packaging, focus is on the avoidance of food spoilage. Aiming at a more sustainable combination, a new balance is sought between the product and the packaging. With the tool, this balance between the environmental impact of the product and the packaging can be explored and the ecologic consequences for the product/packaging chain when using more material for the packaging can be investigated.

Scenario 2. In FMCGs there are countless smaller companies that have expert knowledge on one aspect of the product/packaging chain and outsource all other issues while aiming to maintain coordination and control. The decisions made in selecting a kind of packaging or logistics are made without always knowing the consequences for the entire life cycle and the degree of sustainability. The use of the stakeholder network gives such organizations more insight and control over the process. For instance, the tool can offer guidance in whether to fill wine bottles at the winegrower or close to the point of sale at a dedicated location. The possibility arises to give companies with restricted resources and budgets a meaningful comparison between various chain configurations on costs and ecologic impacts.

Scenario 3. For a packaging manufacturer, the replacement of machinery is a far-reaching decision that asks for careful consideration and trade-offs between e.g. efficiency and costs. Complementing these more or less standard procedures, the tool addresses life-cycle aspects that are more difficult to quantify. For making a thought-out decision, the tool is needed to analyze machine configurations with respect to different aspects. A first important aspect that should be investigated to assess the environmental impact is matching the supply with demand, thus whether the new capacity that assumingly creates the supply, fits the demand of the customers and the intended end users [7]. Furthermore, the desired configuration and needed flexibility to produce different packaging on a machine can be taken into account, translating future demand into requirements for the machine. The replacement of the machine could have consequences for many product/packaging life cycles involving different stakeholder that might have opposing interest. These possible conflict are always a problem in a life cycle were many stakeholders are involved. With the network these possible conflicts can be assessed.

5.4 Requirements

The scenarios in section 5.3 are examples of the broad spectrum of scenarios that can be brought together to depict the actors, environments and aspects that together define the modus operandi of the tool [8]. In other words, the scenarios depict the possible future situations in which the tool may be employed. The scenarios need to be translated into functional specifications and subsequently into technical specifications that ultimately guide the actual implementation and realization of the tool.

From a practical viewpoint, the envisaged tool must make it possible to examine the consequences for different sections of different life cycles. The result of the tool can be an overview containing the consequences on the life cycles regarding for example costs, energy use and match of supply & demand. As a basis for multi-variable, multi-stakeholders decision making, this overview renders a well-structured, transparent and objective representation that allows for mutual comparison of aspects between actors. Therefore, every actor can make a conscious decision based on the outcome of the assessment.

A specific requirement that needs to be addressed in the development of the tool is related to the availability, certainty and reliability of the information that is required or used in the development cycle. As mentioned, information can be lacking, or incomplete, which may directly influence the result of any assessment as well as the reliability of that result. Often, quantifiable uncertainties propagate throughout the assessment, but more often sheer assumptions implicitly influence the result. As a consequence, the sheer values used as inputs might even interfere with the applicability of the result. The tool thus needs to be capable of not only including the sheer quantification of the inputs, but also of including the sensitivity related to these inputs. Even more, if information on sensitivities is available and the actual value of inputs is lacking or uncertain, the tool may be able to give a more accurate result than when only using inadequate input values. Therefore, next to performing 'traditional' ways of impact assessment, the tool needs to be able to incorporate more advanced and elaborate ways of determining impacts while taking into account uncertain or lacking information.

6 Concluding Remarks

In the field of the development of product/packaging combinations, there is a clear need for more transparent and comparable assessment strategies as concerns e.g. sustainability, but also cost, safety etc. Up to now, there are too many approaches that are all based on valid, yet dissimilar inputs, rendering outcomes that have the hint of subjectivity – to say the least. In deriving a set of requirement specifications that can drive the development of an assessment approach in a top down manner, it is envisaged that a tool can be established that can determine and compare impact assessment information in the wide field of expertise involved in the development of product/packaging combinations. For this purpose, it is important to take into account the inherent complexity of the actor network that underlies the product/packaging life cycle.

While exploring this actor network and the processes and aspects that play a role in the development cycles involved, the first contours of a requirement specification for a tool and its architecture are uncovered, giving a first guideline for developing a tool that will enable to gather more experience and expertise in the field, thus giving the ability to adjust, refine and contribute to the requirement specification.

By validating the first drafts by means of case studies and scenarios from industry, the underlying principles as well as the applicability in daily practice can be assessed, from which further (subsets of) specifications and working methods can be determined. In the context of that architecture, the tool will be able to adequately support developers of product/packaging combinations independent of the position in the chain, independent of the phase of the development cycle and independent of the specific field of expertise of the actor.

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Tolerance Specification Optimization for Economic and Ecological Sustainability

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Abstract. In the final stages of product development, dimensional tolerances are specified by designers to ensure high functionality at low costs. A traditional approach to this decision-making process is to minimize economic losses to the manufacturer and the consumer. This paper presents a new approach for tolerance allocation optimization that considers sustainability not only from economic costs but also ecological costs. The framework is formulated as a multi-objective optimization problem and explored with a case study on the design of an automotive body panel. Results of the case study include Pareto frontiers of non-dominated optimal solutions along with a parametric study to explore the influence of material choice on the results.

Keywords: tolerance allocation, variation propagation, sustainability, cost minimization, multi-objective optimization.

1 Introduction

The quality of products is partially determined when designers select tolerances to specify in engineering drawings. Tolerance selection is a necessary step in product design since no product dimension can be manufactured with perfect accuracy, and a tradeoff exists because tighter tolerances increase manufacturing costs and looser tolerances often inhibit the assemblability and functionality of the product. Poor assemblability can result in a high number of defective parts and products being discarded as well as time wasted. Poor functionality, which is typically associated with consumer perception of quality, can result in products being discarded and replaced early in the expected life cycle along with customer dissatisfaction and lowered brand reputation. Discarding parts and products is not only an economic concern for manufacturers and consumers, but it is also an ecological issue, since resource and energy usage in the production and disposal of replacement parts can be significant.

This article presents a multi-objective modeling and optimization framework for considering the economic and ecological ramifications of tolerance selection in the final stages of product design. The design approach is demonstrated through a case study that considers the tolerance specifications for an automotive body panel, where specified tolerances influence a critical dimension that affects the product's assembled functionality. Results include Pareto frontiers as well as a parametric study to introduce the influence of material choice on the optimization results.

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The ensuing section discusses previous literature on tolerance analysis and variation propagation, previous efforts in tolerance-cost minimization, and techniques for environmental impact assessment. Section 3 presents the framework, methodology, and models used in the case study. Optimization results for the tolerances in the automotive panel are delivered in Section 4 and discussed in Section 5. The final section offers conclusions and discusses the broader implications of the work.

2 Background

Dimensional tolerance allocation is a subject currently addressed at several conferences and journals, and there is abundant literature discussing years of investigation on variation propagation and cost optimization in the domain of tolerance specification. Sections 2.1 and 2.2 discuss the state of the art in these two areas, respectively. The novelty of the present approach is the addition of ecological sustainability as an objective for tolerance allocation, and Section 2.3 provides a brief background of research on ecological sustainability and how it is managed in general applications.

2.1 Tolerance Allocation and Variation Propagation

Tolerances of product dimensions must be chosen carefully due to the aforementioned tradeoff between quality and cost, and they are often chosen based on the ways that each dimension influences the functional requirements of the part or product. Variance in one measurement of a part or product is said to propagate and influence the resulting variance in other measurements. Techniques to calculate the relationships and propagation between specified tolerances and critical dimension variations are often referred to as tolerance analysis and synthesis [1].

Designers typically set tolerances based on either worst-case design scenarios or statistical analyses of tolerance probability distributions and the associated critical dimension variations. This is most simply calculated using linear or linearized tolerance accumulation models, where the tolerances of components assembled in series are summed or root-sum-squared to predict the variation across the length of the whole [2]. A more common method is statistical tolerancing, where researchers and practitioners typically assume normal distributions for prescribed tolerances and calculate the distribution of the critical dimension [3]. When this calculation is impractical due to complex geometries, Monte Carlo methods are employed, in which a number of randomly-selected tolerances are generated as inputs to measure the resulting output variations [4].

All of these methods of analyzing and synthesizing tolerances have been implemented in a variety of commercial and proprietary computer software packages to aid in tolerance allocation and, in some cases, optimization [5,6].

2.2 Tolerance-Cost Minimization

Typical tolerance optimization is conducted with the objective of minimizing manufacturing costs, seeking to improve the manufacturer's economic sustainability while preserving product functionality. The two challenges in doing so are in understanding the relationships between specified tolerances and critical dimension variations, as discussed in the previous section, and in modeling the relationships between specified tolerances and costs. Data linking manufacturing costs and tolerances depend on a number of environmental factors and are typically proprietary, so researchers often use simple mathematical functions to describe these relationships for various manufacturing processes [7]. In many cases, the production of a component has more than one eligible manufacturing process, and piecewise functions or discrete tolerance-cost points can then be used for optimization [8,9]. Curves are generally fit to a set of cost-tolerance data when available, but it is common for researchers to present methods using assumed or generic cost-tolerance curves due to either an absence of data or unwillingness to publish proprietary data. One popular function is the reciprocal function, shown in Equation (1) where *c* is cost, *t* is tolerance, and a and b are parameters fit to match actual or estimated costs [10-12].

$$c = \mathrm{a} + \mathrm{b}/t \tag{1}$$

Some previous work in this area treats costs as *losses* to the manufacturer, where the loss is the difference between the cost to manufacture a certain tolerance and the minimum possible manufacturing cost, which is typically associated with loose tolerances [13-15]. This removes fixed costs from the equation and allows comparison of financial costs with functionality losses due to loose tolerances as described by Taguchi et. al [16]. The process capability index is commonly used in this work to measure process performance, normalized to three standard deviations from the mean of a tolerance distribution [17,18]. Söderberg [13] extends the loss function technique with an additional objective representing loss to the customer, as parts with looser tolerances are more likely to fail early during the use phase of a product.

2.3 Ecological Sustainability Metrics and Assessment Tools

In addition to influencing manufacturing costs, product quality for the manufacturer, and quality to the customer, tolerance selection affects the ecological impact of a product. Factors including choices of manufacturing processes, time and electricity requirements, material usage, and rates of defective parts produced link tolerances with ecological sustainability.

Ecological, or environmental, sustainability has been increasingly studied and debated in recent decades, particularly in the context of Life Cycle Assessment (LCA) or Life Cycle Engineering (LCE) techniques, which specifically target the cradle-to-grave impact of products and processes [19]. A number of environmental impact databases, standards, and software packages have been proposed to aid in designing for the health of the planet. These measurement tools include extensive environmental impact databases that associate ecological impacts with various human actions, and many of them include user interfaces to aid in identifying inputs and analyzing outputs [20,21]. Since the outputs typically fall under different categories of impact, such as resource depletion, greenhouse gas emissions, air pollution, water pollution, and landfill use, the tools use different techniques for presenting the results in a manageable format. These include equating ecological impacts with monetary values [21] or normalizing them against an average consumer's annual impact [22].

3 Methodology

The present study combines tools and techniques from the literature to present a framework for analysis and optimization of tolerances to minimize costs and ecological impacts. The approach is illustrated in Figure 1.

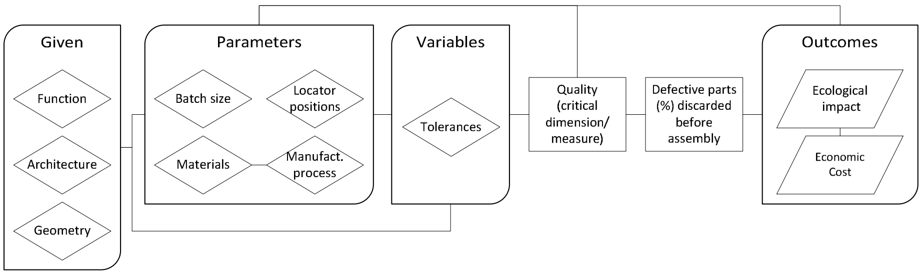

Fig. 1. Framework of product tolerance-cost-environmental-impact relationships

Here, the late-stage design problem is considered where the product function, architecture, and geometry have been decided upon, and batch size, locator positions, materials and manufacturing processes are parameters. Parameters are not allowed to vary during optimization, but they may be modified between optimizations to demonstrate how they influence the solution; this is referred to as a parametric study, and Section 4.2 shows the results of such a study on material choice. The ensuing subsections describe models that link the input parameters and variables to the outcomes in Figure 1, and with them a bi-objective optimization problem is formulated.

3.1 Modeling

The following sub-sections describe the models used to calculate the links in Figure 1 between tolerance specifications and quality, manufacturing parameters and cost, and manufacturing parameters and environmental impact. The models are built around the case study of a D-pillar in an automotive vehicle body, which is comprised of two stamped sheet metal components.

Variation Propagation. To model the propagation of variation from prescribed tolerances to critical functional dimensions, the software package RD&T is used [13]. This program is designed specifically for the purpose of analyzing variation propagation in complex geometries and includes a graphical user interface for creating models and visualizing results. The D-pillar used in this paper is shown in Figure 2, and it is subject to manufacturing variations in places where the parts are supported by other frame components and at the mating surface of the two parts. The functional requirement is that the three-dimensional position of the upper-rear corner, denoted with black squares in Figure 2, be located near the nominally designed coordinates.

The allowed variation for these critical dimensions is unclear and depends to some extent on the judgment of the designer and the design of the connecting parts. In this case, the variation in all three coordinate dimensions is allowed within one millimeter, but parametric studies are recommended to understand the sensitivity of the results to this decision.

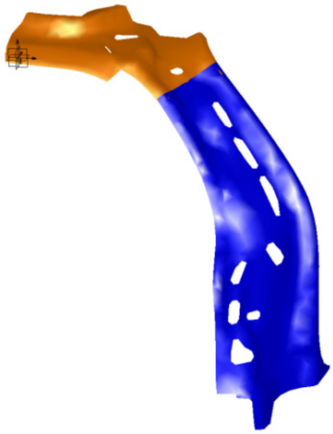

Fig. 2. D-pillar model in RD&T

Cost Modeling. As previously discussed, cost data on manufacturing processes are not widely available or publishable. In this study, like in much of the literature, a reciprocal manufacturing cost function is assumed with the form of Equation (1). As in Ding, the equation parameters are set at a = 0, b = 1 [11].

Ecological Impact Modeling. Since the objective of this article is to discuss the tradeoffs among costs and ecological impacts when making late-stage design decisions, a monetary-based rating system is used to present environmental impacts. Environmental Priority Strategies in product design (EPS) is one such metric for ecological sustainability, and it contains an extensive database that links materials and processes with environmental impacts, quantified in terms of the Environmental Load Unit (ELU) [21]. In this rating system, one ELU is equivalent to an environmental damage cost of one Euro (€).

Environmental impacts for a component such as the D-pillar of a vehicle come in the production phase, the use phase, and the end-of-life. EPS provides production impacts for creating various materials and manufacturing with different processes, as well as end-of-life impacts for different scenarios, including disposal in a landfill, combustion (for combustible materials), and reuse. The reuse scenario, which involves disassembling and recycling the components, is typically assigned negative ELUs, since reusing a material reduces future needs to produce usable materials from raw minerals. This study reports results for the landfill and reuse scenarios, demonstrating the benefits of designing with disassembly and reuse in mind.

The use phase of an automotive part is almost entirely dependent on mass, as higher-mass parts will require more fuel combustion over the life of the vehicle. Studies consistently indicate that a 10% mass reduction on a vehicle results in a 7% reduction in fuel consumption [23]. This is extrapolated and scaled for every percentage of mass change in this study. Using the assumptions that the full vehicle mass is 1800 kilograms, the baseline fuel consumption is 10 liters per 100 kilometers, and the baseline calculation that the D-pillar weighs 4.78 kilograms, the impact of the D-pillar on fuel consumption is calculated. The use phase impact is then calculated using the assumption that an average vehicle drives 300,000 kilometers over its lifetime and the EPS specification that unleaded petroleum costs the environment 1.12 ELU per kilogram. The environmental impact of the use phase is thus calculated by the amount of fuel required by the weight of the D-pillar over the life of the vehicle, compared to how much fuel would be consumed if the vehicle had no right-side D-pillar.

3.2 Optimization Framework

A multi-objective optimization formulation has been developed around the use of these three modeling tools. To simplify the optimization problem, the response surface method (RSM) is used on the computationally-intensive model of variation propagation in RD&T, where each simulation uses the Monte Carlo method with 5000 points. Based on 3600 complete simulations with full-factorial sampling of the two input tolerances on a range of 0.05 to 3.00 millimeters, a polynomial response surface was fit using linear regression to generate a closed-form mathematical function for the probability of unacceptable critical dimensions in the part as a function of the input tolerances. This surrogate model is given as Equation (2), where φ is the percentage of unacceptable parts and t_1 and t_2 are the input tolerances for the mating surfaces and support points, respectively. The model fits the data with a 0.9985 coefficient of determination, suggesting that the structure of the model is acceptable.

$$\varphi = (0.71t_1 - 7.96t_2 + 29.51t_2^2 - 6.32t_2^3 - 0.96)/100 \tag{2}$$

Using this surrogate model, a cost function is formulated with respect to tolerances and the percentage of discarded parts, shown in Equation (3) where C is the economic cost in Euros and C_{mat} is the cost of the materials in Euros, taken from [24]. The final term on the right side of the equation $(1+\varphi)$ represents a multiplier to account for discarded products, as a larger percentage of discarded products raises the effective cost of producing acceptable products.

$$C = \left(C_{mat} + {}^{1}/_{t_1} + {}^{1}/_{t_2}\right)(1+\varphi) \tag{3}$$

An additional model for ecological impact is formulated using the percentage of discarded parts and each of the factors from EPS. This is given as Equation (4), where E is ecological impact in ELUs and is a function of mass m and ecological factors E_i relating to material production, manufacturing process, the use phase, and end-of-life.

$$E = m(E_{mat} + E_{proc} + E_{eol})(1+\varphi) + E_{use} \tag{4}$$

Combining these models, a bi-objective optimization problem can be solved, formulated as Equation (5).

$$\min_{t_1,t_2} w_c C + w_e E \tag{5}$$

Here, the two components of the objective function are economic cost *C* measured in Euros, and ecological impact *E* measured in ELUs, each with its associated weighting parameter *w*. Optimization is performed with respect to the tolerance input variables t_1 and t_2.

4 Results

Multi-objective optimization results are commonly presented as Pareto frontiers, where each point on a curve represents a Pareto-optimal design that cannot be improved for one objective without a sacrifice to the other. Results for the D-pillar case study are presented in this section, starting with the baseline scenario and extending with a parametric study on material choice.

4.1 D-pillar Design Costs and Ecological Impact

The baseline D-pillar is constructed with mild steel sheet metal and an allowance of one millimeter of variance in all three critical dimensions. The Pareto frontier demonstrating the tradeoff between cost and environmental impact is presented in Figure 3.

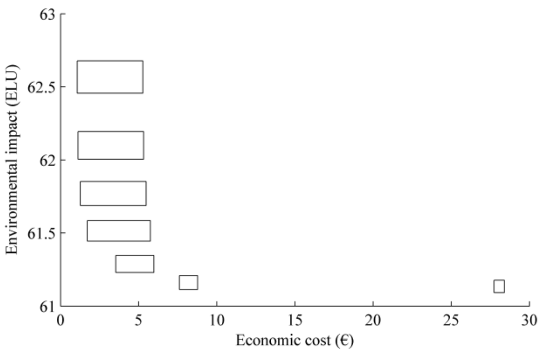

Fig. 3. Pareto frontier for baseline D-pillar, end-of-life landfill disposal

Each Pareto-optimal solution is represented in Figure 3 by a box, the dimensions of which indicate the optimizing tolerances. The horizontal width of the box represents t_1 (a wider box indicates a wider tolerance), and the vertical height represents t_2. Here, the upper-left solution corresponds with a purely cost-minimizing objective, and the lower-right solution minimizes environmental impact. The results shown here correspond with end-of-life disposal in a landfill; when reusing the materials is possible, the optimal economic costs stay the same while the environmental impacts are lowered by 8%. Combustion of mild steel is not feasible.

4.2 D-pillar Design with Parametric Variation of Material Choice

The choice of material in this case study is important to the optimization solutions, as it affects outcomes such as part mass, and therefore the use phase ecological impact, as well as ecological sustainability impacts of extraction, production, and end-of-life disposal. Further, the material thickness is adjusted for each material based on the yield strength to ensure that the part can withstand the same compressive forces as a steel component (e.g., for a rollover/roof-crush test). Data on the strength, density, cost, and ecological impacts of five common automotive body materials were found in [24] and [21], and the resulting Pareto frontiers from optimizing the D-pillar using these materials are given in Figure 4, assuming end-of-life disposal in a landfill.

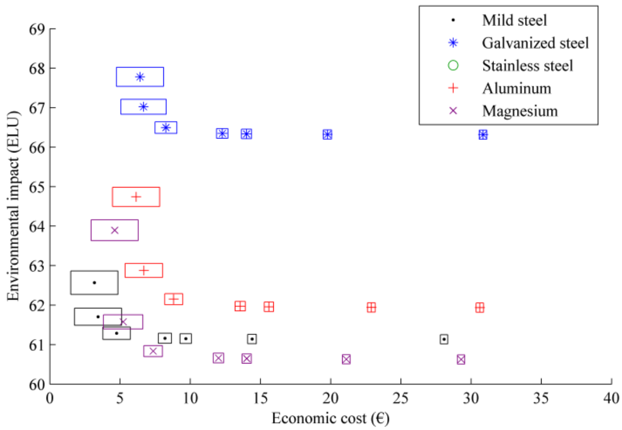

Fig. 4. Pareto frontiers of D-pillar varying material

Stainless steel has a much higher ecological impact of production than the other materials, and so the entire curve is off the visible chart in an environmental impact range of 340 to 380 ELUs. Like in Figure 3, Figure 4 presents data points as boxes where the widths and heights represent the corresponding optimal t_1 and t_2 values. Changing the end-of-life behavior from landfill disposal to reuse reduces the ecological impact by 14%, 63%, 27%, and 29% for the latter four materials, respectively.

5 Discussion

The convexity of the bi-objective optimization results for the D-pillar tolerances demonstrates a clear tradeoff between economic costs to the manufacturer and ecological impact to society. The lower-right corner of Figure 3 shows that at high manufacturing costs, the tightest tolerances are associated with the lowest environmental impact. As the weighting of the objective function shifts towards economic costs, t_1 is observed to increase, followed by an increase in t_2. Even when the environmental impact does not affect the objective function, t_2 never reaches its maximum allowed value, shown by the box in the upper-left corner of the plot. This is attributed to the economic cost of discarding a large number of faulty parts when t_2 is high. Designing parts in which the materials can be reused rather than discarded is also beneficial, as it reduces the environmental impact by up to 63%.

Parametrically varying the material choice shows that, for cost-minimizing firms, mild steel is the best option for the D-pillar. In cases where the environmental impact is more important to the manufacturer and costs are more flexible, magnesium becomes a better choice with tighter tolerances. In a scenario where the use phase becomes more important, e.g., if the number of kilometers driven increases substantially from the assumption of 300,000, lighter materials such as aluminum and magnesium may become more attractive than the mild steel. Likewise, in cases where corrosion of the part is a concern, galvanized or stainless steels may become better choices. When the design allows for reuse of the material, magnesium becomes the best choice.

6 Conclusions

While the specific results presented in this paper rely on assumptions built into the models, the framework provides new and important insights into how late-stage design choices should be considered with respect to internal manufacturing costs and external ecological costs. The automotive panel case shows a substantial tradeoff between economic and ecological costs resulting from tolerance and material choices, and further research is planned to reveal the impacts of additional sustainability decisions by designers and policymakers. As legislation and rising consumer interests in ecological sustainability continue to affect the market, this design approach will become more common for firms seeking to maximize profits in a competitive market.

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Material Selection for Eco-design

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Abstract. Product performances are directly influenced by both classical and non technical properties of the materials used. That is why Material Selection Process (MSP) is an important part of the design process. The objective of this paper is to show that existing material selection approaches including mechanical and environmental criteria are not enough complete to make optimal material choice in preliminary design phase. Indeed, in this design phase, it is necessary to do the best choice in order to optimize technical and economical requirements of a component while reducing the product Environmental Impact (EI) in the whole Life Cycle (LC). Another LC approach is proposed here, including material in several life cycles and influencing the material selection process.

Keywords: material selection, eco-design, environmental indicators, “cradle to cradle” life cycle.

1 Introduction

Product performance is influenced by both classical properties (density, Young’s modulus…) and non “technical” properties (environmental, sensorial, costs…) of the materials used. A lot of tools and methods help designers to optimize the material selection based on technical, mechanical and economical criteria during the product design process.

With green consumer pressure, and to support industry regarding new environmental legislations and competitiveness, designers are constrained to reduce environmental impacts over the whole product LC. New material selection tools based on existing methodologies are developed and include environmental indicators to take into account the environmental impact during the product LC. But those approaches are still focused on classical criteria and the relative importance of the environmental performance during the design phase is low. Also, these eco-design methodologies do not optimize technical and economical requirements of a component while reducing the product environmental impact in the whole LC.

The objective of the approach presented in this paper is to optimize as much as possible the use of material and component including them in a closed loop life cycle model. A discussion is proposed to identify what kind of characteristics designers will require to optimize material selection.

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2 Evolution of Material Consideration in Design Process

The main element which makes that a product is different than another one, more resistant, shinier, lighter or rougher is the materials from which it is made. That is why it is important to consider materials in design process to satisfy design requirements. This next part is an overview of the evolution of material consideration in design process.

2.1 Evolution of the Design Process

To success an industrial project, designers answer to a market request, a need, and in more technical terms, to a functional requirement. To gain time, designers and engineers make a design plan in order to move from a conceptual idea to a physical product. This design plan is a very important part of the success of a project, especially the preliminary step of design process where everything is planned. Product and engineering designers follow systematic approach for product design. The most known and used is the Pahl and Beitz [1] approach with the following steps:

- *Step 1: need, market identification, new design*
- *Step 2: idea Offer: Concept*
- *Step 3: idea development: embodiment*
- *Step 4: technical design, (preliminary sketch, dimension): Detail*
- *Step 5: production*

But for several years, product design process has evolved from a "technical design" based on engineering and mechanical functions to a "product design process" were designers try to take into account the product all over its LC and then several aspects as technical performance and cost [2] (Fig. 1). This evolution of the design process influences the consideration of material selection in the product design process and constrains designers to take into account a set of criteria to choose an optimal material.

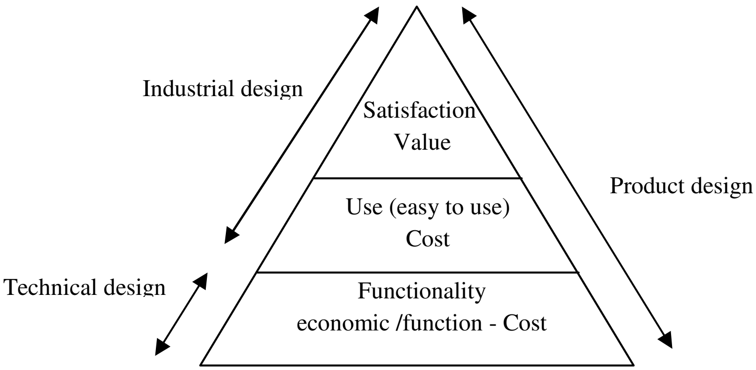

Fig. 1. The requirement pyramid

2.2 Material Consideration in Product Design

For a long time, many researchers and designers were focused on an analytic approach toward MSP based on mechanical engineering aspects (density, weight, Young's modulus). According to Pahl & Beitz, material is considered like a technical input which must be defined on quantitative, qualitative and cost terms. But, in their first version, material selection during conceptual phase, both technical and economical criteria should be specified as early as possible. For most of the product design, designers defined product requirements with classical criteria and cost and compared them with properties of existing materials in database for a first selection. Then potential materials were tested. With this analytic approach, materials are only a way to move from a conceptual idea to a physical object.

Several researchers in material selection fields as M. Ashby from the University of Cambridge changed the importance of material during the product design process.

According to Ashby [3], product design is an interaction among Material/Process/Shape. The start of a design process is the function that specified the shape and the material which had an influence on process. It was still a mechanical vision of the design process but he introduced the importance of the material selection in this process. This element allows going from an immaterial design (CAO) to a physical design. Only material and process associated could provide with their properties the final characteristic of the new product during this transition.

A lot of researchers (Table 1) [4] made a list of different aspects to be taken into account in the design process, in order to meet design requirement and market demands. Also, the vision of the product evolves with Ashby and Johnson. For them, the product supplies a functional use and a new attraction, a "personality". Material has two roles: functional (technical function) and product personality (aesthetic aspect, sensorial).

With this new considerations on material, product characteristics become a mix among function, use and "personality". The functional quality, aestheticism, appearance of a product depend on the material it is made from. The evolution of material consideration makes material selection more and more difficult due to the set of criteria and information to take into account to make an optimal choice at the earliest stage of the design process. As said by Dobranski (2001), material selection is more than fit together all the required functions, but it is a compromise among several constraints that could be completely different and opposite. It is a multi criteria selection.

To sum up, material consideration during the design process has evolved in few years. In 70's year, material selection was considering as a mechanical and engineering approach, based on technical and economical criteria during the early design phase of product design process. But society evolves, consumer needs change and the industry competitiveness is still stronger. In order to meet functional requirement and market demands, researchers in material field consider that is necessary to introduce new criteria as important as "classical criteria" during the product design phase.

For few years, with the increasing awareness of negatives product effects on the environment (resources depletion, climate warming, …) and green consumers pressures, several researchers focused on including an environmental criteria in the material selection [5]. These new external drivers highlighted the necessity to take in consideration environmental criteria in MSP as well as mechanical and cost criteria in conceptual phase of the design process.

Table 1. Review of different sources defining the effective material aspects for materials selection process

Materials (1967)	Patton (1968)	Esin (1980)	Ashby (1992)	Lindbeck (1995)	Budinski (1996)	Mangonon (1999)	Ashby & Johnson (2002)	Ashby (2005)
– Mechanical properties – Cost	– Service requirements – Fabrication requirements – Economic requirements	– Production requirements – Economic requirements – Maintenance	– General properties – Mechanical properties – Thermal properties – Wear – Corrosion/ oxidation	– Mechanical properties – Physical properties – Chemical properties – Electrical properties – Acoustical properties – Optical properties	– Chemical properties – Physical properties – Mechanical properties – Dimensional properties – Business issues	– Physical factors – Mechanical factors – Processing and fabricability – Life of component factors – Cost and availability – Codes, statutory and other – Property profile – Processing profile – Environmental profile	– General attributes – Technical attributes – Eco-attributes – Aesthetic attributes	– General properties – Mechanical properties – Thermal properties – Electrical properties – Optical properties – Eco-properties – Environmental resistence

3 Environmental Consideration

Today, easy extraction fields of some essential resources as petrol, gold and copper are depleting. Their extraction becomes more difficult and consumes resources itself, as water and combustible. This has repercussion on manufacturing processes and on the final cost of the product. Also, the consumption of important resources like minerals, combustibles (fossil and biomass) is still increasing. The UNEP (United Nations Environment Program) [6] states that the consumption volume of these resources could reach 140 billion tons per year in 2050, three times more than today.

In the same way, the world population explosion increases also the natural resources consumption. Developing countries as China, Brazil, India, have to answer to the increasing demands of their populations. And the current consumer society is such as human creates always new needs. So this economical development increases the consumption of consumer goods, raw materials and energy and makes pressure on natural resources.

Other external drivers affect the material consideration during the product design phase: the law. New international laws such as legislation (REACH, WEEE, ErP, ROHS, ROHS2,ELV)[1] and environmental standards lead designers to reduce Environmental Impact (EI) of the product all along its Life Cycle (LC). Of course these environmental legislations are important to integrate eco design in industry, but in material field, they only allow the substitution of toxic materials by others less dangerous. Indeed, it is possible to transfer negative environmental impacts across the product life cycle.

Despite the governmental or green consumer's pressures, material selection is still a compromise between technical performance and costs. The relative importance of the environmental performance during the design phase is low compared to the other "classical" criteria. Regarding to the difficulties to take into account several criteria in material selection process, it exists some tools and methods in order to help designer during the product design process summarized in the following chapter.

4 Material Selection – Tools and Methods

As said previously, product performance is directly influenced by the properties of materials used such as, weight, corrosion resistance, manufacturing processes, and emissions involved in production phase, etc. MSP is an important step in product design process. Several tools included different kind of criteria are developed in order to help designers, to make decision on materials, to structure all the information needed, to deal with multi–criteria selection and to do material hyper-choice.

4.1 Classical Tools

A lot of methods, strategies [7]and tools [8][9][10] are developed like bills of material, material databases, "material library", guidelines and softwares. The objective of material selection is to convert a set of inputs (technical, non-technical design requirements) to output (potential materials). But, in industry no particular strategy or systematic methodologies are used by designers in order to select material during the design process [9][4].

The most known material selection method is from Ashby. He has developed a set of tables which represent relationship among material properties/functional requirements and material/process. Currently, this method is the most complete to choose material during the product design process. Based on the development of performance indicators it is an iterative methodology which doesn't exclude any material solution and evolves during the product design [3]. Most of materials selection tools, as the

[1] REACH : Registration, Evaluation, Authorization and Restriction of Chemicals, Regulation n°1907/2006
WEEE : Waste Electrical and Electronic Equipment directive (2002/96/EC)
ErP : Energy related Product directive (2009/125/EC)
ROHS : Restriction of the use of certain Hazardous Substances in electrical and electronic equipment
ELV : End-of –Life Vehicle directive (2000/53/EC).

well-known software CES Selector, use this multi-criteria methodology developed by M.F Ashby.

4.2 Environmental Criteria in Material Selection Process

To support industry regarding environmental legislations and standards, and to support their competitiveness, new methodologies and tools are developed to take into account the EI during the product over it all LC, Life Cycle Design (LCD) and Design for Environment (DFE) [11][12]. At various stages of product life cycle, natural resources, combustible, chemicals, etc are required and interact with the environment (water, ground, air). As well as classical material properties, environmental material performance impacts on the environmental product performance directly or indirectly. From this stand point, new material selection tools, based on existing methodologies mentioned previously, include environmental indicators able to measure “environmental performance” of a material [13].

But, some problems are observed with these different approaches:

- Material selection with Life Cycle Assessment (LCA) or Simplified LCA (SLCA). This method take into account all the life cycle phases of the product, from the extraction to end of life. This approach is not usable during the preliminary design phase, because a lot of material and product data are required, but unavailable at this design stage. Indeed, a set of material selection tools based on LCA approach are developed depending to the industries. Designers use different environmental profile databases for materials and it becomes difficult to compare them. A problem of Environmental Impact (EI) standardization is highlighted. For instance, if the Inventory Life Cycle (ICV) EI’95 and EDIP are applied, the plastic PVC has a bad environmental behavior, but according to EI’99 and EPS methods PVC environmental behavior is higher [14]. Often, the eco-indicator method is used to calculate EI. This method aggregates all the EI into a single score [15]. It is easier to understand but there is a risk to lose a set of information. Finally, designers should be train with this type of LCA software which can be complicated and take more time.
- Other approach is to translate EI in economical terms [16]. This MSP is a compromise among cost, production and EI. But it is difficult to quantify the EI, that is why this kind of method is most of the time focused on quantifiable data such as energy consumption during the manufacturing phase and End-of life phase when designers obtain the information.
- In his works, Ashby extends his material selection method, known in mechanical field, by integrating environmental notion (energy consumption, recyclable fraction) [5][17].This approach is interesting for designers. Most of the time designers are not expert in eco-design, here MSP is still simple and easy and designers consider Environmental criteria exactly like another one. But this approach does not calculate EI all over the Product LC and there is a risk to make pollution transfer.

All these approach are not sufficient to assess the environmental performance of a material. Firstly, these methods are focused on first phases of the product LC, extraction of raw materials, production and manufacturing phases. Designers meet some problems to calculate EI in use and EoL phases due to a lack of data in early design phase. MSP in eco-design is a multi-criteria and multi-phase method. If designer consider only the first LC phases the risk of pollution transfer increases. Moreover, these methods use only quantifiable environmental parameters such as energy consumption, toxicity, substances (CO_2, NO_x, SO_2 emission). Those methodologies help designers to make material substitution, or to assess environmental impact of an existed product, but at the End-of-Life stage the product is still a waste unusable, it is a classical "Cradle to grave" life cycle assessment.

To summarize, those approaches included either classical or environmental criteria or both are not enough complete to make optimal choice in preliminary design phase in order to optimize technical and economical requirement of a component while reducing the product EI in the whole LC. In the next paragraph, a new LC approach is proposed which allows to take into consideration several end of life scenario and to reduce environmental impact of product in the whole LC.

5 New Life-Cycle Approach

For a few years, the notion of sustainable product has changed product LC moving from "cradle-to-grave"(C to G) approach to the "cradle-to cradle"(C to C) one, which is a closed loop life cycles' model. In material field, one of the most important eco-design focus of research is to optimize, as much as possible the use of material and component including them in a closed loop life cycle model. When a product becomes obsolete it is possible to improve the product lifespan using different product End-of-Life (EoL) strategies, named "3R strategy" [18].

Each element of this product could have several new LC by recovered and Reused, Remanufactured or Recycled. Determining the most appropriate EoL scenarios for each component should reduce the product EI. This new LC approach is a way to complete existing methodologies to minimize EI over the whole product LC.

But designers have to determinate this 3R strategy during the early design stage and none of existing material selection methods and tools seen previously take into account that materials and components could have several usage cycles.

Several researchers highlighted environmental benefits of components remanufacturing [19][20]. According to them, remanufacturing could reduce energy consumption over several usage cycles. Indeed, materials recycling allow consuming less raw materials, water, substances and energy during the extraction and preliminary transformation phases.

This LC approach could really improve product environmental performance in the early design stage. It is a solution to take into account all the stages of the product life cycle. Of course, designers should identify new aspects for material selection process; the best EoL strategy depending to materials which compose the product in order to avoid pollution transfer interaction among those materials, their environment in usage phase, existing recycling process. Designers need new material characteristics, as environmental characteristics, in addition to the classical one (recyclability rate, CO2 emissions…):

- Compatibility among several materials
- Material capacity for recycling
- Material assembly
- Material quality
- Material lifespan
- Life cycle options
- Etc.

6 Conclusion

In brief, material selection is an important step in the conceptual design phase of the product design process. However, there is not a systematic method to select material during this phase, and designers have to deal with an hyper choice of material and material aspects. When considering technical and economical criteria, it is still difficult to identify which parameters are suitable in order to optimize the material selection at the beginning of a design process. But it is even more difficult when designers considering environmental and no quantifiable material aspects.

The objective of MSP is to assess the performance of a material in early design stage depending to material classes, material function, use of material and end of life strategies in order to optimize the use of material and component. To select material during the conceptual phase of product design process, designers have to make a requirement list. For evaluating this entire requirement during this phase, technical and economical characteristics are important but also environmental and 'Life cycle' characteristics should be considered as early as possible. All these criteria are linked to each other. Designers cannot separate these materials characteristics if the objectives of the product design are to optimize technical and economical requirements of a component while reducing the product EI in the whole LC.

To propose a comprehensive material selection method by taking into account those new LC approach and new parameters, it is necessary to understand the complexity of material usage over the whole value chain of a product. This will be the next step of this work. Based on existing value chains of materials in France, the loss of the material value through the whole value chain of a product will then be drawn. This loss will be assessed by taking into account economical and environmental criteria, in order to identify which strategy should be chosen to optimize material value. With this model, the actors involved in the VC should be identified and the best VC strategy should be chosen depending to criteria highlighted previously and while reducing EI on the whole material value chain, by example:

- Insource the material inside its initial VC the material as "bottle to bottle" model.
- Outsource for another usage as initial and develop a new value chain

The aim of this model is not to propose new indicator or a new method to MSP, but help designers to understand the material value chain in order to influence their choices in material selection and design.

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An Information Model of the Design Process for the Estimation of Product Development Effort

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Abstract. Especially for small batch series or customer specific development orders, development costs are a noteworthy part of the overall costs and cannot be balanced by optimized production processes and lower production costs as in the case of mass production. Even though they might not be state of the art in industrial application, there are numerous methods for the estimation of costs that are determined in the course of product development. However, the costs caused by the actual development processes are hardly considered. This gap is supposed to be filled by an estimation of development costs as a direct consequence of development (and with it information handling) effort. For this an information model of the design process and the information handling steps which aregenerating the design effort are presented.

Keywords: process model, information model, development costs.

1 Introduction

Especially for small batch series or customer specific development orders, development costs are a noteworthy part of the overall costs [1] and cannot be balanced by optimized production processes and lower production costs as in the case of mass production. For the definition of a realistic quotation, the expectable costs must be identified as an insufficient quotation either inhibits the possible order, leads to a non-lucrative order or costs have to be changed during the project, displeasing the customer. This cost information has to be at hand before the development takes place (for quotations) or in in the very early phases (for go/no-go decisions).

As development costs depend mainly on labor costs [2], design effort is the crucial driver for design costs. Depending on a defined cost rate, costs can therefore be calculated based on the design effort. Another important benefit of effort estimation is the enabled project scheduling and definition of required resources. Third, effort planning enables project controlling as controlling needs a reliable planning of costs and resources. [3]

This is why this paper proposes an approach to estimate the effort of a design project as a function of product requirements and project-, process- and environment related factors prior to the actual development.

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2 Estimation of Design Effort Based on the Standard Design Process

For the estimation of design effort, a standardized process is to be defined which is generally valid and easily adoptable to a special use case. Widely accepted process models as VDI 2221 [4] are unsuitable here, as they are too generic concerning the actual process steps. It is, as a consequence, not possible to estimate the effort based on this generally valid, but hence not very detailed process. They also differ from "real" design processes, as they are not limited by industrial and organizational constraints, are less dynamic, not affected by personal characteristics and usually aim at an ideal solution instead of a satisfying one [5]. Neither theoretic reflection nor the empirical exploration of the design process could give a detailed, generally valid process model [6]. In contrast to the generic models, a detailed process model describing each single step would be suitable for an accurate estimation but would cause high effort for process definition and, of course, lose its general applicability, as design processes highly depend on the product, which is designed [7]. Hence, the definition of process steps cannot fulfill the requirements of both a suitable level of detail and general applicability.

2.1 Abstracting the Process

For the reasons explained above, a design process model is not a reasonable basis for an estimation of design effort. Consequently, the design process has to be abstracted in a different manner, not regarding the individual process steps.

For this purpose, the design is, in a first step, abstracted to the simple model of *input-black box-output* (cf. Figure 1).

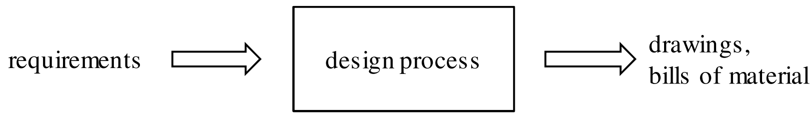

Fig. 1. Input-black box-output model of the design process

In this context, for the starting point of the design process (problem, customer order etc.) the only information considered are the new product's requirements. The process output is not the product but the information which is necessary for the manufacturing of the product, hence the 2-dimensional production drawings and bills of materials (cf. [8]). So, the design effort is the effort for the transition of the "requirements" to the production drawings and the bills of material.

Following this reasoning, the design process itself is abstracted to the generation of documents. These are drawings as the final result but also different documents in the course of the process, such as sketches, block diagrams, descriptions, 2- or 3-dimensional models (cf. [9], [10]).

Abstracting the process to the generated documents, the estimation of design effort is based on the following assumptions:

- In each design process there are similar kinds of documents that are generated.
- The number of documents depends on different influencing factors. Factors like the innovativeness of the product influences the effort as new products require more calculations, certification documents etc.
- The more documents have to be generated, the longer it takes.
- The generation of different kinds of documents requires different amounts of time.

This reasoning follows the research of the 1970s (cf. [11], [12]), assuming, that all generated documents can be normalized to a standard document (DIN A4 drawings in the example of [11] and [12]). For these documents the generation effort can be estimated using data of the analysis of working time recording [11].

But design documents in actual processes differ considerably compared to the documentation in the 1970s. Even though today drawing are still the legally relevant documents, relevant data is mainly stored in computerized models and processes are computer-aided. There are even attempts to integrate the entire geometric and calculation data in just one file [13]. This leads to the conclusion, that the consideration of design documentation is not suitable for the estimation of design effort anymore. It is much more the generation of information that is contained in the documentation, which has to be considered.

Neither the actual process steps nor the information container define the information, but it is determined by the design task and influencing factors, which will be explained in detail in chapter 4. Hence, abstracting the process to the information, it is possible to estimate the design effort on a basis, which is generally valid and easily adaptable to a special use case.

3 Information Model of the Design Process

3.1 Approach

A three step approach is executed (cf. Figure 2). First relevant design information is collected and clustered. Then the operation action (i. e. handlings steps, cf. chapter 3.4) for the information items are defined. In a third step the factors influencing both operation action and amount of information are analyzed. These will be the basis for the quantified estimation of the development effort in future research.

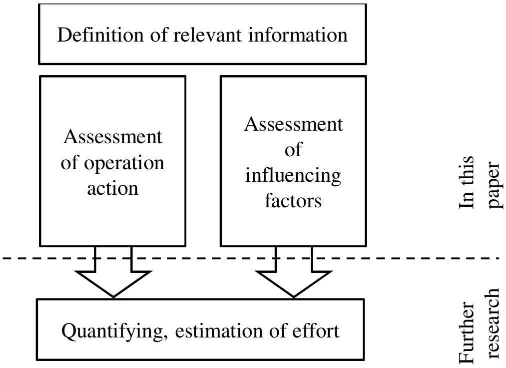

Fig. 2. Research approach

3.2 Relevant Data

First of all, process information has to be collected and structured according to the relevant literature (e. g. [8-10, 13–19] etc.).

Here documents as well as single information were taken into account and consolidated into one table of information. The information was clustered to “presumptive documents” for a clearer arrangement even though these documents themselves may never occur during design. For a specific process, information could be clustered to different groups resulting in completely different documents. It is also possible, that information only exists as tacit knowledge and is never displayed. Nevertheless, the information has to be at hand.

Table 1. List of information (exerpt)

Information cluster	**Information**	**Information cluster**	**Information**
List of requirements, technical specification		Concept, principle solution	
	Requirements		Rough calculations
	Wishes		Sketches
	Operation area		Function defined tolerances
	Aim/purpose		Function defined fittings
Function structure			Function defined surface conditions
	Function		Rough kinematics
	Interrelation of functions		

3.3 The Information Model

The relevant development information, the interrelationship within the information and the information cluster (cf. Table 1) are, in a second step, graphically represented in the information model (cf. Fig. 3).

The small white boxes represent the pieces of information that are connected with lines, representing the nondirectional relations. Dashed lines border the information clusters. In the left upper corner, requirements, wishes, operation area and purpose of the new product represent the process input, whereas production drawing, bills of material etc. represent the output in the bottom right corner. The lines of interrelation show that there is no strict and consistent process flow, but that information from the very beginning of the process are needed for all following design steps. There are no technically relevant information (i. e. information considered for the information model) items that have neither input nor output, but all information are linked.

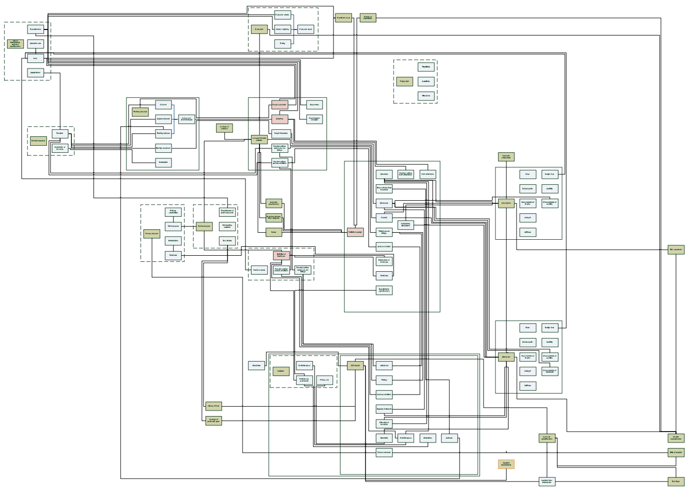

Fig. 3. Information model (full size view: www.ikt.rwth-aachen.de/information_model)

The most densely connected area can be seen in the middle of the model, where information is concentrated in the preliminary design. (As mentioned before, the term "preliminary design" is used for the clustered information and is not a specific document resulting from a specific process.) Here, all concept information is concentrated and used as a basis for calculations, simulations and the following embodiment design. In the end, most information is linked to the CAD model and processed here.

3.4 Information Operating

After identifying and clustering the relevant data, it has to be assessed in regard to handling steps each item causes. For each piece of information, there are several handling options (operation action in the following) and the authors assume that each one causes a different amount of effort.

Generation
The information considered must be generated completely up to the actually necessary degree of detail. If a piece of information is considered repeatedly in the information model, the completed definition is only executed once. For the intermediate steps only partly generation can be assumed.

Example: For the dimensions, generation would be the definition of the required dimension and the value.

Processing
The information exists in a form that has to be revised. It has to be handled to be available in an adapted/changed way. This can either be the adaption, the check or the combination of already given values/information.

Example: For dimensions, processing would be the definition of the value based on a known dimensioning item. It could also be the combination of given values/properties in a known calculation formula.

Display

The information is known, either from predecessor projects/products or because it has been generated or processed before, and is documented in this step. The action of display is to be considered in addition to the generation and cannot simply be a part of it for numerous reasons. For example even given information has to be graphically/textually displayed to fulfill legal or customer requirements causing additional effort. There is also a difference in documentation frequency and the ratio of information display and tacit information depending on special influencing factors (cf. chapter 4)

Example: For dimensions, display would be the notation of a dimensional value into the drawing (or the CAD-Model).

For a first assessment of the operation action for each piece of information a standard scenario has to be defined as most of the handling depends on special influencing factors (cf. chapter 4):

The product to be developed is represented by a set of standard requirements, which is typical for the array of products of the company. The company is experienced concerning the type of product. The actual requirements are predefined but the values/characteristics depend on the specific use case. For this scenario, the characteristics are close to the current average (cf. chapter 4), i. e. the new product is rather an incremental than a radical innovation. There is a predecessor product available within the company, which has to be changed. New components have to be added but both product structures have a substantial similarity.

4 Influencing Factors

There are factors influencing the product development process and hence the design effort coming from several different fields [20]. As the process itself is not considered in this estimation approach, the influencing factors considered here affect the number of one information item ("How many dimensions does the part have?") and the operation action ("Do I have to generate the dimension or do I only have do display given information?").

Several factors could be identified in a literature review [3, 20–34]:

- Innovation
- Product size
- Employee experience
- Multi-site development and development outsourcing
- Difficulty of the design task
- Team aspects and working environment
- Criticality of the designed product
- Educational level of the employees

Exemplarily the factors "innovation – product newness" and "product size – complexity" shall be described in the following.

Innovation –product newness
There is evidence for the direct link of a product's innovativeness (deviation of the standard requirements' values from the current average) to its development costs [35] and its newness (deviation of a product from previous generations) to the development cycle time [31]. As for this approach, innovation is only considered regarding the developing company ("new to the company"), both terms can be regarded equally here. As development cost and cycle time both depend directly on the development effort, it can be concluded here, that there is an impact of company internal innovation on the product development effort.

For the detailed analysis of this impact the assessment of the operation actions concerning the development information is expanded in two ways. First, the operation action is redefined concerning an increased innovativeness ("For an innovative product, the concept has to be newly generated and cannot be adapted, i. e. processed"). In a second step, a possibly increased amount of information ("Innovative concepts need more simulation for feasibility studies") is assessed.

Table 2. Impact of the influencing factor "innovation – product newness" (excerpt)

Information Cluster	Information	Operation action	Change of operation action	Change in information quantity
Product structure				
	Planned assemblies	Process	Generate	No impact
	Planned parts	Process	Generate	No impact
	Interrelations	Process	Generate	No impact
	Interfaces	Process	Generate	No impact

Product size – complexity
For software development an accepted method for estimating the development effort is based on the product size, i. e. the lines of source code [36]. It is obvious and proven that also for the development of physical products, the size has a reasonable impact [31], but the number of parts of the product is a measure that is usually not available at the point of time, when development effort and costs are to be estimated. In early phases the product size is therefore defined as the number of functions, a product has to fulfill [3], [23], [31]. In literature often the term "complexity" is used instead of size.

For the detailed analysis of the impact on development effort, the assessment of the list of information is again expanded. As the mere existence of more functions and accordingly more product parts does not affect the operation action, only the effect on the amount of information has to be reconsidered.

Table 3. Impact of the influencing factor "product size –complexity" (excerpt)

Information Cluster	Information	Operation action	Change of operation action	Change in information quantity
Product structure				
	Planned assemblies	Process	N/A	Strong increase
	Planned parts	Process	N/A	Strong increase
	Interrelations	Process	N/A	Strong increase
	interfaces	Process	N/A	Strong increase

5 Summary and Further Outlook

For the estimation of product development effort, the examination of the design process itself is not likely to deliver results as the process model can either be generally valid but in a consequence too generic for direct applicability or very detailed but only suitable for one special use case. To handle this contradiction an information model of the design process was introduced. For the evaluation of the design effort, the information was assessed regarding their operation actions. In a second step, influencing factors on design processes were analyzed concerning their impact on both the amount of information and the operation action.

For the estimation of the product development effort, standard values for the operation actions have to be summed up for the design information. The effect, influencing factors have on these values, has to be taken into account as relative changes, too.

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Assessing the Relationship between New Product Development Practices and Performance in the Norwegian Manufacturing Industry

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Abstract. This article reports on a survey for determining the current status of lean product development (LPD) practices among Norwegian manufacturing companies using a generic LPD model as basis. The model includes six main dimensions and was developed based on a systematic review of existing models, practices and interpretations, including the Toyota Product Development Systems amongst others. Using non-probabilistic design, a sample of 258 responses out of 356 invited subjects, demonstrates the relation between product development performance and the following elements: clear project prioritization based on portfolio thinking and balancing the workload; loyalty to the agreed upon design strategy; project dynamics cause project members to continuously update themselves on critical product characteristics; and the use of simple and visual communication modes is deployed in the organization.

Keywords: lean product development, survey, company performance.

1 Introduction

During the past several decades, lean principles and techniques have become the benchmark for Western manufacturing companies competing in the global market place. Nearly all significant market players nowadays have introduced lean principles in one way or the other, strongly founded in the success of the Toyota Production System (TPS). For the companies involved the ultimate goal is to sustain competitiveness in an increasingly hostile global business environment.

Recently, a common strategy to secure competitiveness has been associated with sourcing production to low-cost countries, which may provide short term benefits as immediate cost reductions and expanded marked presence. However, this does not necessarily guarantee long-term competitiveness; for example, many automakers have been struggling financially for a long time despite outsourcing strategies, cuts in labor and development costs, and open e-bidding for sourcing parts. A major concern in this respect is how manufacturing companies can position themselves better in the global

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market place, especially if the companies primarily operate in high-cost countries in, say, Northern Europe? One answer may be to dramatically improve the companies' capabilities to invent, develop, and produce new products, and at the same time increase customer value. Hence, companies in high-cost countries must improve their focus on innovation and product development activities to develop more attractive products, ones that satisfy user (customer) requirements, needs and desires. These improved products must research the market place earlier than the ones provided by the competitors, and before new and improved technologies are available for other market players or the market changes [1].

This article aims to address this outermost important challenge by drawing on available extant scientific and management literature on lean and integrated product development. By assessing and understanding current lean product development practices in the Norwegian manufacturing industry, companies can establish strategies for closing the gap between current performance and best-practice in areas critical to their performance. Hence, the overall objectives of the present article are as follows:

- To present the theoretical background of a lean product development (LPD) model. To present and explain the LPD model which is believed suitable for western-style climate, culture, and management, and for companies (not limited to large corporations) with a strategic focus on development and manufacturing of innovative products for the global markets.
- To present the new results of a survey in Norwegian manufacturing companies using the LPD model; that is, to identify current practices relative to several components related to lean practices in new product development.

In the following, when referring to (new) product development, this process is herein defined as: *"the collective activities, or systems, that a company uses to convert its technology and ideas into a stream of products that meet the needs of customers and the strategic goals of the company*". Moreover, lean product development is referred to as *"a company-wide product development system aimed at maximizing customer or user value, within the constraints of value of other stakeholders"* [2]. Lean product development is in this article used in a broader term than presently described by, for example, Liker and Morgan in Toyota's Product Development System (TPDS) [3].

2 Theoretical Background

2.1 Lean Product Development

Lean in a historical perspective has its roots back to the Japanese industrial success after World War II, mainly as a result of their knowledge of modern manufacturing techniques and principles utilized in a 'zeitgeist' of product and technology driven transformations. As a paradox, many of these techniques and principles originated from USA and Europe, but were adapted, customized and developed to fit the Japanese culture and context. The Toyota Production System (TPS) being the most successful example in this context [4]. Today, lean manufacturing is mainly an operational management strategy derived from TPS in the early 1980's, [5],[6],[7] and [8]. Later, lean manufacturing principles have been further developed from a manufacturing context, to organization and leadership, healthcare, military and also public organizations [3].

As relevant elements concerning LPD was scattered across fields, a new model for LPD was developed grounded in a review of scientific and management literature and the authors' interpretations based on personal experiences from industrial companies.

2.2 The LPD Model

The LPD model used is based on six core components with different sub-characteristics derived from lean thinking applied to new product development: 1) (lean) culture, 2) stabilization, 3) standardization, 4) knowledge, 5) customer value, and 6) continuous improvement [1]. The model shown in Figure 1 is based on various interpretations of the TPDS found in management and research literature, in addition to new thinking, views and practices captured from various sources. As the model is meant for LPD practices in Norwegian manufacturing companies with strategic focus on value-added products, the characteristics of the model are to some extent adapted to the climate, culture, organization and management (style) believed typical in Norwegian and other Scandinavian companies. In the following, each core component, or category, is briefly described.

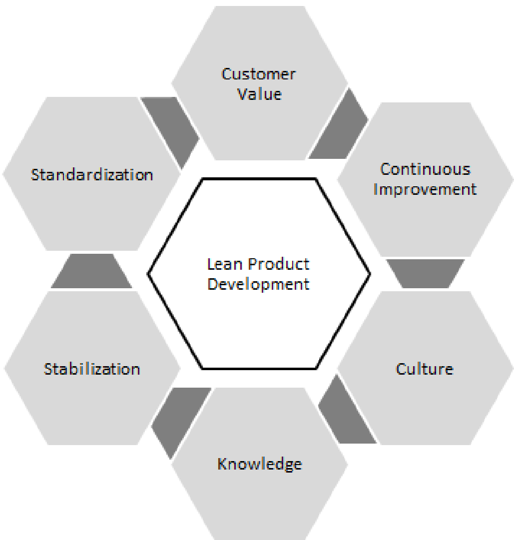

Fig. 1. The lean product development model

Customer Value (CV)

In lean, a generally accepted definition of value generation is when a specific operation meets all three of the following requirements [9]:

- The customer is willing to pay for the activity.
- It transforms the physical shape of the object or product.
- It is done correctly first time.

Waste, on the other hand, occurs when an operation fails to meet just one of these criteria. However, separating value from waste is more complicated in product development than in manufacturing since there is no physical object, the process is iterative, and the cycle time is months and years, not seconds or minutes. Product development typically involves problem-solving, information transformation [10] and knowledge creation [11], in which the work product is information and knowledge aimed at reducing the risks of taking a new product to market [2].

Mascitelli [12] claims that the values in PD are embodied in the essential deliverables needed to launch a new product: "*any activity or task that transforms a new product design (or the essential deliverables needed to produce it) in such a way that the customer is both aware of it and willing to pay for it*". Value starts with the customer, i.e., the user, consumer or ultimate customer, and the perception of value based on his or her needs, wants (spoken and unspoken), and meanings of a product [13]. Customer value then represents all the benefits that a customer, explicitly or implicitly, acknowledges with a product relative to its price.

Culture (C)

Lean thinking represents an important, but often neglected element of a company's culture [14]. Hence, LPD is an integral part of the business system, at all organizational levels and functional areas. Important in lean culture is trust, respect and responsibility. Everyone's opinion is respected, valued and considered. Responsibility is delegated to the lowest possible level, the one closest to the problem, and decisions are fact-based. Other typical elements in lean culture involve a desire for learning and use of knowledge to solve problems at the root cause. Lean culture also involves experimentation and outside-the-box thinking as seeds to innovation. Finally, visual communication to create understanding, involvement and commitment of people is integral part of lean culture.

Stabilization (S)

A PD system (infrastructure, organization, management and process) must provide a fundament for continuous improvements (CI), quality work and organizational performance; that is, there has to be an organizational infrastructure that facilitates strategic deployment and long term commitment to build excellence in PD. Browning [2] states that LPD is commonly applied with a system perspective. LPD includes defining a technology and product strategy, product leadership, portfolio management, and a design reuse strategy. In all organizational levels, management focuses on deliverables—rather than processes, activities and tasks—as most of the value is embodied in the deliverables. To secure predictable conditions in product development, resource and workload planning are important. In addition, integration of manufacturing early in PD is a key to prevent waste, i.e. design loopbacks, resource squeezes and overruns [7]. Finally, defining core and strategic products, along with the suppliers' strategic roles in delivering value, are important for establishing a design strategy founded in lean principles.

Standardization (Std)
Standardization is important for allowing more experimentation and innovation, rather than providing a means for enforcing discipline. True customer value is believed to be best and consistently delivered from multidisciplinary work based on the same knowledge standard. A standardized product development process is not only vital for variability testing, but also for making room for creativity and entrepreneurship. The purpose of standardization is generally to reduce waste, development time, risk, errors, and output variability from product development [7],[15]. Primary focus should be on standardizing output deliverables—and not on enforcing a rigid structure of activities, say, between phase gates in a rigid business governance process.

Knowledge (K)
Knowledge is important as a value stream and competitive factor for lean companies; in fact, Kennedy [16] refers to LPD as a "*world of knowledge, rather than a world of tasks*". Companies that lack systems, processes and culture for generating, capturing and standardizing knowledge for later re-use will suffer from dilution of market value when losing people (downsizing)—and not the opposite in an instant perspective, as commonly seen in the stock market. Collective knowledge generation and ability for learning are the only permanent advantages as markets, technologies and competitors change over time.

Continuous Improvement (CI)
Continuous improvement (CI) is one of the core components of lean. CI is perhaps the lean principle with the most obvious transparency between manufacturing and new product development. CI involves high involvement of people and incremental changes in products or processes for enhanced business performance [17]. CI may also be looked upon as a learning process in which a deliberate effort is made to manage and accelerate learning by as many people in improvement tasks as possible [18]. CI work is a systematic exercise and practice over time and not quick fixes, most commonly involving the use of productivity measures (performance indicators). Finally, the understanding of relationships between lead time, product performance, development cost and product cost, and business performance (profits) is required to prioritize improvement work.

3 Research Methodology

3.1 Research Design

A wide set of Norwegian manufacturing companies were chosen to participate in a descriptive survey to gain preliminary insight into the status of LPD. The main purpose of the study was, more importantly than theory development in itself, to describe facts that may be used for theory building or theory refinement [19]. The population frame (i.e. the list of all elements in the population in the sample is drawn from [19]), was based on company size (minimum 50 employees in company), having in-house product development department, manufacturing of physical non-commodity products (not services), at least 30% value added in the manufacturing process, and customer specific or engineered products.

Non-probabilistic sample design was used as it was important to obtain information relevant to and available from only certain groups [19] (i.e. personnel involved in product development and design). The subjects in the sample were product development and design engineers, quality engineers, process development engineers, project managers and functional managers. The sample size in each firm was based on firm characteristics as well as size of product development departments. The distribution of firms by industry is shown in Figure 2 below.

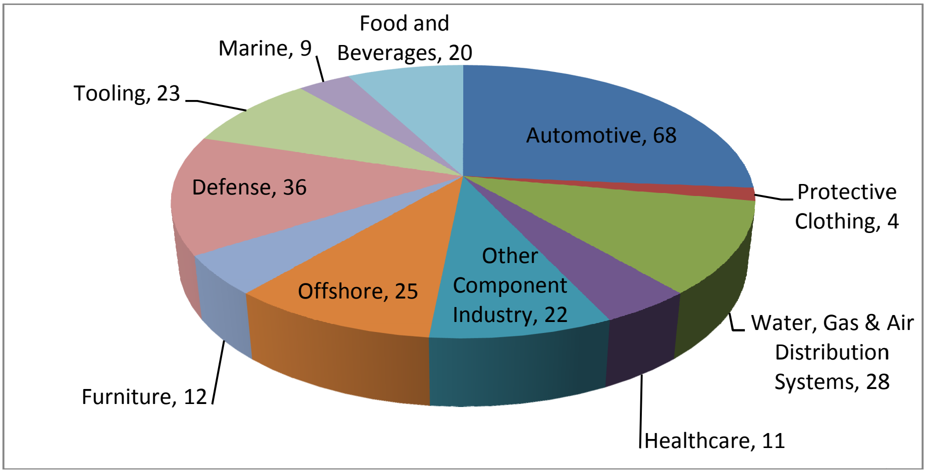

Fig. 2. Number of respondents per industry sector (N=258)

3.2 Data Collection Method

The survey was conducted in the period between September 2011 and April 2012. It was based on a questionnaire with 24 questions with predefined categories for answers. The survey was distributed on e-mail to all subjects and managed electronically and was made open to the respondents for approximately three weeks. The survey was pretested within the academic faculty before distribution to industrial companies.

The questionnaire was based on a Likert scale. The Likert scale is widely applied to measure subjective meanings, preferences, opinions, emotions and attitudes within the field of social science, and was therefore chosen as appropriate for measuring companies' current performance with respect to LPD. In the current research, a five point scale was used as presented in Table 1. McDonald found that most survey respondents prefer a five-point rating scale because the number of options is adequate and that it is easy to use [20]. The adopted scale provides the respondents with the opportunity of indicating neutrality, even though the respondents may see the middle response as the easy way out [21].

Table 1. The five point Likert scale used in the survey

Ranking	Explanation
Level 1	Strongly Disagree – There exist no evidence of this specific component
Level 2	Mostly Disagree – Awareness has begun and top-down implementation is initiated
Level 3	Neutral – Component established and ownership in place
Level 4	Mostly Agree – Component undergoing refinement and technology introduced where appropriate
Level 5	Strongly Agree – Culture change clearly evident, world-class performance achieved

3.3 Data Analysis

For each of the categories Customer value, Culture, Stabilization, Standardization, Continuous improvement and Knowledge (described above), a set of statements was outlined. The results from 24 statements, see Table 3, were compared against an indicator describing new product development performance, which was developed based on the six statements listed in Table 2. These were indexed through a factor analysis giving a Cronbach's alpha value of 0.71. Cronbach's alpha is used to calculate how well each individual item in the scale correlates with the sum of the remaining items. When Cronbach's alpha is sufficiently high for a group of items, it is reasonable to treat them as an indicator instead of in terms of individual items. The threshold-value for a reliable measure is widely discussed; for example both Kline [22] and Halvorsen [23] argued that alpha-values of 0.7 or higher are acceptable, and that 0.8 or higher indicates good reliability.

Table 2. Statements defining product development performance index

S1	Customers are generally satisfied with the true value realized in our new products
S2	Product development projects are launched on time
S3	Product development projects are launched at budget
S4	During the last three years, new product introductions have met profitability targets
S5	During the last three years our product portfolio have been extended by introducing (new to us) type of products in the marketplace
S6	During the last three years new product introductions have contributed as expected to our sales objectives

In total 258 respondents from 35 companies answered the survey. Finally, a multiple linear regression analysis was conducted to define the relationship between the dependent variable, denoted the NPD performance indicator, and the 24 exploratory variables representing the six lean product development dimensions. Support criteria are defined at $p<0.05$.

4 Results and Discussions

This study shows that four out of twenty-four statements are significantly related to the product development indicator. These four are: (1) "Every project team member knows critical product characteristics at any time, the ones that influence perceived customer value"; (2) "Selection criteria for projects are based on defined metrics, and primarily driven by our ability to mitigate risks while satisfying customer value"; (3) "Our design engineers follow the design strategy and see standardization as a means to create products of high value to customers"; and (4) "Use of simple and visual communication is strongly anchored in the company's culture". The first statement (1) is defined within the category "Customer Value" and may be perceived as a fundamental and practical way of fulfilling customer requirements.

Statement (2) is interlinked with the customer value dimension but has a more strategic perspective, which may be seen as mandatory or as more distant from everyday

Table 3. Results multiple regression analysis (* = significant at $p < 0.05$)

LPD factor	Statements (abbreviations)	Mean	Std. Dev	$Pr > \|t\|$
CV	Customer value in company's mission/vision statement	4.1	0.91	0.820
CV	Customer value drives strategy and activities in PD	4.1	0.77	0.358
CV	Customer is integrated in PD activities	3.7	0.99	0.167
CV	Team member knows product characteristics related to customer value	3.4	0.89	***0.035****
K	Knowledge gaps in PD are identified	2.8	0.93	0.749
K	The company always develops multiple design concepts early in PD	3.1	1.06	0.435
K	Insight and new information is discovered by physical testing	4.1	0.85	0.787
K	Information and knowledge is sought actively from outside company	3.6	0.88	0.141
CI	CI in PD is part of company strategy	3.9	0.92	0.206
CI	Responsibility and roles in PD are clearly defined	3.4	0.90	0.677
CI	Value added work and waste in PD are clearly defined	2.9	1.00	0.683
CI	Plan-Do-Check-Act problem solving cycle is used in PD	2.7	0.90	0.388
S	Holistic approach for project selection and portfolio planning is used	3.0	0.93	0.600
S	Risks and satisfying customer value drives project selection	3.1	0.86	***0.049****
S	Resource planning is used in PD	2.9	0.92	0.357
S	Design for Manufacturing (DFM) is used in PD	2.9	1.09	0.079
St	A formal product realization process is followed	3.3	0.96	0.138
St	Cross training is used to increase resource (management) flexibility	2.7	0.89	0.223
St	The roles of reuse, modularization and customization are defined in design strategy	3.1	0.92	0.956
St	Design strategies are followed and standardization is sought in PD	3.4	0.92	***0.023****
C	Opinions and views are equally respected of all employees	3.5	0.99	0.401
C	Responsibility is delegated to the level closest to the problem	3.7	0.83	0.656
C	Decisions are based on a process of involvement	3.6	0.82	0.928
C	Simple and visual communication is part of company culture	3.4	0.89	***0.042****

work of satisfying customers. Secondly, stabilization of the product development environment by selecting the projects where the company has the higher probability of mitigating risks and solve problems is rated high in relation to financial success. In lean this phenomena refers to 'balancing the line'—which is as important in product development to avoid overburden and unnecessary interruptions by defining a project portfolio that balances risk and reward. Here an issue may be that too much focus on stabilization and low risk projects can harm the company's ability to come up with breakthrough innovations.

The significant statement (3) belongs to the category standardization, highlighting the importance of following the agreed-upon design strategy. Deploying a design strategy means that people know what to make and do, why they should do it and how to achieve the defined objectives. This statement is highly interwoven with dimension 'Knowledge' since a defined design strategy also expresses what knowledge is important to the company, including actions in place to capture, generalize and reuse it.

The significant statement (4) is primarily related to the 'Culture' dimension, indicating the importance of simple and visual communication in the product development environments. The non-linear dynamics of product development processes, with information being the work product, calls for shared communication practices to overcome this over-complexity between different functions, competencies, countries and even time zones in order to maximize value—i.e., make the right information available to the right person when needed.

5 Conclusion

To dramatically improve the capabilities to invent, develop and produce new products, while increasing customer value, is key to sustain and increase competitiveness of Western companies. Grounded in lean theory, a model for LPD has been developed based on a literature review and interpretations and the authors' own industrial experience.

Based on survey results from Norwegian manufacturing companies, current practices relative to key LPD components have been identified. To generalize from these initial findings, and to give advice about practical application, there seems to be a pattern that PD team members emphasize clear project prioritization based on portfolio thinking with basis in the capabilities of the company. To enforce standardization and level the work load, the agreed upon design strategy is to be followed. In addition, a successful outcome in PD presumes that every project member continuously update themselves on critical product characteristics. Finally, the use of simple and visual communication modes is essential to overcome the complex dynamics and invisible nature of PD as a 'process' within the organization. Overall, this study cannot tell that these elements should be prioritized in any case; however, in context of LPD in Norwegian manufacturing companies these four characteristics seem to be highly correlated to both company and new product development performances.

For further research, the authors will increase the population to strengthen the data set and to conduct comparative analyses across borders and industries.

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An Indicator-Based Process Monitoring Cockpit for Controlling and Enhancing Product Development Processes – An Industrial Case Study

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Abstract. The need for shorter development times, lower costs, and higher quality requires improving the performance of the product development process (PDP) continuously. Therefore the evaluation and monitoring of the product development performance is of great interest for companies wishing to increase their competitiveness. However, there are very few approaches for the performance measurement of the PDP. For this purpose, a process monitoring cockpit with the overall goal to enhance the PDP regarding time, costs, quality is presented. This approach for measuring and continuously improving the current state of a company's PDP has been validated in an industrial case study.

Keywords: product development process, evaluation methodology, knowledge management, decision making, continuous improvement, industrial case study.

1 Introduction

Today's challenges facing product developers are in particular shorter product life cycles and increasing product complexity and customized products. Therefore product development processes (PDP) have to be thoroughly planned, adapted to a specific project or enterprise and constantly improved in terms of certain target criteria. This however, requires a consistent, indicator-based monitoring of each step of the product development process in order to measure its performance [1]. But, one of the biggest problems in practice is the difficulty of process improvements, as the process performance cannot be measured easily and adequately enough [1], [2].

For this problem, literature contains a variety of possible process management advices; for example, that changes in the actual process can increase the efficiency of the product development process [1], [3-5]. Moreover, there are also lots of industrial projects that seek to introduce a suitable product development process or to improve it. However, an appropriate generic process evaluation tool for the considered enterprise could not be found because existing evaluation tools are particularly not sufficiently detailed or objective or systematic [2], [6], [7].

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This paper introduces an indicator-based evaluation methodology for monitoring and enhancing product development processes in terms of quality, costs and time. The aim is to optimize the holistic product development processes with respect to its process design and organization as well as to its execution. To validate the developed process monitoring cockpit, a product development process has been introduced in an international civil engineering company with the intention to improve the processes during the development of new products in terms of these three target dimensions.

2 Background and Related Work

In the following section some fundamentals and important approaches which are the scientific background of this paper will be delineated.

2.1 Product Development Process

In times where challenges for companies are growing more complex, product cycle times are decreasing and more individual demands on products have to be considered, the development, production and first operation of new products require an efficient, transparent and detailed product creation process to enable the cooperation of the involved employees from different departments [8]. In order to monitor and optimize the single process steps as well as their interdependencies, new approaches are oriented particularly to a comprehensive product life cycle [9]. Thereby, all phases – starting from a placing of order (or market research or product idea) to the final disposal of the product – have to be considered [9], [10]. The focus of this paper is the product development process, which is part of the product life cycle, and includes, among others, the phases of product planning, definition, development, design, simulation [10].

Essential preconditions for the structured evaluation and monitoring are the consistency, completeness and logical feasibility of the product development process [11]. Once these have been checked and revised (if necessary), all steps of the product development process with their respective relations have to be displayed with the help of process modeling method (e.g. ARIS, BPMN) in form of a flowchart in order to describe and visualize each process step in detail.

2.2 Development of the Monitoring Cockpit by Existing Methods

The approach to the development of a monitoring cockpit described below can be found in [12]. In order to design an efficient and effective performance measurement system to evaluate a product development process, the company-specific requirements have to be analyzed first of all. This leads to the following requirement specification which has to be fulfilled by the performance measurement system. Thereby the main requirements are: the monitoring of the target dimensions quality, cost, time (A); the definition of individual target figures (B); the applicability to the process design (C) and to the process execution (D); the graphical presentation of the evaluation results (E); the indicator-based results (F); the low expenditure of time for evaluation (G); simplified feasibility of a repeated evaluation (H); the highly objectivity (I). Subsequently, a literature research has to be conducted. The following five methods were identified and served as a basis for the developed and in this paper outlined conceptual design of such an indicator-based monitoring cockpit:

- Requirements oriented weighted evaluation by Breiing [13]: Multi-criteria evaluation methodology in which especially customer requirements are taken into account. Determination of overall weights by multiplication of weights and values as a basis for decision making between different alternatives.
- Process audit of the VDA [14]: A process audit is used to evaluate the quality capability for specific products or product groups and their processes with the help of a detailed questionnaire.
- Technical-financial evaluation by VDI 2225 [15]: Subdivision of the criteria for technical and financial aspects and the overall evaluation results in a graphical diagram. In this two-dimensional diagram the position of the technical and financial value of one variant is shown.
- Cost utility analysis by Zangemeister [16]: Target criteria are displayed in a tree structure, in which any clusters can be formed. After the preparation and weighting of the target system, the target dimension matrix and subsequently the target value matrix have to be set up before the utility matrix can be determined.
- Performance measurement system of the ZVEI [17]: Evaluation of corporate success with the help of business indicators and thereof developed business performance measurement system.

These five methods described have to be compared with the requirement specification of the cockpit – see Figure 1 – in order to identify the respective methodological components that meet all the requirements (marked with a tick). These components are used in the following chapter to develop a methodological approach for an indicator-based process monitoring cockpit for controlling and enhancing product development processes.

Evaluation methods	Requirements									Respective components
	A	B	C	D	E	F	G	H	I	
Requirements oriented weighted evaluation	✓	✓			✓			✓	✓	✓
Process audit			✓	✓						✓
Technical-financial evaluation		✓			✓			✓		✓
Cost utility analysis	✓	✓						✓	✓	✓
Performance measurement system						✓	✓		✓	✓

Fig. 1. Overview of the fulfillment the of requirements by methods

3 Methodology for the Monitoring Cockpit

As a result of this preliminary work, an indicator-based process monitoring cockpit regarding the mentioned requirements is developed. This cockpit consists of three levels "process step", "target criteria" and "evaluation criteria". For the evaluation of the product development process, the three target dimensions “quality” and “cost” and “time” of the target criteria have to be broken down to the evaluation criteria level for each process step (see Figure 2). The company-specific evaluation criteria themselves can be optionally split again [11]. To reflect the importance of each single criterion for the fulfillment of the target dimensions, a weighting is necessary. The weighting is based on the mentioned cost utility analysis by Zangemeister [16] and has to be done for each process step and target criterion and evaluation criterion. This results in multiple target systems that include the entirety of all evaluation criteria at the finest differentiation level. Furthermore the consistency of all criteria and the same direction in terms of their target fulfillment has to be ensured.

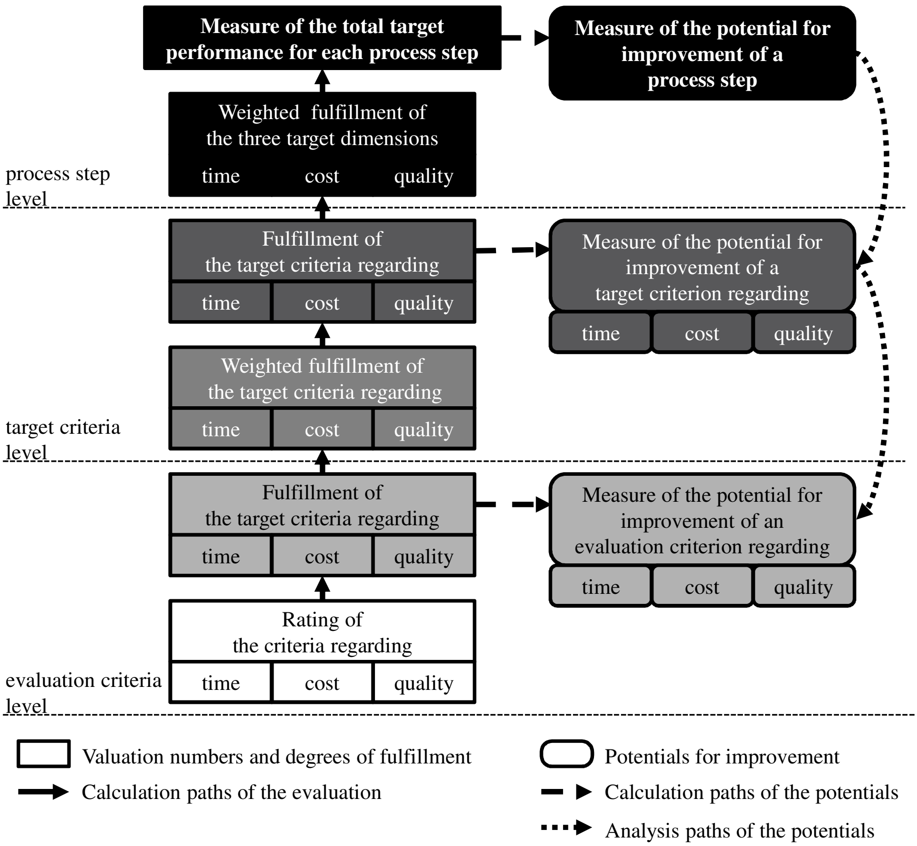

Fig. 2. Simplified overview of the indicator-based process monitoring cockpit

For each level, potentials for improvement of the three target dimensions can be calculated by using appropriate characteristic values (calculation paths of the potentials). Moreover, it is also possible that the potential for improvement (analysis paths of the potentials) of a process step (e.g. project kickoff) can be broken down into the target criteria level (e.g. personnel costs) and the evaluation criteria level (e.g. hourly rate). It will be searched, for example, for the maximum potential (see Figure 4) and then selected in the level below the corresponding target values and criteria.

Generally, it is possible to weight evaluation criteria as well as target criteria and process steps. For this weighting two different perspectives of the indicator-based process monitoring cockpit are introduced.

The first perspective is the target dimension view that allows a view on the PDP concentrating on the total fulfillment of the three target dimensions. Therefore a weighting at the target criteria level is necessary, which determines the importance of the process steps for the fulfillment of the target criteria considering the whole PDP. Because of the great number of process steps, a weighting following the principles of Zangemeister is not the ideal solution. In contrast, the requirements oriented weighted evaluation by Breiing allows to proportionate objects compared with only one reference object [13]. Afterwards the proportions between the other objects can be calculated. For this purpose consistent decision matrices are used. This results in percentage weightings of the target dimensions for all process steps.

The second perspective on the PDP is the process step view, which focuses on the importance of the target dimensions for the fulfillment of the different process steps. Therefore a process step internal weighting of the target dimensions is conducted. Because of the recurring weighting objects, a graphical weighting procedure which requires only the determination of a so called balanced weighting point is reasonable to be used (see Figure 3).

This is done by a weighting triangle, which is stretched between the three target dimensions process quality, process cost and process time. From any point within the weighting triangle, lines can be drawn parallel to the three sides of the triangle to the outside in order to read off from the respective scale the target dimensions weightings for the considered process step. Placing the balanced weighting point inside of the triangle and following the lines parallel to the sides of the triangle the intersection points with the scales positioned at the triangle's borders show the process step internal weighting (e.g. process quality 30%, process cost 40%, process time 30%), which is already normalized to 100%.

Since each process step is associated with a specific department and because for each department characteristic minimum and maximum weightings can be derived from their importance for the PDP, a standardized restriction field can be defined. In Figure 3 a grey colored area is marked in the middle of the triangle which represents the part of the triangle that is possible for setting of the balanced weighting points for all process steps which belong, for example, to the product development department.

These restrictions are set up for each department depending on their specific characteristics and objectives. The restriction, which applies to all departments, is the so called ten-percent-rule, which limits the lowest weighting for all target dimensions at ten percent in order to ensure a minimum in terms of balanced weighting.

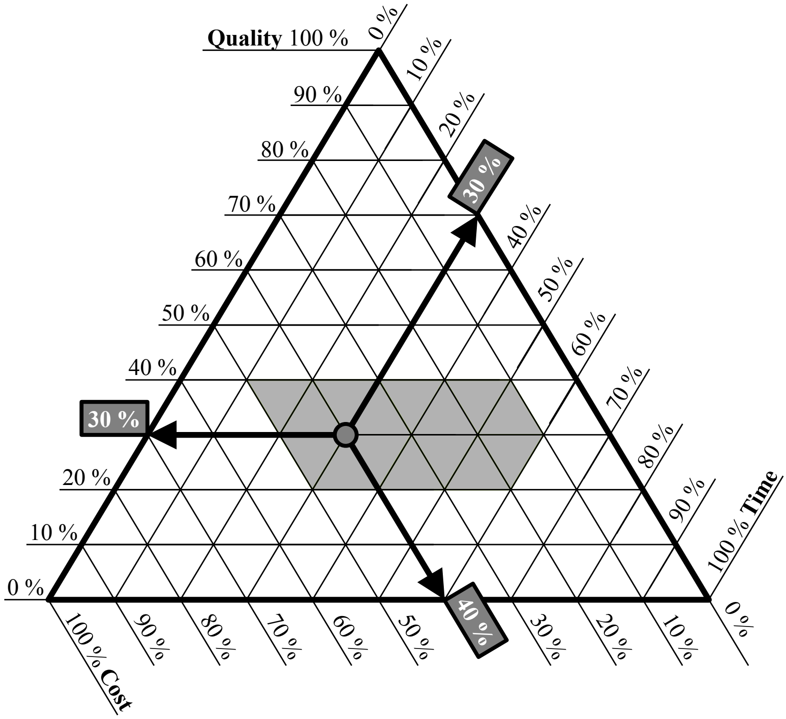

Fig. 3. Weighting triangle with an example

For instance, the weighting of the target dimension quality depends on the position of the process step in the PDP. Is it in an early phase of the PDP and the results are only first estimations which includes that there will be an overworking process step, the quality can be depressed down to 20 %. In the opposite case of a process step occurring in a late phase of the PDP the weighting for the process quality consequently has to appointed higher. So the upper limit in this example is placed at 40 %. The process costs of the process steps affecting the product development department depend on, for example, the used IT-infrastructure which can be very expensive in the case of finite elements method software or other highly specialized software solutions partially necessary in this department. So the upper limit is expanded up to 50 %. But, there are also process steps that require almost no IT-infrastructure and lower paid employees, and therefore the lower limit can be set to 10 %. In Figure 3 has the third target dimension a very great spread from the lower limit of 10 % and the upper limit of 60 %.

For the evaluation of the single criteria (e. g. expenditure of time on searching documents, time required for installation) have to be linked to target values (T) (e.g. eight hours) at the “evaluation criteria”-level. Using the actual values (V), the degrees of fulfillment (F) can be calculated. The specific degrees of fulfillment are calculated by dividing the actual performance value by the target value like it is shown in formula (1). The addition of the (weighted) degrees of fulfillment of the criteria leads to the degrees of fulfillment regarding the three target dimensions. By their process step internal weighting and addition, the degree of fulfillment of a process step can be obtained.

$$F = \frac{V}{T} \tag{1}$$

The potential for improvement (P) is calculated of the difference between the degree of fulfillment and the corresponding maximum value of one hundred percent which represents the gap to the top. To ensure, that this potential also indicates the value as well as the importance of this gap for the process performance (e.g. time), the gap has to be multiplied by the respective weighting (w). The correspondent equation is represented by formula (2).

$$P = w \times (1 - F) \tag{2}$$

The weighting is depending on the perspective of the PDP. For the target dimension view the target dimension weighting over the whole PDP is used and consequently the calculated potentials are called target dimension potentials. In contrast the potentials in the process step view are denominated step potentials and are calculated by multiplying the fulfillment gaps by the step internal weightings. For a structured analysis of the potentials in the process step view, an additional potential concerning all target dimensions is necessary. It is positioned on the process step level, calculated by the process step internal weighted sum of the degrees of fulfillment and multiplied by the process step effectively. This is a new weighting over all process steps, which respects the portion of the PDP output which is generated by the single process steps. Its calculation is elaborated analogical to the target dimension weightings with the consistent decision matrices of Breiing [13].

In order to realize the identified and calculated potentials regarding the desired target dimension, as it is shown in Figure 4, it is important to analyze the maximum potentials at an appropriate level. For instance, if the target dimension quality has to be improved, it is recommended, to concentrate on the quality potentials in the target dimension view. After locating the process step with the highest potential, the corresponding criteria potentials have to be analyzed in detail. However, there are not only positive but also negative potentials – as can be seen from the below figure 4. The time targets, for example, in the fourth step of the process were exceeded. In this case, resources or efforts can be reduced and used for the optimization of other process steps or target dimensions.

If there is otherwise no preferred target dimension, the effectively potentials serve as a starting point for concrete improvements. After finding the maximum, a process step for the optimization is determined. So its step potentials have to be investigated, to identify the most effective target dimension, which leads again to the corresponding criteria potentials.

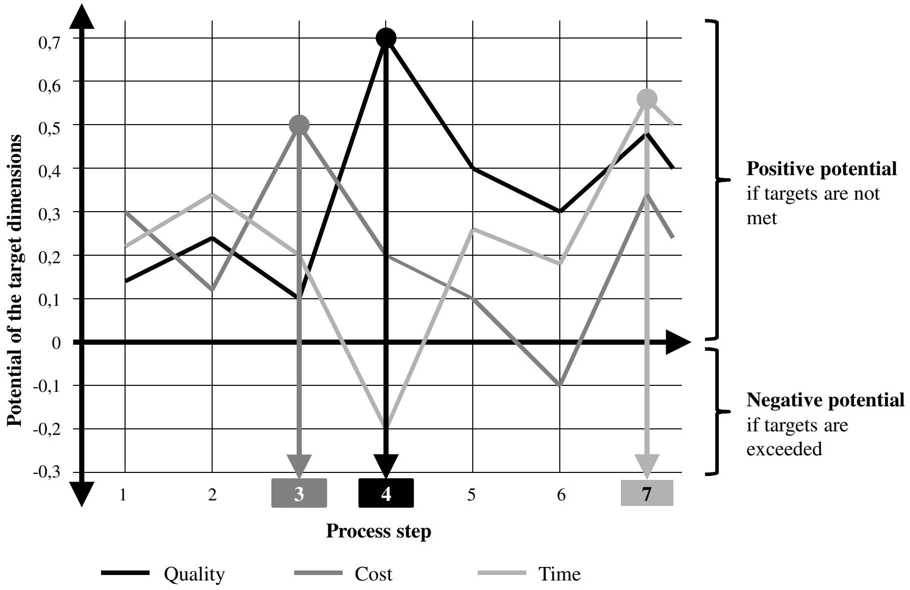

Fig. 4. Simplified example of an evaluation report of the potentials of the target dimensions

The entire execution of the product development process is monitored by the process monitoring cockpit at the mentioned levels. The graphic representation of all relevant information provides a comprehensive, objective and key-performance-indicator based evaluation for decision making in quality gate meetings. In addition, various projects can be compared with each other. Moreover, the managers get in-depth analyses about what benefits can be achieved at which process step or in respect of which target dimension through what effort. As a result, the potentials with the most effective leverage (usually corresponds to the highest positive potential) can be identified very effectively with the help of the diagram in figure 4 (see also the approach by [7]). To realize these potentials, appropriate approaches and methods for optimizing the process steps or target dimensions will be proposed automatically [6]. Negative potentials caused by the overfilling of targets indicate over-engineering or a waste of resources. In step four, for example, resources are freed up by the reducing the target fulfillment of the target dimension time. These freed resources can be used to improve the achievement of the target dimensional quality.

Beyond that, this process monitoring cockpit can be applied not only for process design but also analogously for adjusting and improving the process execution of the product development process (e.g. to avoid unnecessary iterations [18]). Therefore the differences between the execution potentials and the design potentials have to be calculated to make sure that the high execution potential does not have its source in a high design potential. This is indicated by a potential difference close to zero. In this case it would be recommended to improve first of all the process design and not the process execution.

4 Applying and Evaluation of the Monitoring Cockpit

The assessment of the indicator-based valuation methodology for monitoring and optimizing the product development process is done by its application in an industrial case study. Thereby strengths and weaknesses become apparent. Practice has shown that in particular the measurability of key criteria in the selected process steps during the product development process is crucial to the overall decision making process as well as to identify and realize optimization potentials. However, some criteria are difficult to measure and sometimes the setting of target values is difficult due to lack of information and experience. The key findings resulting from the application of the developed methodology are used for its continuous improvement.

Furthermore the application of the weightings in the industrial case study has revealed another challenge. As the process steps are executed by different departments, the knowledge about the importance of the steps to each other regarding the different target dimensions and the importance of the target values for the process steps itself have only a couple of persons. Consequently the head of each department has to define the weightings concerning the process steps under his responsibility and control. To ensure the objectivity, the weightings have to be reviewed by at least one of the executive directors. Besides this pure analysis and optimization of the product development process, the methodology can also be used for monitoring of concrete projects and for the motivation of employees through the comprehensive communication of performance charts.

5 Conclusions and Further Work

The goal of this paper was to present an indicator-based process monitoring cockpit for controlling and enhancing the product development process as well as to apply and evaluate it in an industrial case study. Practice has been shown that the developed methodology supports optimizing product development processes in their design and in their execution by connecting both aspects without losing the focus on the target dimensions quality, cost and time. This aspect-link even goes along with very useful synergy effects like the revealing of positive or harmful deviations of the execution in contrast to the process design.

In order to realize the potential benefits in future work, it is necessary that the methodology is implemented in all development processes and carried out by qualified employees. This can be ensured only when all employees are convinced of the usefulness of the process monitoring cockpit.

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A Method to Design a Smart Home Interface

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Abstract. Smart home grids require that their control devices are both usable and acceptable. The assessment of device usability and acceptability is often neglected due to the cost of prototyping solutions to be submitted to end-user during the different stages of the design process. In this context, the present paper describes a structured User-Centered Design (UCD) approach to develop usable control devices. It exploits advanced Tangible Augmented Reality (TAR) technique to represent the achieved design solution and perform usability testing without increasing development time and costs. Experimental results prove that such technology sensibility increases timesaving compared with traditional prototyping approaches and demonstrate its reliability to detect usability problems.

Keywords: Smart Home, Virtual Prototyping, Tangible Augmented Reality, Human-Computer Interaction.

1 Introduction

A smart home environment can be defined as "a dwelling incorporating a communication network which connects the key electrical appliances and services, and allows them to be remotely controlled, monitored or accessed" [1]. In the context of energy efficiency, emerging smart grid technologies have been applied to reduce the energy consumption of electric devices installed at home, to seek out the lowest rates, and contribute to the smooth and efficient functioning of the electric grid. Although most of them are commercially available, the limited service scalability, the complexity of configuration and the low usability prevent their mass adoption [2]. Rashidi and Cook [3] have demonstrated that many of these technologies are brittle and do not adapt to the user's explicit and implicit wishes. It has been demonstrated that the success of a management system for home energy efficiency is mostly determined by its ability to motivate users to adopt it in everyday life [4]. As motivation passes through the usability and acceptability of home automation control devices, they both become key requirements in device design. A computer-based interface is then necessary to properly display information and manage the system.

The increased need of accessible and usable human-computer interfaces has triggered research to develop structured methods and related tools to evaluate their utility

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and usability. Two main approaches are currently used: empirical approaches (i.e. test methods) and analytical approaches (i.e. inspection methods) [5]. In analytical evaluation, the testing process only involves expert analytics performing the assessment with the help of some well-known theoretical methods (e.g. heuristic evaluation, cognitive walkthrough, predictive methods, etc.). Contrariwise, empirical approaches are user-focused. This means that a set of representative sample users is directly involved for examining and comparing alternative design solutions while experts conduct both qualitative and qualitative evaluations. According to ISO 13407 standard [6], User-Centered Design (UCD) approach can be used for robust HMI development. In fact, involving users in the design process has been demonstrated to lead to more usable satisfying designs [7]. Notwithstanding these benefits, the problems of UCD implementation in real product design still remain costs, development time consumption and complexity of managing multidisciplinary teams to perform comprehensive analysis of user behaviors. In addition, the construction of high-fidelity interactive prototypes to conduct empirical testing at the preliminary design stage is difficult to achieve in short time and at low cost.

Over the last ten years Virtual Reality (VR)-based technologies have been introduced to replace physical mock-ups with virtual ones to achieve time saving and reduced development cost. Some studies demonstrate how VR can be useful for usability testing [8]. Although traditional VR-based mock-ups provide a good visual fidelity, they lack in behavioral simulation and natural interaction. Consequently, Mixed Reality (MR) environments have drawn a lot of attention in the field of UCD as they combine real and virtual worlds in various proportions and present them as a unified whole. Within the MR framework, the Augmented Reality (AR) technique is one of the most adopted one due to the low cost of the technologies and to its ability to enhance the real scene with computer graphics and emerging tactile and sound rendering displays [9-10]. While there has been substantial research on the underlying technology, user experience and interaction techniques are poorly explored.

In this context, the present paper describes a structured UCD approach to design highly usable control devices dedicated to manage the functionalities of smart grid platforms for home automation. The focus of the study is on the development of the graphical user interface (GUI) dedicated to desktop PCs, smart phones and other personal digital assistant devices generally used as preferred tools for software platform access and control. To improve the efficiency of the proposed UCD approach, Tangible Augmented Reality (TAR) techniques are exploited to virtually prototype the conceived design solutions and carry out usability testing with sample users. Experimental results show that designers do not require extra work to build TAR prototypes or modify solutions to meet users' explicit and implicit needs. TAR sensibility increases timesaving compared with traditional prototyping approaches.

The proposed approach and TAR prototyping technique are adopted in a particular case study that is an innovative domestic smart grid platform, called Homeline, to monitor and manage energy at home consumptions. The research partner is Indesit Company S.p.a, World leader manufacturer in household appliances, that developed the Homeline platform.

2 The Method

A UCD approach is adopted to design the Homeline interface for a large range of users with medium-level skill and expertise in using web-based applications.

After design requirements are set, the design stage starts with the definition of the system workflow and the implementing layout. Software designers, graphic designers, psychologists, marketing experts and usability experts are involved in a multidisciplinary team for brainstorming. Storyboarding is used to realize and assess various interface layout options. Once ended Homeline ideation, interface design starts. At this stage two different prototyping techniques are used to support design evaluation and performance comparison is made possible.

Firstly, a traditional technique based on the use of throwaway low-fidelity prototypes (built in Adobe Flash CS5) that allow experts to assess alternative design solutions at the early stages and a high-fidelity prototype to subsequently perform usability testing. In this case the high-fidelity prototype is developed in the same programming language of the final software (Silverlight 4 and C#). In both stages the interface is visualized on a desktop computer. The visualization on alternative displays requires additional software development efforts;

Secondly, an innovative technique that exploits MR technology to build low-cost disposable prototypes able to simulate the functionality of the interface in the same way as high-fidelity prototypes do and to simultaneously enable users to manipulate real world objects where the graphic interface is displayed (e.g. desktop computer, personal digital assistant device, portable tablet). The use of TAR prototypes allows the easily representation of system logics and graphics in an intuitive and interactive way.

Five experts in HCI are involved in preliminary testing to assess the usability of the Homeline interface. Two additional experts support test moderation and data collection. Tests are carried out both on the low-fidelity prototype and on the first TAR prototype. Experts assess usability according to Nielsen and Mohlic's heuristics [11] and then define a set of guidelines to improve the GUI. They do not find significant differences in interaction quality in case of traditional and virtual prototypes. Recommendations are followed both to build the high-fidelity prototype and to modify the preliminary TAR prototype to provide reliable prototypes.

Finally, usability testing is conducted by involving end-users. Tests are performed both on high-fidelity prototype and TAR prototype. Two samples of users, each composed by 8 typical users of the Homeline system, are involved: this number was chosen because Nielsen (1993) suggests that least eight users have to be involved to detect usability problems. Both samples presented homogeneous features: aged 30-35, 3 males and 5 females, computer and internet skilled.

The first sample is asked to carry out the usability test with the high-fidelity prototype, whereas the other one is asked to assess the usability of the TAR interface. In both cases, users have to perform a series of tasks and think aloud while a moderator takes note of any difficulties they encounter. Two experts in HCI are involved in the test, one to moderate and one to note problems.

Table 1 shows the experimental protocol used. It is based on ISO 9241-11 guidelines. Different observation techniques are used to collect data during testing: Video Interaction Analysis (VIA), direct observation and questionnaires. VIA allows human-computer interaction to be captured by recording user behaviour, words, gestures and facial expressions. Objective data such as task completion time, number of requests of assistance and clarification and errors is registered. The eye-tracking system is used to analyse eye movements and identify the GUI areas where user attention is focused during task performance. User satisfaction is explored through a questionnaire. Users are asked to express a judgement according to the 5-point Likert scale to a pre-defined set of questions.

At the end of the design process the *Homeline* GUI interface is developed both for desktop and handheld devices.

Table 1. The experimental protocol for usability test

Usability dimensions	Evaluation metrics	Units	Investigation techniques
Effectiveness	Completion rate without assistance	%	VIA, direct observation
	Completion rate with assistance	%	
	Assistances occurrence	number	
	Error number	number	
Efficiency	Time to complete Task	time (s)	
Satisfaction	Ease to use	1-5 judgment	Questionnaire
	Understandability		
	Utility		
	Sense of order		
	Pleasantness of the graphics		
	Global satisfaction		

3 TAR Prototype to Support User Testing

The Virtual Prototyping (VP) technique supporting both analytical and empirical study aims to involve multiple sensory channels, mainly touch and to simultaneously provide an interactive GUI without the effort of developing the final software before design has finished. It exploits both Tangible User Interfaces (TUIs) and AR techniques to allow users to interact with digital contents by manipulating real objects representing the physical mean of interaction.

TUIs describe physical objects able to translate user actions into input events in the computer interface. They make virtual objects accessible to the user through physical proxies by implementing what Shniderman [12] called “direct manipulation”, which can be seen as taxonomy of TUI. To fill the gap between virtual and real, AR technique is used. The final result is a Tangible Augmented Reality (TAR) prototype. It provides an immediate relationship between the virtual model, representing the GUI and the aesthetic appearance of the device where the GUI is displayed, and the physical object (a mock-up realized by rapid prototyping techniques without any surface finishing or aesthetic features) on which the first is projected.

To be interactive and usable TAR prototype (Figure 1) requires the realization of three key elements [13]: the *physical elements* of the system, the *visual display elements* and the *interaction metaphor* mapping the user-object interaction in the real world to virtual object manipulation.

The *physical elements* of the system comprehend:

- the product interface physical prototype that is equipped with a set of removable supports both for an AR id-encoded marker to calculate the camera position and orientation in real time, and for reflective markers to detect the object position during user manipulation. These components are first modeled by a CAD system and then prototyped by a 3D printer (ZPrinter 450 by Z Corporation).
- a wearable glove with four reflective markers to detect the hand position in real time (Figure 2). The fourth marker is mounted on a special ring slipped onto the user's forefinger. The glove is made of latex to ensure maximum fit. It is created to keep all user fingers uncovered to enable the sense of touch. This allows the achievement of a comfortable barrier free glove and an increasing naturalness of manipulation to minimize the user mental load during interaction.
- a Head-Mounted Display (HMD) (i.e. Wrap920AR eyewear by Vuzix), which has an optic display in front of each eye. The real world is captured by its stereo camera system and displayed in standard 2D or 3D in the eyewear. Computer-generated data is overlaid to the real image thanks to the use of AR markers.

The *visual display elements* concern the type of GUI representation and the way to realize the logical connections implementing the whole system workflow. In the developed application, the ARToolKitPlus plug-in for Virtools is used to show a virtual screen model overlaid on a user view of the physical prototype. The custom software updates the current screen in real time while the user finger interacts with the physical display selecting a specific area corresponding to a GUI control. Screens are realized by changing the virtual display “material” that consists of the interface graphics and the virtual prototype rendering. The graphics are created in Adobe Photoshop CS5.

The *interaction technique* is based on the metaphor of a real touch screen. The user accesses a new site page or interactive menus by “tapping” on these areas. Touch is simulated by the user’s forefinger staying on a sensitive area of the display prototype for 1 second. This temporal interval allows the software engine to discern between a fingertip shift without pressing and a functionality selection and represent a compromise between the prototype intuitiveness and its functionality. The interaction is computed by calculating the mutual positions between the user finger and the display area detected by it.

An optical tracking system (Optitrack by Natural Point, equipped with 6 IR cameras V110:R2 and the Tracking Tools software granting 6DoF rigid object tracking) is used to capture relative positions. The “touch sensitive” areas for each simulation screen are defined by using virtual layers.

The software system used to manage the software application is 3DVIA Virtools by Dessault Systems, a development platform for VR applications.

TAR actually allows true spatial registration and presentation of both 3D virtual objects and contents in the physical environment. The involvement of a haptic feedback and the creation of continuity between the interaction space and the display space lower the mental load due to the fact that the user is able to directly experience the effects of their actions on the object. A Head-Mounted Display (HMD) is adopted to keep the user viewpoint focused on the GUI projected on the object they are holding in their hands.

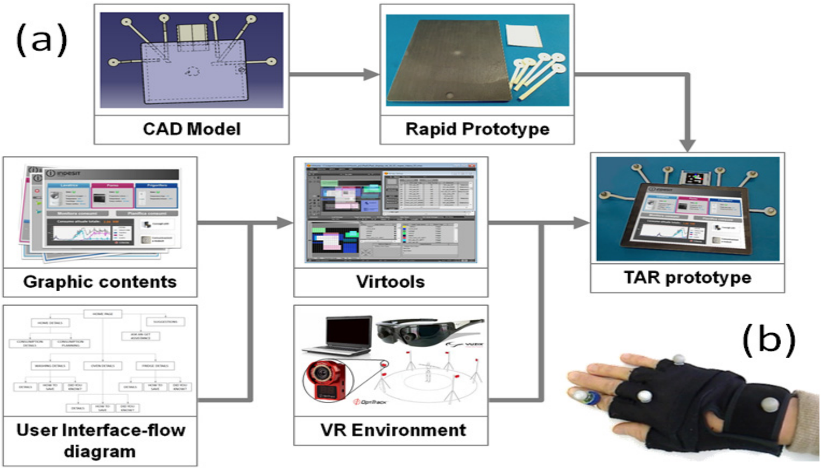


Fig. 1. How to build TAR prototype (a). The glove and the IR-marker holder ring (b).

4 The Experimental Case Study

Usability tests are first carried out on the traditional high fidelity prototype. They involve 8 sample users (5 women and 3 men), aged between 35 and 40 years. They currently use computer applications and navigate Internet sites. The laboratory is equipped with an HW workstation with Internet connection and a VCR camera and microphones for VIA. Product usability is evaluated by task analysis (Table 2) following the above-mentioned experimental protocol (Table1).

Table 2. Task description

	Task description
1	Imagine that this is the situation in your home at this time. What is the total consumption in your home?
2	What appliances are running at the moment and what they are consuming?
3	Check out the consumption of your home last week.
4	Check the trend of consumption in the last hours of your oven.
5	Check how much it costs to start a wash at this time and how much it would cost at 23:00. The data set: wash "Cotton White", temperature 60°C, centrifuge at 800 rpm and extra rinse option.
6	Find tips on how to prepare the chicken.
7	You would like to have the laundry washed and chicken cooked by tonight at 20:30. You have to simulate various solutions time to run appliances and to examine how the costs vary. Set data: OVEN: traditional cooking at 180°C for 60 min., WASHING MACHINE: coloured cotton at 30°C with 1000 rpm spin.
8	Your washing machine has problems in the centrifuge. Ask for technical assistance.

Before starting the test, all users are informed of the testing purpose. Then, the Homeline home page is shown to the users and they are asked to answer a questionnaire to assess their first impression (i.e. before use satisfaction) (Table 3).

Table 3. The satisfaction questionnaire

	Evaluation metrics	Questions (1-5 Likert judgement)
A	*Ease to use*	The website is very ease to use
B	*Understandability*	Information provided by the website are very ease to understand
C	*Utility*	The information provided by the website are very useful
D	*Sense of order*	The information inside the website are very well organized
E	*Pleasantness of the graphics*	You find very beautiful the look and feel of the website
F	*Global satisfaction*	Overall, you are satisfied with the website

At the end of the test, the same questionnaire is newly submitted to the users to assess the quality in use (i.e. satisfaction in use). For each task performance data about percentage of task completion, completion time, number of errors and clarification requests are collected. The achieved results show that the Homeline interface has serious usability problems. In particular, task success is low for tasks 3, 6 and 7 (Figure 2).

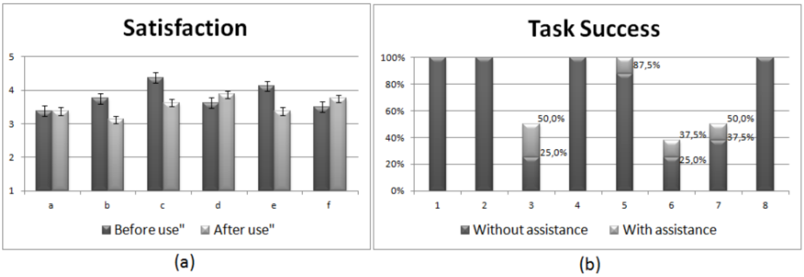


Fig. 2. Usability result with high-fidelity prototype: judgment about the average user satisfaction metrics before and after use (a); task success (b)

The percentage is higher in the case of very simple tasks. The measured low usability strongly influences users' opinions about the system. Satisfaction ratings pre and after-use are low (Figure 2). In particular, the average judgment expressed after use regarding ease of use, sense of order and understandability, is significantly lower than that expressed before use.

Nevertheless, the average rating for system usefulness after use is higher than before use. This demonstrates that the system is able to motivate users and communicate the benefits offered by provided services. It was not possible to make an objective assessment of the efficiency of the system SW, based on a comparison of average time taken by users and the expert user time, because of large differences in page loading times between the various users.

Once the TAR set-up has been arranged, usability testing is carried out with end-users. The same protocol of Table 1 is adopted without any variation with respect to the traditional approach. The laboratory where the tests are carried out is equipped with: an eye-tracking system (Optitrack V110:R2 by Natural Point, equipped with 6 IR cameras and Tracking Tools for tracking rigid bodies, which allows 6DoF object tracking), a PC with the Optitrack Software and Virtools 4.0 by Dassault Systems and the developed plug-in applications, two gloves in different sizes (small and large) and a resizable ring with reflective markers, an head-mounted display iWear VR920 HMD, and, finally, a digital camera and microphones for VIA.

A second group of users with the same characteristics as the ones involved in the tests on the traditional high-fidelity prototype is involved. Before starting with the test, all users are informed of the testing purpose. A calibration stage is required to ensure that the optical tracking system captures the position of the user's hand and forefinger. Users are asked to wear the two gloves in succession to identify the one, which fits their hand size better. The position of this ring is continuously varied along the forefinger to set the right position of the virtual pointer.

The experimental procedure is the same as the test with the traditional prototype. Both efficiency and effectiveness metrics are measured as well as satisfaction before and after use. Performance and satisfaction tables are fulfilled for each task and involved user. The results of task success (Figure 3) reveal that the interface is not able to assist users in performing tasks 3, 6 and 7. This strongly influences the user's judgments after-use (i.e. ease to use and sense of order metrics). However, the global satisfaction is partially high due to the enthusiasm deriving from the use of an innovative technology and the iPad-like interface.

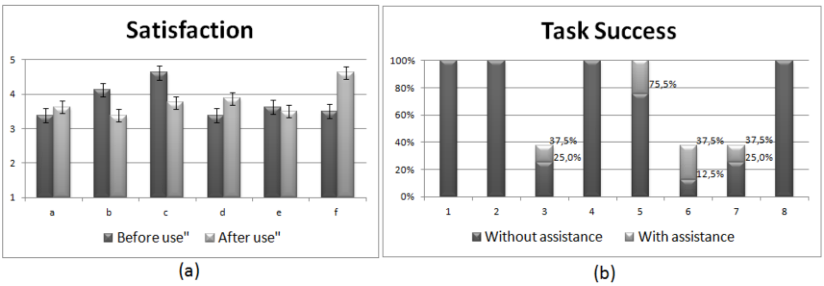


Fig. 3. Usability result with TAR prototype: judgment about the average user satisfaction metrics before and after use (a); task success (b)

By analyzing the results, it is possible to infer that TAR interactivity guarantees the simulation of the final software behaviour still conceptual design. Comparison of Fig.2b and Fig.3b highlights that the technological set-up does not affect task success and satisfaction perceived before use. Although TAR enhances satisfaction in use it does not affect the trend of satisfaction perceived after use. Accordingly, results point out TAR effectiveness to create interactive prototypes for usability testing.

In order to prove the efficiency of TAR techniques to carry out usability assessment in place of high fidelity prototypes an additional evaluation is performed. It consists in the analysis of the effort to virtually prototype alternative solutions and to set the proper experimental environment.

Table 4 reports the time spent for design the system by following both approaches. This achievement is fundamental to increase the use of these technologies in industry. Total time comparison shows that TAR sensibly reduces prototyping time.

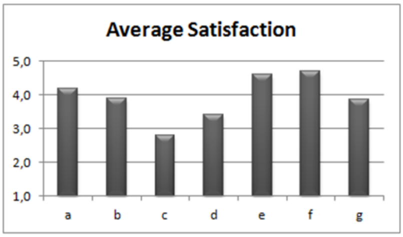
Table 4. Comparison between traditional UCD and TAR based approaches

Traditional UCD approach		TAR based approach	
5 days	Brainstorming and storyboarding		5 days
30 days	Construction of a low fidelity prototype using Adobe Flash CS5	TAR prototype construction	10 days
2 days	Tests with experts		2 days
40 days	Construction of a high fidelity prototype using Silverlight 4 and C# according to new design solution	Edit the TAR prototype according to new design solutions	2 days
5 days	Task analysis with users		5 days
15 days	Development of final SW	Development of final SW	40 days
97 days	**TOTAL TIME**		**64 days**

An additional analysis is carried out to evaluate the perceived interactivity of TAR. Users are asked to answer a post-hoc questionnaire by expressing a judgement according to the 1-5 Likert scale of 1-5 (Figure 4).

	Evaluation metrics	Questions (1-5 Likert judgement)
a	*Intuitiveness*	You understood immediately how to use the system
b	*Ease to use*	It was easy to accomplish the task
c	*Customization*	You have not felt the need to change some parameters display at all
d	*Interactivity*	Overall you are satisfied with how you interact with the environment
e	*Absence of constraints*	You did not feel obliged to comply with procedures that do not feel natural to the way you interact with the products at all.
f	*Natural involvement*	You did not seem to be within a simulation at all
g	*Sense of realism*	The environment is realistic

(a)



(b)

Fig. 4. Post-hoc questionnaire and results

Each question is correlated to evaluation metrics which is significant to assess the exploited technology performance. By analyzing post-hoc questionnaire results (Figure 4) it is possible to infer that users find the interaction with the TAR prototype intuitive (average intuitiveness judgement = 4.2). The exploited technology enables users to interact with the prototype in a realistic way and natural way (average judgement for interactivity, natural involvement and sense of realism respectively are: 3.9, 4.7 and 4.2). However, most users need to customize the display mode. In fact, even if the focus point of the lens video cameras mounted on head-mounted display can be changed, this does not overcome the need for lenses in case of high dioptres. Free movement is still an open issue.

5 Conclusion

The proposed TAR interaction approach to control Smart Home energy consumptions actually represents an important challenge in UCD. TUIs are combined with AR display methods to create a very intuitive and natural application, which allows users to physically interact with a product and explore virtual contents in real time. Its value has been investigated through rigorous user studies, comparing ease of use with this style of interaction to other traditional methods. For this purpose, numerous analyses are carried out to demonstrate the efficiency and effectiveness of the proposed TAR prototype. The proven main benefits regard achieved timesaving (-34%) due to the ease to carry out design modifications without a significant HW/SW development effort. Future work will be focused on the collection of additional case studies in order to support the experimental findings. Additional applications should be implemented and tested.

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Virtual Reality Coupled with Adapted Physical Interface for a Better Evaluation of the Innovative Surgical Instrument

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Abstract. In the domain of designing innovative products in the medical field, investigations are often oriented towards communication between actors and needs comprehension. In the DESTIN (DEsign of Surgical/Technological INnovation) project, User Centered Design methodology with concrete experiments is applied. Researchers propose emulations in an operating room for co-evaluation of innovative products and new adapted surgical procedures. In this paper, they intend to evaluate the usage of the product in a virtual environment using a 3D haptic feedback system. Researchers not only propose a better ergonomic situation of the physician in front of the operating screen, but also increase the performance of the simulator in order to allow the manipulation of the innovative surgical instrument developed. We used virtual reality environment and the manufactured prototype with the aim to validate the new surgical procedure and the innovative designed surgical instrument.

Keywords: Virtual Reality, 3D-Haptic feedback system, Prototyping, User Centered Design (UCD), Minimally Invasive Surgery.

1 Introduction

The development of new technologies in medicine can significantly improve the effectiveness. On the contrary, the use of more complex systems tends to make the practice of medicine more difficult. In particular, this complexity reinforces the importance of preoperative planning and postoperative monitoring. New technologies in informatics and virtual reality allow physicians to better interpret the enormous amount of information that is provided by the imaging systems or therapy systems [1]. Specifically, virtual reality allows better understanding, better planning and better work through visualization of three-dimensional images of anatomy and pathology. In addition, virtual reality supports the practitioner through the stages of diagnosis, therapy, and postoperative monitoring.

The main aim of DESTIN project (Design of Surgical-Technological INnovation) is to propose a new methodology focused on this specific context: How to create a

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new operative surgical procedure and innovative surgical instrument when a new medical approach is imagined?

The specific surgical application we are working on addresses thoraco-lumbar fracture. The current "classical" procedure is carried out with the patient in the prone position under general anesthesia. The surgeon performs a posterior open approach through a 15cm large incision. The posterior vertebral arch is exposed. Pedicle screw entry points are chosen by direct visual control and they are fixed to the vertebrae. Rods are placed to connect the pedicle screws together. Prone placement added with rod-screw connection provides reduction of the trauma deformity and durable stability Thus, vertebrae are preventing from moving while bone healing and graft fusion takes place.

The new surgical procedure proposed by the surgeon consists in inserted the rod inside the pedicular screw in MIS (Minimally-Invasive Surgery). Thus, new little incisions should allow the insertion of the rod in the three pedicle screws.

Currently, researchers, designers and the medical staff regularly work in the real operating room. This work was very effective but necessitates heavy organization and management (mainly in the hospital), the creation of mannequins, the manufacturing of many prototypes, etc.

To facilitate this procedure, we create a CATIA CAD model of the virtual operating room. It integrates patient, medical equipment and surgical instruments. In this virtual environment, the surgeon has to manipulate the virtual surgical instrument on the virtual patient's spine (the spine has been modeled in a compatible format as the CATIA environment and integrated in a mannequin placed on the operative table). The goal of this exercise is to provide information to the designers for the validation of the innovative surgical instruments during the design process. At the same time, it also allows surgeons to perform the operative procedures with haptic feedback as in the real operative case.

The difficulty in our research concerns the ability to sufficiently represent the virtual environment for the co-validation of the medical procedure and the innovative surgical instrument.

Knowing that surgeons can already manipulate the virtual innovative surgical instrument using a 3D-Haption© haptic system in the virtual operating room, the research questions can be summarized as follow:

- How to modify the configuration of the virtual reality room and the physical interface for a better integration of the physician in the virtual environment?
- Which are the optimal dimensions of the virtual surgical instruments for a best representation and manipulation of the real surgical intervention using the 3D-Haption© haptic system?

To answer these questions, this research methodology is proposed:

- To research some ergonomic references in the surgery domain and compare them to our virtual reality room organization,
- Secondly to design and to link a new physical interface to the arm of the 3D-Haption© haptic system,
- To modify the virtual model and to compare the surgical intervention feasibility with the real one.

In this article, we firstly present the User Centered Design methodology we use during our study. Then we focus on the virtual reality and ergonomic applications and research in the surgical field. This first step allows us to analyze the general situation in the world. From this work, we propose modifications and adaptations of our current virtual operating room and 3D-Haption© haptic system user interface.

Next, we present the results of the manipulation in virtual environment and conclusions concerning its efficiency related to the situation in real situation.

2 User Centered Design

User Centred Design (UCD) is considered as one of the cornerstones theories about user involvement. UCD, as a design approach, was first time introduced in NF EN ISO 9241-210: Human-Centred Design Processes for Interactive Systems [2]. The main issue is how to involve, integrate and consider the end-user and its requirements throughout the product design process. This ISO 13407 model proposes technical points the project must encompass to be considered as *human centred: 1* – a certain knowledge of the end-users: their tasks and of their environment – 2 – an active participation of these end-users, the clear understanding of their needs and the requirements linked with the tasks – 3 – an appropriate distribution of the end-users/technological functions – 4 – an iterative design solution – 5 – the intervention of a multidisciplinary designing team. This is necessary to better interpret the end-user, its knowledge and how-know: human factors, information architecture, design, quality, marketing, etc.

The UCD cycle is decomposed into six main steps (Figure 1). It is an iterative cycle (step 2 to 5) which ends when the system answers the end-user requirement (step 6).

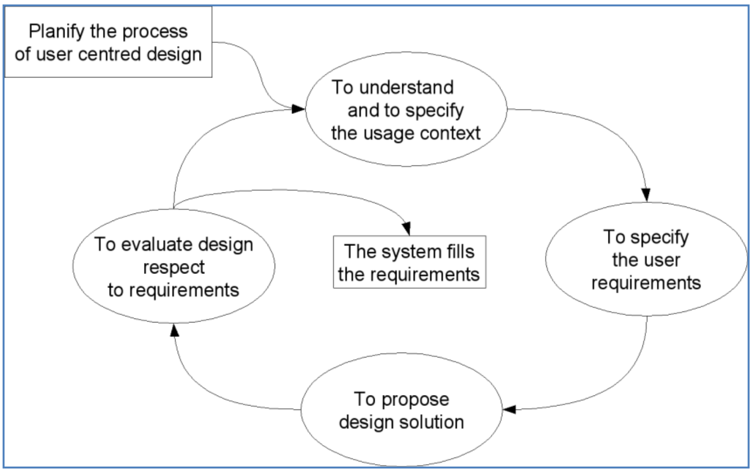

Fig. 1. The six steps of the UCD cycle

To better understand this UCD design steps, Jokela et al. propose another interpretation of this NF EN ISO 9241-210 UCD Process. They explain more concretely how it can be applied on a project and suggest a new UCD process model [3]. Another important issue in UCD is how identifying and selecting relevant end-users in the development work. In practice it is commonly possible to involve only a limited number of users, and therefore it is very important to define criteria in order to select the most "representative users" to centre the design on their requirements and expectations.

3 Virtual Reality, Ergonomics and Their Application in Surgical Field

3.1 Virtual Reality and Application to the Surgical Field

Virtual Reality (VR) is an interactive immersive data-processing simulation in real or imaginary environments. Currently, the technology of RV was applied in many different fields such as: formation by simulator (driving vehicles, aerospace), design of products, the simulation of surgery, meteorology…

In the surgical field, the laparoscopy is a new procedure which requires surgeons to observe the operations on a monitor and requires acquisitions of new competences. This Minimally Invasive Surgery (MIS) differ from the opened surgery by the fact that the surgeon operates through small incisions and uses specific instruments as scalpel, grips, nets, etc. [4]. In spite of its many advantages (faster recovery of the patients, less damage with healthy tissues and smaller scars, less pain and less need for drugs), the MIS requires a long time training eyes-hands coordination.

Researches developing the haptic control feedback device can be found in [5-7]. To follow the user intentional movements, by interaction between hand and device, high powerful haptic devices must be able to produce force feedback. Consequently, it is essential to closely examine the human touched and the constraints of application during the construction of these devices. A haptic interface with 4 degrees of freedom was designed by Guiatni et al. to compare it with devices commercially available [4]. This device has the capacity to offer force feedback in all the degrees of freedom available during the MIS procedure.

In our case, researchers, designers and physicians work together on the development of a virtual environment to simulate a MIS operation on the spinal column. The goal is to create an integral virtual surgical environment with surgical instruments and haptic feebdack in a model of the operating room.

3.2 Ergonomics in the Surgical Field

Ergonomics is a relatively new science. It is based on the models in the design of machines and tools that optimize the performance of users. In order to improve the simulation conditions in virtual reality surgery environment that create the better immersion for surgeons who will eventually be the primary user of this innovative surgical instrument, we had to first study some articles to find the factors that influenced the comfort of surgeons during operations in the operating room. The optimum ergonomic position of the monitor was defined according to various sources in the literature [8], [9], [10], [11]. The monitor was at a distance of 0.6 m apart from the subjects' eyes. The monitor height (from the middle of the screen to the ground) was between the operating surface and eyelevel height, and the monitor was inclined (to a maximum of 15°) as by the subjects.

The optimal operating surface height was 80% of the elbow height and the table was positioned in 20° tilt. [12].

In an article submitted by Gurvinder Kaur [13], he conducted a test to find the height of the ergonomics table in the minimally invasive surgery. This study aims to propose an ergonomic table height required for the surgeon height so they can perform comfortably in the operation. In this study, the height of the table has an effect on the upper joint movements of the shoulders, arms and wrist during laparoscopy. Table height should vary from 65 to 90 cm from the floor. The surgeon should be able to adjust the table corresponding to his/her height in order to bring upper joint movements to the minimum position with the resultant less discomfort in the shoulder, back elbow and the wrist. After analyzing the ratio between the surgeon's height with the height of the operating table, it was assumed that the height of the operating table should be calculated as follows:

Table Height = Surgeon's Height X 0.49

The ideal posture for the MIS is supposed in the literature [14] and [15]. The arms are slightly removed, retroversion, and turned inward at the level of the shoulder (abduction <30 °). The elbows are bent at about 90-120° of flexion. This position leads to the maximum force to be applied for a maximum duration. The head is slightly bent with an angle of between 15 and 45°.

Through this study literature, we find that the virtual reality technology plays an important role in many areas. In particular, the applications of VR technique in surgical simulation have been developed to provide better and better ergonomic solutions which satisfy users. Through these studies, we can better consider the virtual reality room and design the components that give a better immersion for the surgeons. Thus, we can improve the ergonomics in surgical simulation by changing haptic interface, the position of the surgeon and his posture.

4 Related Works

4.1 The Surgeon Posture

To perform their operations with haptic sensation as in real surgical environment, we adapted and modified the haptic interfaces as well as the position of surgeon:

- Setting the table height corresponding to the surgeon's height. We chose table height is equal to 0.49 of surgeon's height. [14]. Notice that it is now possible to adjust at real time the position of table?
- Adjusting the distance between the screen and the surgeon's position. Normally, this distance is 0.60 m, but with the giant screen in Virtual Reality room at our laboratory; we chose the distance of 1.5 m.
- Changing position as well as the posture of the surgeon: the surgery is always in front of the screen, the direction of movement of the tool should be parallel with the spine.

4.2 The New Human Machine Interface

The practitioner manipulated the haptic arm using the 3D-prining machine handle (figure 2). The position of the physician was not comparable to the real operating room environment and the conditions of experimentation not ideal:

- The surgeon was not in front of the screen and the posture position not comfortable.
- The 3D-printing handle material was different than the final product's one.

Moreover, the idea is to use the same surgical instrument on mannequin in operating room and during the simulation.

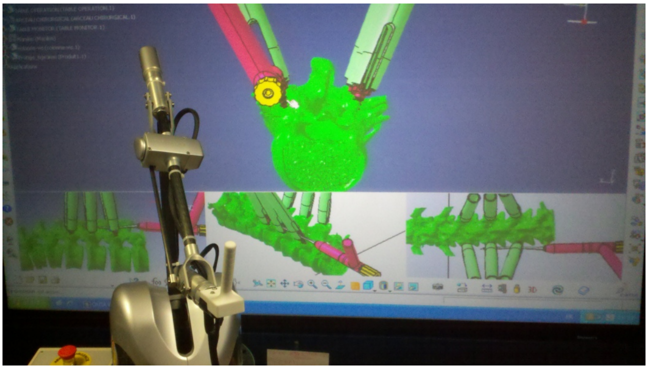

Fig. 2. Picture of the 3D-prining machine handle at the end of the haptic arm

Through ergonomics studies, we can better consider the virtual reality room and design the components that can make a better immersion of the practitioner. Thus, we can improve ergonomics in surgery simulation by changing haptic interfaces to adapt with the position and posture of the surgeon. In order that the surgeon can use the haptic arm in the operating simulation as in reality, we thought to create an intermediate mechanical piece to hang the surgical instrument prototype (Protige) at the end of the haptic arm. The objectives of this adaptation are to give the surgeon a real sensation when holding the real instrument Protige and then to carry it in a direction parallel to the spine's main axis.

Before the mechanic piece was fabricated, we carried out a numerical simulation to ensure the strength, deformation and constraints of the piece to work properly when it tightened the surgical instrument .We divided the simulation into two cases:

- Test the strength of the piece under the Protige's effort when the simulator is running maximum the instrument.
- Test the tightness of the piece under the load of the screws so it could tight well Protige.

The intermediate piece of aluminum has been made at our workshop by the Numerical Control of Machine Tools (figure 3). We observe the 90° modification orientation compared to the previous 3D-prining machine handle (figure 2)

Fig. 3. The instrument tightened by the piece is tied to the haptic arm

4.3 Testing the Haptic Sensation in the Insertion of the Rod with Screw Holes

Concerning the simulations, the previous virtual surgical instruments dimensions never allows the insertion of the rod inside the pedicle screws head. The main objective of this test is to find optimal dimensions of the virtual surgical instruments and verify the friction sensation when inserting the rod into the holes of the pedicle screws head. Using a simplified virtual model, we test different manipulation situations (figure 4): changing screws holes diameters and rod diameters. We modified the diameter of the pedicle screw hole from 6 to 9mm. We also used different rod diameters: from 4 to 6mm.

To simplify the simulation with many different cases, we proposed a simple model of vertebral column and screws. Of course, the positional parameters between the screws and spine are respected as the MIS procedure. The new versions of models vertebral column and the screws are created using CATIA software.

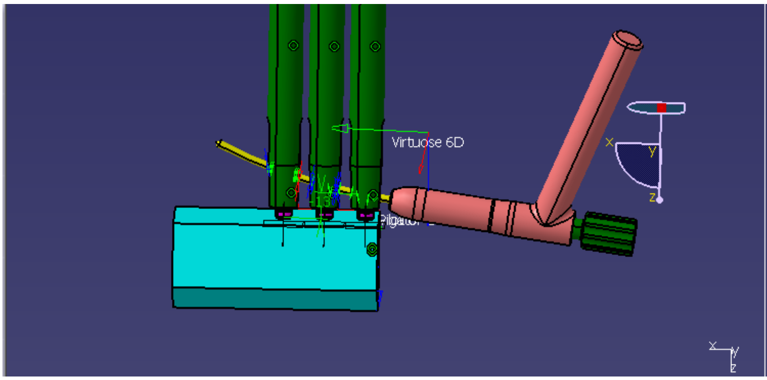

Fig. 4. The translation of Protige parallel with the spine position

We ran several simulations with different views ("multiple views" on IFC CATIA software). So we set up a kind of viewpoints allowing the surgeon to possess more isometric views, each vignette characterizing a different spatial view.

User moves the virtual instrument over the spine and we set the test duration up to one minute to validate the feasibility of the procedure phase. Five trials are conducted for each case. The experimental duration for each case were taken in order to determine the levels of difficulty in inserting the rod into the holes. A test was considered successful if the positioning time of the rod through the holes did not exceed one minute.

We got the test results with different cases (see an extraction of the results in table 1). Simulation is recorded by video to analyze the results as well as confirmation of results.

Table 1. Results of the trials (in duration time)

Rod diameter (mm)	Duration of the trials (s) Screws' hole: 8 mm					Mean (s)	Duration of the trials (s), Screws' hole: 9 mm					Mean (s)
4	8	7	6	4	10	7	12	8	7	4	7	7,6
4,5	60	50	120	90	60	76	5	7	8	8	9	7,4
5							5	8	9	8	7	7,4
5,5							10	8	8	11	9	9,2

We have tested a maximum of the possible experimental conditions. Depending of the trauma cases, the physician has to use two or more screws inside the body. We asked the user to test the virtual insertion of the rod in 1, 2 and 3 screws. An extraction of the complete results is presented in table 2.

Table 2. Conclusion for one specific configuration: extraction of the complete table. Hole of the screws: 8mm / diameter of the rod 4 and 4,5 mm

Rod diameter (mm)	Number of screws			Duration of the trials (s)					
	1	2	3	1	2	3	4	5	Mean (s)
4	OK	OK	OK	8	7	6	4	10	7
4.5	diff.	imp.	imp.	60	90	120	50	60	76

"OK" means that the corresponding experiment is working well. For example, inserting a 4 mm diameter rod through 3 pedicle screws' holes of 8mm takes less than 1 minute. Inserting a 4.5mm diameter rod through 1 pedicle screws' hole of 8mm takes around 1 minute. We qualified this situation as difficult (diff.). Finally, it is impossible for the user to insert the 4.5mm diameter rod through 2 or more pedicle screw holes of 8mm.

The complete experiment shows that the 9mm pedicle screws' holes always allow the insertion of the rod from 4mm to 5.5mm. For the 8mm pedicle screws' holes, they are compatible with the 4mm rod diameter (insertion through 3 screws) and 4.5mm rod diameter (insertion through 1 screw). One of the reasons that prevent this insertion is the precision of the collision detection between parts using the IFC CATIA software coupled with the haptic device. It doesn't allow the relative movements between rod and holes even if the rod's diameter is smaller than screws' holes. Moveover, the durations of the trials depend of the user's experience.

5 Conclusion

In this study, we not only propose a better ergonomic situation of the physician in front of the operating screen, but also increase the performance of the simulator in order to allow the manipulation of the real innovative surgical instrument developed.

We used virtual reality environment and the manufactured prototype with the aim to validate the new surgical procedure and the innovative designed surgical instrument. For that, an adaptation piece has been designed, manufactured and manipulated. This adaptation has really increased the real sensation of the user in front of the virtual reality screen.

Moreover, the disposition of the experimental room and the user has evolved. The modification of the model and the different trials with different users allow researchers to find parameters which influence the quality of physical sensation. This activity will allow

- Designers to propose tools and models more realistic for effective simulations during the design process. In consequences, design choices can be more precise
- Physicians to quickly evaluate and validate an adapted operative procedure.

These experiments with users and researchers give us some qualitative results. The next step will be the evaluation of the complete virtual environment (with different dimensional models) with numerous expert surgeons to:

- validate the design of the surgical instrument
- quantify the sensations of the experts

The surgical instruments developed are generally composed of multiple mobile parts. One of the future objectives will be to work on the possibility to manipulate all the parts of the product in virtual reality. This objective imposes the integration of multiple cameras and markers in the experimental room.

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Application of AR Technologies to Sheet Metal Forming in Shipbuilding

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Abstract. This paper describes the application of AR (Augmented Reality) technologies to shipbuilding. General overview about AR technologies is introduced at first, and its potential of utilization especially given in shipbuilding is discussed in this section. The paper introduces actual development of an AR system which is applied to sheet metal forming works in shipyards. Workers can get quantitative information about the geometry of the curved plate or the work procedure intuitively by looking the plate through a tablet PC to which this AR system is installed. The paper also covers technical problems and solutions to put this AR system into practical use in a shipyard. Finally, the paper introduces some possible applications of AR technologies for an entire shipbuilding process.

Keywords: augmented reality, shipbuilding, sheet metal forming.

1 Introduction

Manufacturing Enterprises are highly forced to improve their development and production processes regarding time and quality. Digital supported methods are the substantial enabler to achieve improvements in this area [1]. Also Digital Manufacturing is getting to be familiar in a research field and a practical use in a shipbuilding industry which is characterized as a small batch production, hand working-dependent and to be done under special condition that a ship not fully designated and planned before starting its production. Although various approaches can be considered to digital manufacturing for an entire shipbuilding process, key approach should be an effective connection to a 3D CAD model which is generated in a design stage. Some previous studies introduce examples to apply the 3D CAD model to digital manufacturing in a shipyard, and those are mainly related to a 3D model viewing in a shop floor, a control of NC machines or various robots, and production simulation [2]. Virtual reality technologies are a new way especially for production simulation by feeling in an immersive environment [3-4].

On the other hand, even there exist above mentioned proposals to use 3D model to digital manufacturing, new demands are emerging about a further utilization of the 3D CAD models in the shop floor or a building yard. AR (Augmented reality) technologies would answer this need. By introducing this technology, there would be

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expectations not only to watch the 3D view directly on the real object, but also to new paradigms which change the way to use information around the shipyard. Examples of those new paradigms are concepts for 3D drawing sheet with AR or an interactive information exchange between the shop floor and the design division. These aspects are discussed later in this paper.

Application of AR technologies to shipbuilding is not popular at present, and only few reports which are almost written by European researchers are found in international journals or conference papers [5-6]. This study introduces the application of AR technologies to sheet metal forming works in shipbuilding, and this application of AR technologies to a hull fabrication would be a first attempt. Although implementation of applying 3D CAD to ship production has been slow in the industry mainly due to the large cost associated with developing the models, this new technology would promote ideal utilization of 3D information in shipbuilding.

2 Development of AR System for Sheet Metal Forming in Shipbuilding

2.1 Sheet Metal Forming in Shipyard and Proposed AR Application

Surface of a ship consists of many pieces of a steel plate which has thickness of nearly 10 – 30 mm. Fore and aft part of the ship are usually dominated by elliptical surface and hyperbolical surface, and those curved plates are formed to the designated shape by pressing and gas heating. This sheet metal forming can be regarded as a typical example of a skilled work operation in shipbuilding because of the following reasons: difficulty in imagining an accurate 3D form; difficulty in judging the geometric forming procedure; difficulty in processing to the objective surface, especially in the gas heating process; and difficulty in confirming the shape by traditional way, as illustrated in Figure 1.

To facilitate these complex tasks as described before, AR technologies would be efficient to support workers by providing intuitive information in real time and directly. Following AR application are proposed to get imagination and quantitative information directly and intuitively:

- Imagination of a shape and a work procedure;
- Indication of the status of work procedure while execution;
- Confirmation of the resulting shape without templates;

To give an appropriate support to these applications several requirements have to be addressed and considered:

- Provide information on large scale parts;
- Provide effective visualization of context oriented information with situation awareness;
- Maintain accuracy in terms of correctness of deformation of steel plate;
- Provide a practical system by considering a particular circumstance of work condition in shipyards;

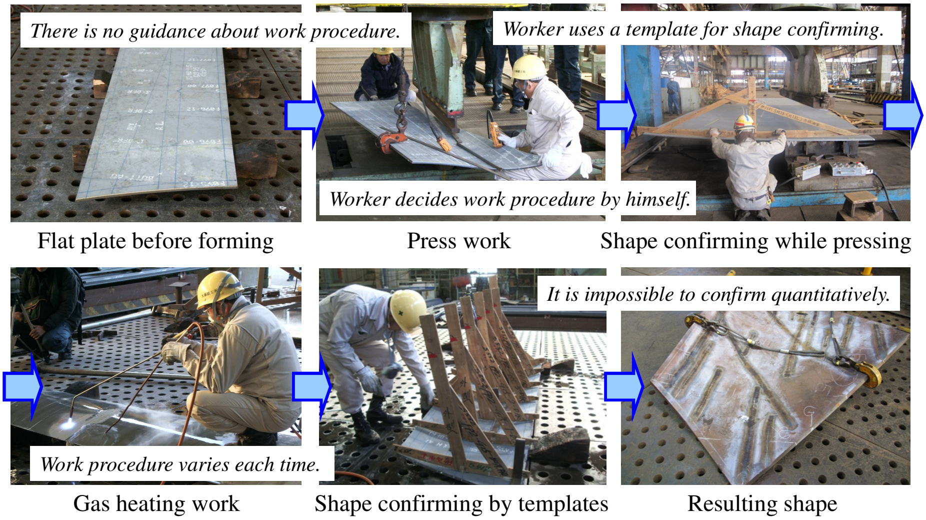


Fig. 1. Sheet metal forming in shipbuilding and its difficulties

2.2 Development of the AR Application for Sheet Metal Forming

The main characteristic of these application scenarios using AR is to provide capability to see information directly on the plate in real world through a mobile device such as a tablet PC or a smart phone. For satisfying this, AR applications are composed of a series of functions which are developed specially for this study.

Figure 2 shows the conceptual image and the flow diagram of the AR system. Once a camera which is installed on a mobile device captures video of the real world, AR applications identify the plate under sheet metal forming work. Identification is conducted by using markers which are put on the plate, and a number of markers are arranged on the plate as they compose a lattice pattern to cover the entire area of the plate. Because position *(X,Y,Z)* of each marker is estimated from the position of a single marker which is arbitrarily selected from among all markers, identification can be done about location and orientation of the plate in space and the entire shape of the plate, Figure 3.

AR applications prepare information which is displayed on the captured scene in the next step. This information is one which is concerning to the work of sheet metal forming, and information includes design data such as a target shape of the plate, work process data such as information for next work procedure or geometric data of the present shape. This information is not only generated and imported by a separate system such as a CAD system or a special program which analyzes sheet metal forming, but also generated directly by analyzing the shape of the plate which is identified by using the series of markers. It is important and distinguishing characteristic of the AR application to use markers as this way, because this enable a good correlation with a general way to represent ship's surface, and be able to provide static and prepared data set by utilizing an existing software. As is shown in Figure 3, once the lattice pattern which covers the entire plate is generated, geometric analysis is conducted by mathematical representation of the surface. Work procedure such as a next work step is also obtained by importing from the sheet metal forming program.

A coordinate system in the captured scene is generated by using a single marker on the plate. 3D objects which are generated from information described above are correctly transferred and superposed on the plate in real world according to relation between the coordinate system and the plate.

The AR application is developed by utilizing “ARToolkit” which is a software library for building AR applications [7]. “ARToolKit” is able to perform camera tracking in real time, objects recognizing by looking a marker, and ensuring that a virtual object al-ways appear overlaid on the tracking markers.

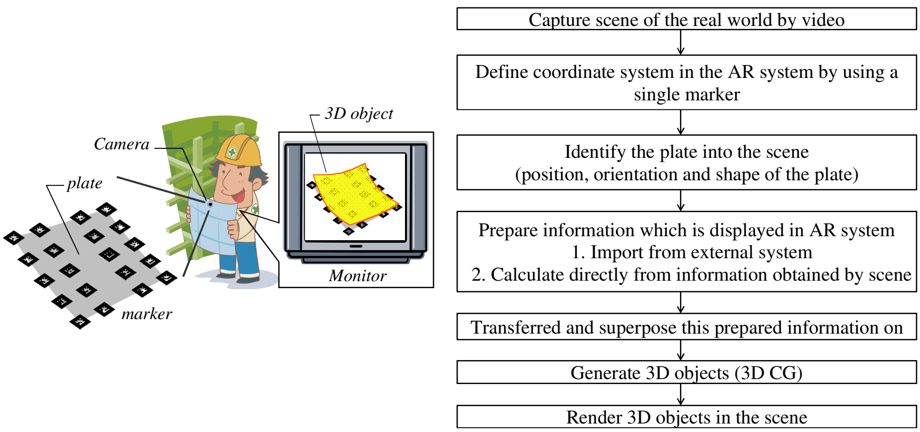


Fig. 2. Conceptual picture and the flow diagram of the AR system

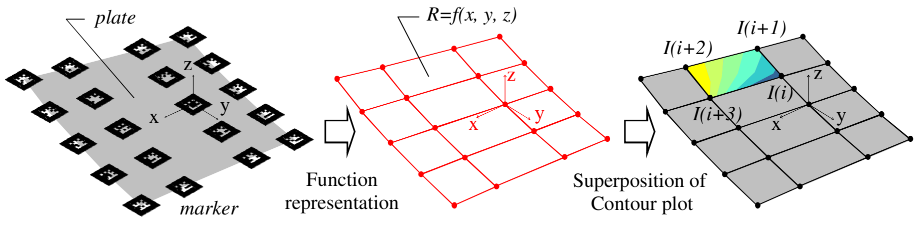


Fig. 3. Identification of the plate by using markers

2.3 Demonstration of AR Application and Improvement for Practical Use

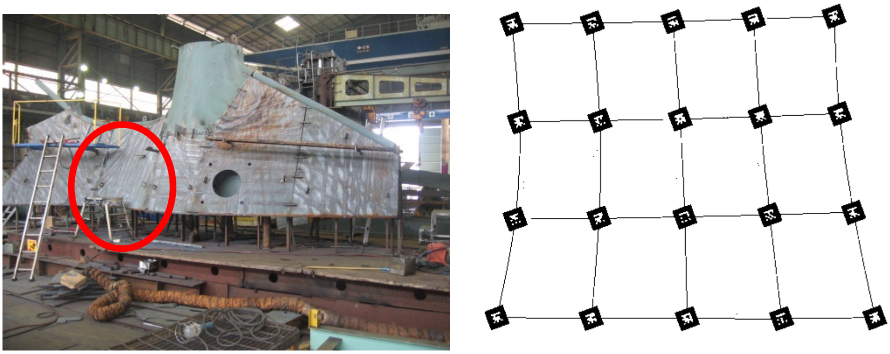
An experimental demonstration was conducted to verify how to utilize the AR application to sheet metal forming work and which kinds of benefits to be expected. In this demonstration, an actual-size model is prepared to simulate sheet metal forming in shipbuilding.

The actual-size model which is equivalent to a ship's plate is prepared as shown in the Figure 4. This plate is one which composes a stern part of actual ship, and has a size 1.7m length and 1.5m height. In this demonstration, a series of markers are put on the plate to recognize the shape, and the lattice pattern is generated by those markers to represent mathematical surface.

Demonstration is carried out along workflow of actual work procedure of sheet metal forming, and AR application is used to confirm following functions.

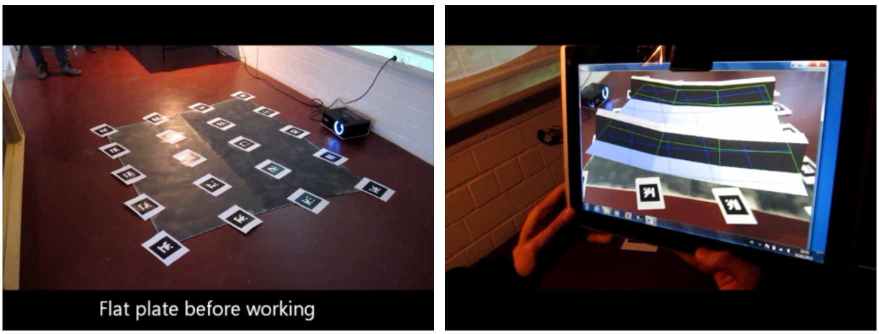
- Getting an image of the target shape before beginning of the work;
- Confirming the work procedure before beginning of the work;
- Confirming the present shape with its target shape while or after the working;

Figure 5 are snapshots of the demonstration which is held in a laboratory.



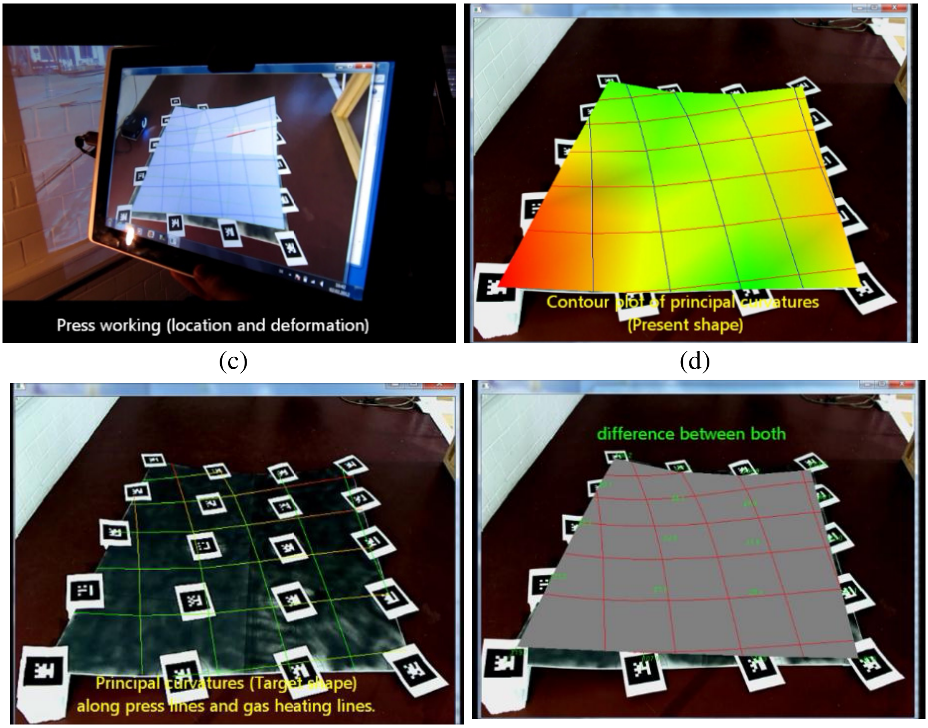
(a) (b)

Fig. 4. Location in a ship and marker arrangement of the test piece



(a) (b)

Fig. 5. Snapshot of the experimental demonstration



(c) (d)

(e) (f)

Fig. 5. (*continued*)

2.4 Consideration through the Demonstration and Improvement of the AR Application

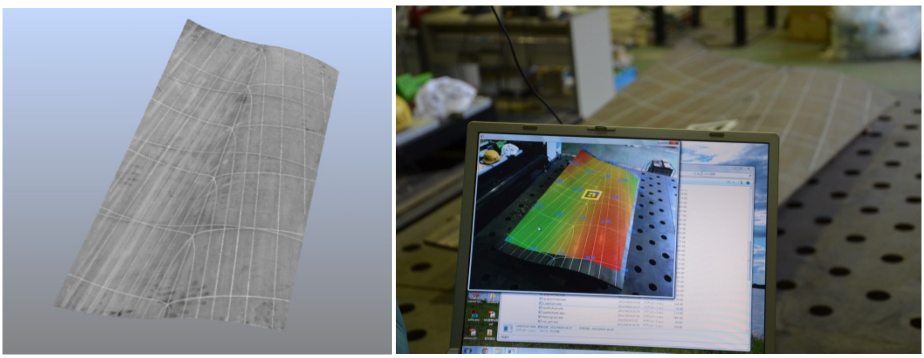
Following remarks including technical problems toward practical use in shipyards arise from the demonstration.

- It is easy to get a visual imagination about a 3D shape by watching the 3D object from arbitrary eyesight.
- A confirmation of the shape of the entire area of the plate with quantitative analysis is possible. This removes constraint to use traditional templates, and contributes to save time and money to use templates.
- Some shortcomings are found in the AR application. Tracking markers becomes unstable when the camera is put at the point from which it is hard to look marker. Size of a plate used in shipyards is usually huge length about 20m. Even it is far from a worker to an objective plate, performance of perception should be maintained in high level. A stable tracking is required to the huge plate, even when worker wants to watch from both near side and far side.

- For practical use of sheet metal forming it is not reasonable to put several markers on the plate. There also exist other problems to rely a marker such as when the plate is turned upside down while working.
- Accuracy is not stable to recognize the shape of a plate. Most important factor to realize practical use is to maintain enough accuracy to recognize the shape of a plate. Considering quality control in Japanese shipyards, accuracy concerning the position needs less 10mm. On the other hand, a high-speed response is not required in this case, because a plate usually deforms slowly.
- It is hard to handle tablet PC while working.
- Typically the factory environment dark, vibrating and dusty. Thus, a robust and stable system is required to use in such environment.

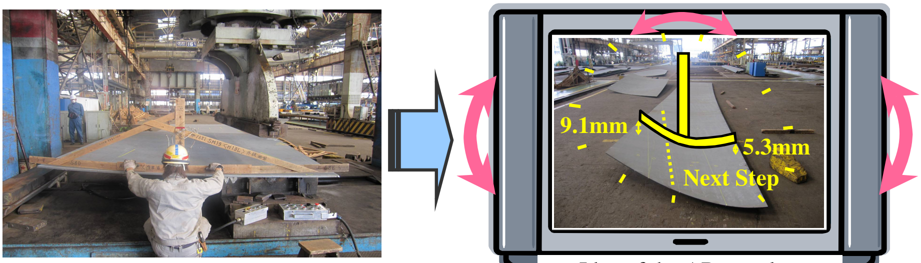
Following solutions are proposed to solve above technical problems:

- To recognize the shape of a curved surface with high accuracy, a laser scanning system is connected to the AR application. Figure 6 (a) shows point data around the plate in our factory which is scanned by the "FARO Laser scanner Focus3D" with accuracy of 2mm. By utilizing this point data for identifying the shape of a plate, a series of quantitative amount of gap between the present shape and the target shape is acquired with high accuracy (Figure 6 (b)).
- Effective GUI should be developed to understand more friendly and instinctively. New concept about new GUI is conceived from the demonstration, and this concept is one which duplicates traditional templates in AR system as shown in Figure 7. This GUI connects new technologies to traditional ones, and helps workers to access to new technologies.
- Some hardware should be required to support a stress-free usage of the AR system in the factory. Especially, some kinds of a mounting device to fix the tablet PC near the worker would be required to let the worker be free to use his hand. Also, a projection based AR system would be raised as another approach to this solution.



(a) (b)

Fig. 6. Connecting to the laser system to the AR system



Traditional way to confirm the shape

Idea of the AR template

Fig. 7. New concept of GUI of AR application

3 Consideration about Application of AR Technologies to Various Shipbuilding Work Process

In case of labor-intensive work which it is inevitable to depend on individual skills such as shipbuilding, the new technology such as AR plays important role to communicate information effectively. AR technologies realize the following advantages:

- Process related information, which are otherwise not visible are available;
- Transfer design information (e.g., CAD information) directly as the natural 3D object on the surface. This means realization of a 3D drawing sheet with a tablet PC or an electronic paper in future, and 3D information is transferred as the 3D information without passing the 2D drawing.
- Worker are be able communicate interactively;

Besides the presented application of AR many other tasks within the entire shipbuilding work process which would benefit from introduction of AR-technologies:

- Provision of information such as for factory management (e.g., part number, processing status, etc.) or physical properties (weight, temperature, etc.)
- Provision directions to and supports workers with an instinctive viewing (e.g., for sheet metal forming, block assembly, pipe fitting, maintenance, etc)
- Realization of interactive communication to design data and floor shops (e.g., drawing at a floor shop, control of NC machines or welding robots)
- Inexperienced worker to be instructed are assisted by convenient methods (educational purpose)
- Platform of a measurement instrument (e.g., template in sheet metal forming, etc.)

4 Conclusion

In this paper a developed AR application which addresses specific requirements of sheet metal forming is presented. A comprehensive demonstration is conducted for verifying the AR application. General overview is described about future utilization of AR system for an entire shipbuilding in last section. In the following result of this study are summarized:

- AR application improves understanding about the work by direct and instinctive expression of information. The application will contributes improvement of sheet metal forming works in shipbuilding.
- Some defects are found about the accuracy and stability. Effective GUI is also necessary for practical use in shipyard.
- Connecting a laser scanning system to the AR system improves the accuracy to recognize the shape of the plate. It does not lose the functionality in the practical use for sheet metal forming in shipyard, even it lose split-second operation.
- There are many proposed AR applications for various purposes in shipbuilding.

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Are Smart Products Foiling Automated Design?

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Abstract. Design Automation (DA) implements the idea of deriving the physical design of a product automatically from within codified engineering knowledge. If a product is no longer limited to be a physical device, it should be analysed if the idea of DA can be enhanced or if DA becomes obsolete for smart products. The authors believe that DA can even play a major role for the smart products development. Thus this paper additionally aims to provide a concept for an enhancement of DA. Instead of case based and locally implemented solutions, the concept relies on a central knowledge-based system in order to process the smart layer on top of the geometrical design. The proposed system should be grounded upon an ontology in order to represent the physical and the virtual domain at once. This way different kinds of product development applications can rely on one central knowledge-base.

Keywords: Smart Products, Design Automation, KBE, User-Centered Design, Collaborative Design, Ontologies.

1 Introduction

So called smart or intelligent products offer the potential for consumer goods to become more intelligent and better suited to the requirements of the users. The possibility to adjust functionalities during the usage phase and customize the product on item level offers an added value to the user and provides new business opportunities to manufacturers and service providers [1].

Expanding on the idea of smart products, current research proposes a user-centred and collaborative design. Such design would focus on the identification of interactions and services to fully reflect user requirements and preferences from early development stages, rather than improvements driven by technology [1], [2].

On the other hand, Design Automation, which is an area of Knowledge Based Engineering (KBE), has significantly improved product development especially in the domain of repetitive, routine tasks. According to [3] about 80% of the time during the product development phase is dedicated to repetitive tasks. That means, that the enormous potential of successfully implemented DA solutions has already been validated by several research and development projects [4]–[7].

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Design Automation and its underlying domain KBE, demands for codified knowledge. In other words a KBE solution relies on rules, formulas, constraints and other codified knowledge to "autonomously" derive the physical design of the product from the knowledge base (e.g. a product shape derived from aero dynamical constraints). The deterministic approach of KBE seems to be in opposition to the user centred/collaborative design. Even if KBE has already proven its validity some important questions remain to be answered: Is it possible to develop smart products if the design is processed by knowledge bases? Is knowledge-based engineering contradicting the paradigm of user-centred design?

Of course it can be argued that Design Automation is still of importance on component or sub-component level (e.g. casings for a device), but the authors believe that the approach of KBE can even play a major role for the overall development of smart products in the near future.

2 Background

According to e.g. Mühlhäuser [8], Smart Products can be defined as entities designed and made for self-organized embedding into different environments in the course of its lifecycle, providing improved simplicity and openness through improved product to user (p2u) and product to product (p2p) interaction. The capabilities to interact can rely on context-awareness, semantic self-description, proactive behaviour, multimodal natural interfaces, Artificial Intelligence planning, and machine learning [8]. A smart product is embedded within an environment that provides the intelligence to download, process and store information on individual users, their prior interactions with products and the ability to create a context to p2u interaction.

In compliance with the definition above Maass and Varshney characterize smart products by several dimensions [9]:

1. *Situatedness*: recognition of situational and community contexts
2. *Personalization*: in terms of tailoring the product according to buyer's and consumer's needs and affects
3. *Adaptiveness*: the ability to change product behaviour according to buyer's and user's responses and tasks
4. *Pro-activity*: anticipation of user's plans and intentions
5. *Business-awareness*: consideration of business and legal constraints
6. *Network capability*: the ability to communicate and bundle with other products

Herewith different classes of smart products can become possible ranging from customer to products communication in order to help selecting (and buying) a perfectly suited product up to the ability to create pleasant experiences along the usage phase (e.g. game apps running on a mobile phone and this way enhancing the experience to use the mobile).

Different types of smart products require different enabling technologies, which are directly influencing the product development process itself (e.g. *weather-conditions* can be recognized by on-board sensors of a device or alternatively provided by an internet service). As mentioned above, the design has to focus on the identification and interpretation of interactions and services to fully reflect user requirements and wishes from early development stages, rather than improvements driven by technology.

Product development teams become not only responsible for the definition of a digital representation of the product, which enables adaptation to situations and consumers and its respective environment. But they have to identify the interplay between the physical and the virtual world. The existence or absence of a physical button on contemporary mobile devices can serve as a prominent example. The respective design decisions are neither technology/feature driven nor assembly or manufacturing related. Moreover, user centred design has become the driving force [1], [2].

However, to pick up the introductory question, user-centred design is by far not in contradiction to Design Automation. Nowadays DA is usually performed by KBE solutions. KBE (DA respectively) is implemented on many levels in different industries: From simple templates in CAD software to extensive stand-alone software solutions with integration towards other CAx systems, there are many ways of implementing codified knowledge through rule-sets on product design. Within a KBE solution, engineering knowledge is represented in a formal manner and enables the system to automate specific development tasks (thus it is called Design Automation). Each KBE system provides on the one hand an interface to capture the knowledge in terms of logical rules, algorithms, or constraints, and on the other hand an output module to trigger adjacent CAx systems or/and visualize results [10].

In this sense, KBE can be seen as the process of gathering, managing, and using engineering knowledge to automate the design process by usage of a KBE system [11]. The meaning of "automate" even covers analysis tasks in terms of validation or quality checking, such as compliance to required safety parameters, or ISO standards. Next to time savings a KBE solution can enable a broader variety of detailed design studies of a given master-concept by usage of a rule-based approach for an automated detailing and examination of design variants and in consequence extensively support the optimization of a given (mechanical) design against defined constraints and requirements. KBE as an enabler for easy and fast examination of design variants can be of high value for user centred design, because it is an established idea in this context to provide users with different kinds of virtual or physical mock-ups (e.g.[12]).

However, current KBE is not an one-solution-fits-all approach. By an analysis of more than 500 scientific publications in the area of KBE, major limitation of contemporary KBE approaches have been identified [13].

Currently most KBE-solutions are still very much case based and not grounded in structural frameworks or methodologies [14]. In addition many product developers seem to improvise a KBE solution based upon a customized development process and an unstructured problem analysis[13].

This kind of unstructured approach is followed by contemporary CAD systems. Leading CAD applications provide add-on modules (e.g. [15]) for KBE related features.

In such modules the KBE intelligence (e.g. a design rule) directly remains inside a CAD-model and is directly stored within the CAD file. Based on a parameterized CAD model, they provide functions like formulas (to create dependencies between parameters), rules (such as *If. . . then. . .*) and user defined features, allowing to partly reuse design procedures [15].

Herewith an enormous disadvantage appears with respect to collaborative engineering, neither an intelligent usage of the companies gathered codified knowledge nor an ability to combine such KBE-models into an overall solution is easily possible. Even if it would be possible to break up this encapsulation, which is given by the proprietary structure of such files, a sharing of the implemented design knowledge would fail, due to a lack of standardization of at least these items:

- *Namespaces*: different naming of parameters (e.g. “surface” ⇔ “shape”)
- *Relations*: dependencies between parameters (e.g. “if … then …” ⇔ “if ….else”)
- *Operators & Rules:* (e.g. “if … then …” ⇔ “if ….else”)

In addition to the encapsulation, [13] criticizes that many KBE-Solutions store and represent codified knowledge decoupled from its original context. An adequate documentation is missing and formulas or equations remain unexplained [5]. The cause is often grounded in an unstructured knowledge acquisition process. Without a documentation of the problem in terms of objectives, constraints etc. the traceability of the implemented solution becomes impossible. Along with the insufficiency of a structured knowledge codification, a lack of knowledge reuse has been identified. Due to missing knowledge - e.g. neglected alternatives for a desired solution – KBE solutions are too often limited to their origin context and thus the reuse of knowledge will be hindered or impossible [13].

All of those KBE limitations (lack of openness, lack of documentation, lack of knowledge reuse, etc.) may not to be seen as super critical for contemporary solutions in context of Design Automation. But due to the interdisciplinary nature of smart products development (mechanical engineering, informatics, etc.) black box approaches or unstructured codification may become a key hurdle for Design Automation.

3 Enabling KBE for Smart Products – An Approach

The authors believe that to achieve a support for smart products, KBE-systems must be enhanced and adapted, particularly in the sense of paying special attention to the potential interaction of products with different sorts of information and content.

This is of course by no means possible, if the KBE intelligence (e.g. a design rule) directly remains inside a CAD-model and is solely stored within the CAD file (pls. see above). Further, to represent the semantics of intelligent functions, the systems have to capture product as well as content knowledge. This means that a structured knowledge acquisition and codification becomes a precondition. The knowledge of different domains has not only to be captured, but merged into one integrated model.

The underlying IT-layer, which has to be set up for this purpose, already exists: formal ontologies expressed in a formal ontology language (e.g. Web Ontology Language – OWL [16]) at the level of so-called description-logics:

In context of KBE and DA respectively, ontologies have been successfully implemented [3], [17]. Own research activities already show the potential of ontologies to process rules and constraints for KBE [18].

Even more common is the usage of ontologies to add machine-readable meaning to (web-) content. The latter is for instance covered by the so-called semantic web. Herewith the idea is to provide the content of the WWW not only on behalf of humans but also according to software.

With respect to the ability to merge knowledge from different domains, ontologies are capable to enhance current Design Automation solutions. The basic idea is therefore to provide a central knowledge based system on basis of description logics. The proposed ontology will comprehend a semantic representation of both worlds:

1. Smart layer: representing context, user and usage scenarios interactions etc.
2. Physical layer: product related dependencies, physical constraints, etc.

Herewith smart product related knowledge will rely on both layers and the product design is no longer limited to the physical layer.

In this context it should be mentioned, that the “standard” ontology notation is very limited with respect to typical requirements of codified engineering knowledge: Especially features are needed to compare values or parameters and enable simple calculations respectively. Hence it has become common for ontology related KBE approaches to rely on enhancements such as SWRL [19] or RuleML [20]. In consequence the use of those enhancements makes sense also for the “smart product ontology” approach.

Against this background the authors believe that the ongoing research and standardization activities for ontologies and formal logic languages are going to have huge impact on KBE and especially on possibilities to enable the above mentioned two layer approach for KBE. The already noted demand for a *“move from black-box applications (proprietary software) to applications with user-friendly knowledge bases”* [14] can only be grounded on those activities.

Next to the knowledge base itself, it remains a critical issue to define a user-friendly interface to such a KBE-System. GUIs have to reflect that the target-group is no longer limited to mechanical engineering. To define for instance software features and GUI elements demands for specific expertise from the field of informatics. An ideal solution should be to provide a middleware layer with respective application programming interfaces (APIs) and thus use existing product- and software development applications as a front-end access to the envisaged system (Fig. 1):

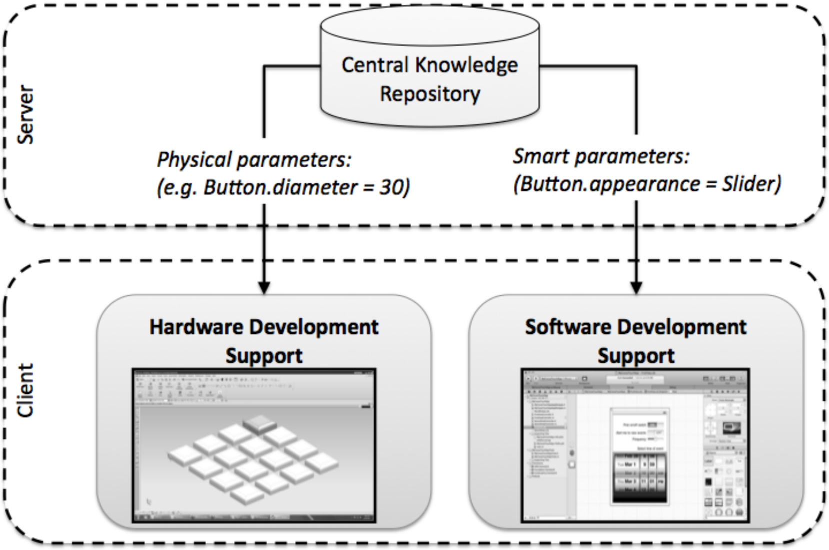

Fig. 1. Reduction of geometry related parameters to a core set of parameters

Even if KBE systems for smart products can not rely on encapsulated engineering knowledge inside a CAD-model, it does not mean that a central storage of all design parameters is the best approach.

Product shapes can be referred to a minor set of core parameters by usage of the on-board features of contemporary CAD systems (refer to Fig. 2). For the example illustrated below only the core parameter „buttonsize" has to be delivered by a knowledge based system. This way - if the knowledge repository is not blown up with overloads of geometrical concepts – consequently it becomes much easier to handle the envisaged "smart product ontology" (and the knowledge based system respectively).

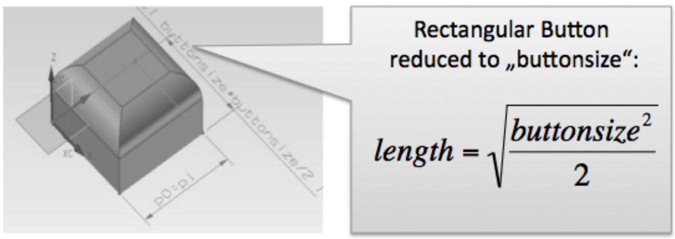

Fig. 2. Reduction of geometry related parameters to a core set of parameters

4 Practical Benefits Drafted in Two Sample Scenarios

To visualize the potential of the approach, a scenario is provided upon the envisaged approach consisting of two parts:

- a decision support, capable to recommend, if user interfaces (e.g. a knob or button) are to be placed virtually on a touch screen or physical as part of the casing.
- content/scenario related definition of the products shape: an electronic device for home office leads to product shape A, an electronic device in a mobile environment leads to casing B.

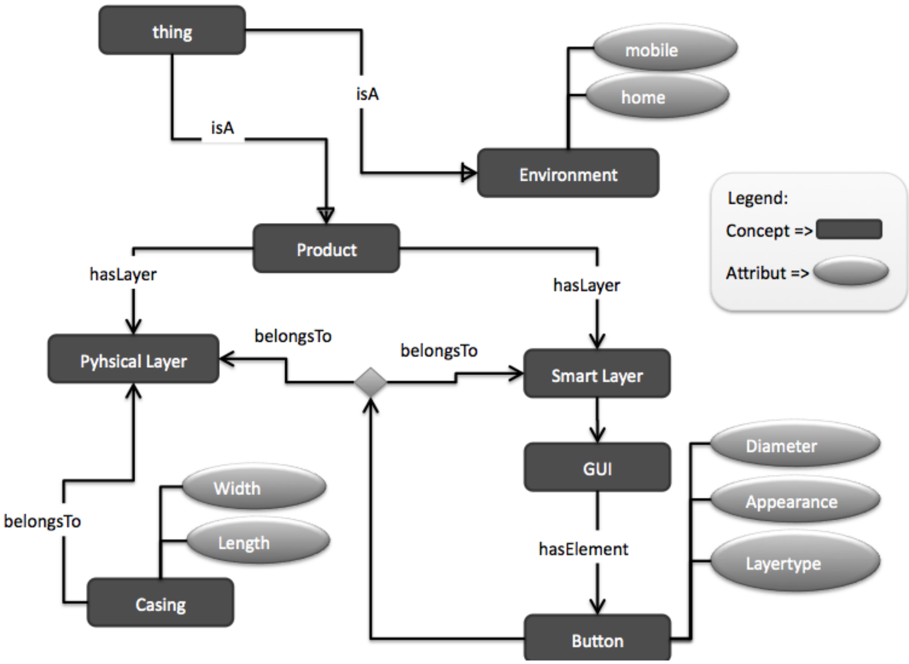

Fig. 3. Simplified ontology representing the User-Interface element button

Figure 3 illustrates a simplified ontology addressing both layers (smart and physical layer) for such a button development. In the centre you will find two concepts representing both layers (physical and smart). Further a *switch on/switch off* functionality is implemented by a concept called *button*. As illustrated, a button can belong to both concepts since the respective user interface (UI) element can be either realized virtual (e.g. as a slider in GUI) or physical (e.g. as a push-button integrated in the casing). Based upon this model, simple engineering rules can be set for the scenario:

if environment.home = true **then** casing.lenth = 300
if casing.length > 250 **then** button.diameter = 30
if casing.length > 250 **then** button.layertype = physical

Not even product-related entities can be modelled in such an ontology, but also other concepts: The sample ontology (Fig. 3) includes on the top-right corner an environment concept together with two status attributes. This expands the degree of freedom for modelling rules within the domain. By choosing enviroment.home the button becomes *physical* and has a diameter of 30. This can be further processed by the CAD system, in terms of automated sizing of the geometrical representation of a parameter. The value of the button.diameter may serve as an input for the associated CAD model, such as illustrated above (Fig. 2).

Carrying the thought a bit further, modelling of complex semantics become possible: the button could be a component of a keypad with additional core parameters (such as numberOfbuttons) and other dependencies (such as spaceBetweenbuttons or positionInkeypad).

Further, the existence or absence of a physical button leads to different casings and product layouts, rules such as below may complete the scenario:

If button.layertype = virtual
then casing.length = casing.length – button.diameter

With respect to the above mentioned easy and fast examination of design variants this rule based approach enables to change the design and appearance of a product quickly just by switching attribute values. In fact, the underlying description logics of ontology languages enables, that nearly all dimensions of smart products can be considered for a DA of a smart product:

1. *Situatedness*: concepts and rules representing and reflecting the situational and community context
2. *Personalization*: in terms of modelling personal needs and affects, e.g. rules such as: if person.impairment = true then button.layertype = physical
3. *Adaptiveness*: the ability to process rules in order to change product behaviour according to concepts representing user's responses and tasks
4. *Pro-activity*: not applicable directly (but not in contradiction to the approach)
5. *Business-awareness*: consideration of business and legal constraints by respective ontology enhancement
6. *Network capability*: not applicable directly (but not in contradiction to the approach)

The six dimensions may not only be represented by a single concept such as the environment concept, but can cover other - even already existing - ontologies (namespaces). The semantic sensor network ontology can be such an example. Its description supports not only the physical structure of a device, but also the processing structure of the sensors. The sensor itself is not limit to a physical object, but can be seen as anything that can estimate or calculate the value of a phenomenon, so a device or computational process or combination could play the role of a sensor [21].

5 Conclusions

According to the analysis in this paper, there is no contradiction between Design Automation and product development of smart products. Even more, the development of smart products can directly benefit from knowledge based engineering, if the latter is realized under consideration of specific constraints. However in some contemporary solutions initial hurdles do exist, such as encapsulation of engineering knowledge in proprietary files. But nevertheless it is possible to provide a support to the product development process of smart products by Design Automation, if these hurdles can be solved.

To achieve this, the authors propose an architecture, where smart product related knowledge is stored in a central knowledge repository and managed by a knowledge-based system. An ontology is proposed to become the core of the underlying IT-infrastructure. As drafted above, ontologies provide the required flexibility to represent classical engineering knowledge and at the same time the “smart layer” domain. Even better the possibility to use existing (fully elaborated) ontologies as an integral part becomes possible. Consequently, there is no need to reinvent domain specific knowledge.

Such a central knowledge-based system may become an integrative part of PLM, thus being implemented as services (as already proposed by [22]). Grounded on this approach product development applications can not only use stored information (such as parameters and functions) in order to control the mechanical design, but in addition can gain benefits for further knowledge acquisition by reasoning and data mining. If ,for instance semantic reasoning can be set upon a “smart products” ontology (which covers all kind of information from the smart products life cycle), the product quality itself may benefit from the proposed approach as well. Findings gained from a central knowledge-based system can directly push a smart product to become smarter.

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Management of Cost Knowledge in Product Design – Integration of Upstream and Downstream Life Cycle Phases

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Abstract. To design products that meet the customer and market requirements as well as given cost limits, knowledge from the whole life cycle is essential. On the one hand, important parts of this knowledge are generated before and after design decisions. On the other hand, knowledge has to be distributed among various internal and external knowledge carriers. Thus, there is a need of methods supporting the integration of cost (related) knowledge from upstream and downstream phases in design processes. The paper presents such methods as part of a holistic cost knowledge management approach for product design.

Keywords: cost knowledge, design-oriented knowledge management, knowledge integration, product life cycle.

1 Introduction

In today's industrial markets products should fulfill functional, ecological and cost-related requirements concerning their manufacturing, use, maintenance, disassembly, and recycling/disposal, respectively. Product characteristics and, thus, the fulfillment of these requirements are largely determined by product design decisions, since they limit the scope of action in later steps of the product creation process and not least the following life cycle phases. As a result, on the one hand, design decisions have a great influence on products' successes. On the other hand, a lot of information from market research and (strategic) product planning (as upstream phases of product life cycle) as well as manufacturing/purchase, sales/marketing, use, maintenance, and end-of-life (as downstream phases) has to be gathered and processed in order to enable design decisions leading to products that meet the requirements mentioned above [1].

This constitutes a great challenge. Especially in the early phases of design processes, only little solid information about the prospective cost and other effects of design alternatives is available. Different departments as well as external actors (suppliers, customers) have to participate and, thus, communication barriers between these participants have to be managed. Additionally, design-relevant knowledge from the

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whole product life cycle has to be handled and the lag of time between decision making and knowledge generation about its effects has to be closed. Concluding, it is essential to systematically identify, acquire, develop, share/distribute, use and preserve the knowledge that is useful for design. This especially applies to cost knowledge as an important part of the knowledge needed. But until now only little attention has been paid to a systematical cost knowledge management focused on design. And particularly the integration of cost knowledge from the upstream and downstream phases and its methodological support has been neglected so far. This motivates to present methods for the handling of cost knowledge from these life cycle phases as part of a holistic cost knowledge management approach for product design. The following presentation of methods is based on literature review and analytical/conceptual considerations. An application and validation in corporate practice has not been conducted yet.

The remainder of this paper is structured as follows: In section 2, the relevant knowledge from upstream and downstream life cycle phases is structured. Section 3 provides an overview of useful approaches and a holistic concept for the design-oriented management of cost knowledge. Based on this, section 4 presents methods for the integration of cost knowledge from upstream and downstream phases.

2 Cost Knowledge in Upstream and Downstream Phases

The relevant cost knowledge from upstream and downstream phases comprises factual (declarative) knowledge, i. e. objective knowledge about processes, products and their cost, as well as methodological (procedural) knowledge, i. e. knowledge about operations and sequences to process this factual knowledge. This knowledge can be explicit (i. e. conscious knowledge that can be articulated and stored in the form of data) or tacit/implicit (i. e. personal, partially unconscious knowledge that is developed through practice and cannot or can only incompletely be articulated) [2], [3].

The first basic category of knowledge is the *factual cost knowledge*, which is either *specific*, i. e. related to a specific product, component or process, or *generalized* from several existing objects [3], [4]. Design-relevant factual cost knowledge from *upstream phases* includes specific market-/customer-based requirements and their future trends as well as the customer's willingness to pay. This knowledge is a prerequisite to design cost-efficient products that meet the customer needs. With respect to *downstream phases*, this knowledge category comprises:

- cost relevant requirements from different downstream phases, e. g., resulting from available production technologies and utilities (inside the company as well as at the supplier), concepts for assembly, use or disposal, existing legal regulations as well as from sales/marketing information,
- cost drivers and their effects in different downstream phases, e. g., the used material determining the production technologies and the options for recycling/disposal, or the manner of connecting different parts with its influence on (dis-)assembly,
- the post calculation of existing products and their components, differentiated by cost categories (like material and labor cost, depreciation), by periods and by

different phases and processes (especially manufacturing or purchasing, use, maintenance, disassembly, and recycling or disposal – partially dependent on customer specific conditions like maintenance intervals or frequency of use) (see Figure 2).

This cost knowledge has to flow back into the design stage for usage in future design processes. In order to make it applicable for life cycle-related cost prediction, it has to be converted into design specific knowledge (e. g., by using post calculations to deduce rules for low-cost design or cost functions based on specific product characteristics) [5].

The second basic category is the *methodological cost knowledge*, which allows the use and generation of factual knowledge in every step of a specific design process as well as cost analyses in other life cycle phases. This category refers to cost calculation and the estimation of the life cycle cost impacts of different function or embodiment variants as well as experience regarding cost estimation, cost impacts in downstream phases, and the accordance of estimated and realized cost. Especially in design phases, various development-concurrent cost estimation methods, e. g., similarity calculation, calculation with relative cost, and calculation formulas [6], life cycle cost calculations or simulations of process times and cost are applicable.

Summarizing, Figure 1 shows the flows of cost knowledge from, within and to product design. On the one hand, existing factual and methodological cost knowledge from upstream and downstream phases is used to design cost-efficient products. On the other hand, by applying existing methods and knowledge new factual and methodological cost knowledge is generated. At the end of design specifications of products are fixed and, therewith, the cost in the downstream phases is largely determined.

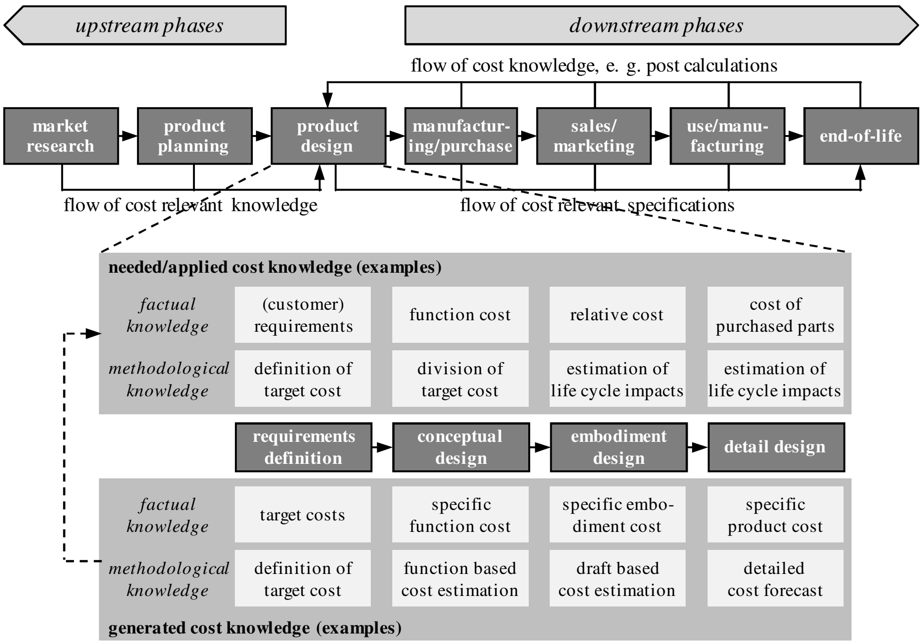

Fig. 1. Flows of Cost Knowledge in the Product Life Cycle (based on [3], p. 97)

3 Cost Knowledge Management for Product Design – Useful Approaches and Holistic Concept

First, it has to be noted that (life cycle) engineering literature and engineer standards are full of cost related knowledge items that can be used in design processes. Within this literature, different lines exist. Several *engineer standards and codes of practice* (e. g., VDI 2884 [7], VDMA 34160 [8]) define elements of life cycle cost and cost drivers and describe procedure models for forecasting life cycle cost. But they are mostly focused on cost from the user's point of view (i. e. purchasing, using and recycling of capital goods). In addition, the effects of cost drivers on life cycle cost are often not considered. Besides, *methods of development-concurrent cost calculation* are discussed intensively (e. g., in [6]). As a basis for this, some life cycle-oriented approaches are focused on life cycle process models and the estimation of process parameters (i. e. times for manufacturing and assembly) (e. g., [9]). Indeed, methods of development-concurrent cost calculation become more and more life cycle-oriented, but in many cases the calculation either deals with simple, standardized tasks/objects (e. g., [1]) or refers to a very abstract level (e. g., [10]). Existing *knowledge-based concepts* for (life cycle-oriented) product design are often not focused on cost knowledge. Furthermore, in most cases the optimization of a product is only limited to one specific stage of the life cycle, e. g., manufacturing or maintenance ("Design for X"). The emphasis is put on the modeling of knowledge (e. g., in form of rules), the structure of IT-systems (like, among others, PLM-systems and collaboration systems) or other technical aspects (e. g., [11]). Generally, the existing approaches do not mention any ideas to manage cost knowledge in a systematic and holistic way.

Motivated by the need to successfully handle the various and complex (life cycle-related) cost knowledge required in product design, on the one hand, and the corresponding deficits in literature on the other hand, a concept for the management of this knowledge was developed by KÖHLER [3]. This concept is composed of a theoretical framework with different knowledge management building blocks and recommendations for their elaboration. The definition of the building blocks bases on the general (not design-specific) knowledge management approach by PROBST/RAUB/ROMHARDT ([2], p. 34). This approach includes "operational" building blocks as core processes of knowledge management: knowledge identification, acquisition, development, sharing/ distribution, utilization, and preservation. The blocks are interrelated, since "interventions … in single core processes … will inevitably affect others" ([2], p. 30). In addition, the activities in the operational blocks need a direction. As this depends on the goals a company pursues with a cost knowledge management, the framework is enhanced by two "strategic" building blocks, knowledge goal definition and knowledge assessment. Together with these blocks a superordinate management cycle is constituted which is similar to the Plan-Do-Check-Act-cycle by DEMING.

As mentioned, KÖHLER formulated recommendations for the elaboration of the building blocks. However, these recommendations are not focused on the specifics of managing knowledge from upstream and downstream phases. Thus, this point is taken up here by presenting methods for the integration of cost knowledge from these phases in product design on the basis of the holistic approach outlined above.

4 Design-Oriented Management of Cost Knowledge from Upstream and Downstream Life Cycle Phases

4.1 Overview

The integration of cost knowledge from upstream and downstream phases in product design processes requires intensive use of a variety of methods that support the gathering and processing of cost knowledge. Thus, based on literature and referring to mechanical engineering, Table 1 gives an overview of relevant methods for all knowledge management building blocks (some phases are summarized, since the distinction between methods for these phases does not seem to be useful).

Table 1. Methods for the Integration of Cost Knowledge from Upstream and Downstream Phases in Design Processes – Examples from Mechanical Engineering

life cycle phases / building blocks	upstream	downstream		
		manufacturing/ purchase	use/maintenance and sales/marketing	end-of-life
knowledge goal definition	methods of the goal setting process, like creativity techniques, portfolio techniques, analysis of the information demand, SWOT analysis			
knowledge identification	questioning of or direct discussion with customers, analysis of items on internet platforms	group discussion between staff members, analysis of own and suppliers' calculations	questioning of customers/users/maintenance staff members, analysis of (customers') cost documents	questioning of customers, recyclers or staff members, analysis of (recyclers') calculations
knowledge development/ acquisition	market research methods (e. g., conjoint analysis), product clinics, quality function deployment, target costing	LCC/TCO, cost accounting and cost benchmarking, creation of process models, development-concurrent calculation with the application of generated and prepared cost knowledge from downstream phases		
		analysis of manufacturing and assembly data, open book accounting	analysis of machine use and maintenance data, cooperation with customers	analysis of disassembly times, recycling/ disposal data, cooperation with recyclers
knowledge sharing/ distribution	open book accounting, product clinics	collaboration with suppliers for access to production cost	collaboration with customers, providing incentives	collaboration with recycling/disposal companies
	establishing suitable conditions to stimulate sharing/distribution of cost knowledge (between design and other departments as well as external knowledge carriers), e. g., direct communication across organizations and life cycle phases, integrated IT-systems			
knowledge utilization	establishing suitable conditions to stimulate the usage of cost knowledge, e. g., preparation of cost knowledge for reuse; (semi-)automatic application of IT-based cost models for cost estimation			
knowledge preservation	storage of requirements in catalogues and specifications	storage of cost knowledge in relative cost catalogues, in cost data bases, PLM-systems, cost models, in terms of calculation rules; regular verification and actualization with new generated data		
knowledge assessment	methods for the collection and evaluation of key figures, e. g., questioning knowledge carriers or analyzing IT-systems with stored cost knowledge			

Results from the strategic building blocks "knowledge goal definition" (for methods see [2], [12]) and "knowledge assessment" (see [2], [13]) are starting points of activities in operational blocks. A selection of methods supporting these activities with respect to knowledge integration is presented in the next sections.

4.2 Upstream Phases

As mentioned in section 2, cost relevant knowledge from upstream phases comprises the customer's willingness to pay as well as specific market-/customer-based requirements. This knowledge is used both in the first stage of the design process (requirements definition) and as a framework in following design stages. In order to make such knowledge available for product designers, several methods for distributing/sharing existing or developing/acquiring missing knowledge can be used.

With the application of *market research methods*, like different forms of conjoint analysis or testing products with specific properties [14], new cost relevant knowledge about requirements is generated or acquired by the company. For example, the *conjoint analysis* is used to detect customers' preferences regarding specific characteristics of requirements. For this, customers have to evaluate different product profiles [15], [16]. If the product price is included as a product characteristic, the preferences regarding this item indicate the customers' willingness to pay [17]. The method is applicable in B2C-markets as well as in B2B-markets. However, companies acting in B2B-markets should observe changes in demands of end-customers in addition to direct customers' requirements, to be aware of market trends at an early stage.

In order to evaluate different product concepts, these can be presented to and tested by key customers or lead users (both real and virtually) in so-called *"product clinics"*. The advantage of this method is the direct contact that can both decrease communication and motivate customers to share their cost relevant knowledge in terms of requirements and experience in product use [18], [19].

The derived preferences provide the basis for *target costing,* a "cost management tool for reducing the overall cost of a product over its entire life cycle with the help of the production, engineering, R&D, marketing, and accounting departments" ([20], p. 41). With this method, the products' target cost can be derived from pricing preferences and the designer obtains indications for decomposing this cost to specific product properties, functions, and components, which support cost-oriented design [21].

To provide design engineers with generated cost knowledge, it can be aggregated, structured, and stored – in terms of data – in generally applicable *requirements catalogues* or in *functional/performance specifications* for a specific design task [22].

4.3 Downstream Phases

Figure 2 shows a methodological concept for the integration of cost knowledge from downstream phases in product design. The core of this concept is built by cost models with cost items differentiated according to products and their components, processes, cost categories, and periods. The cost models are linked with product models representing the product structure and process models for the product-related processes and activities accomplished during downstream phases (together with their cost relevant characteristics). Additionally, further cost drivers are included. Data bases store the huge amount of cost (related) data and make it available for design processes.

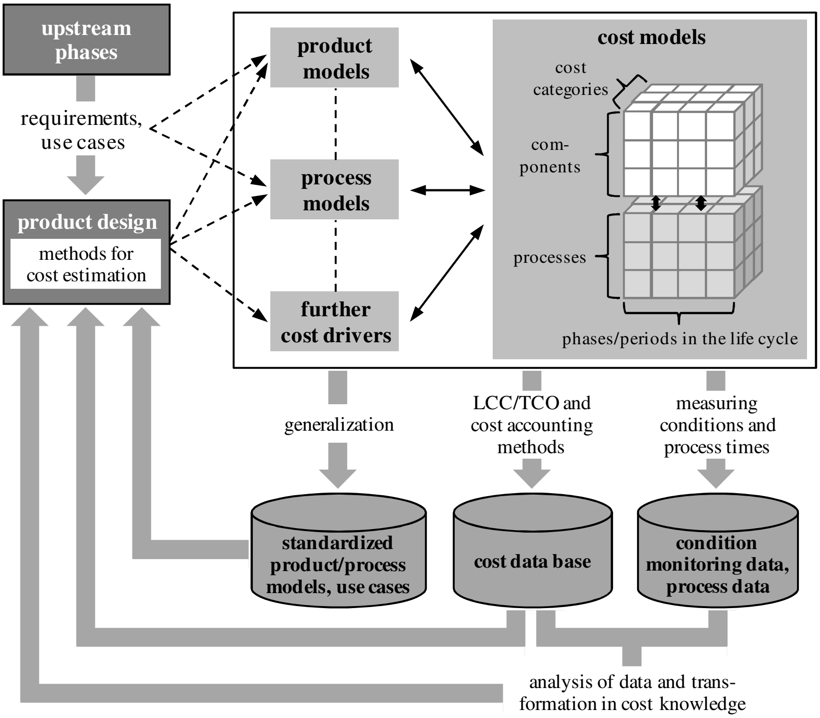

Fig. 2. Concept for the Integration of Cost Knowledge from Downstream Phases

For *cost knowledge generation during downstream phases* a variety of methods exist; some important methods are briefly introduced in the following:

- To evaluate total life cycle cost, approaches of *Life Cycle Costing (LCC)* or – with regard to customers that purchase the specific product – of *Total Cost of Ownership (TCO)* can be used [23], [24]. In order to collect the life cycle cost, differentiated according to Figure 2, particular methods of (standard) *cost accounting* are needed [21]. In some cases, these methods have to be refined or extended to grasp the monetary effects of design alternatives in the downstream phases (e. g., the maintenance cost of a machine or the cost of an end-customer using a car). Based on this, new factual knowledge about cost drivers as well as the amount of cost according to specific conditions (e. g., use cost in several utilization profiles) can be generated – depending on the cost incurrence either by the product designing company itself or by suppliers, direct and indirect customers or service companies.

This external cost knowledge is necessary for both estimating customers' requirements and willingness to pay and considering TCO-commitments in customer contracts. Together with experience from the practical performance of activities, new methodological knowledge about cost-efficient design is developed that can be edited in terms of cost calculation formulas, rules or relative cost [6].

- As a basis for a life cycle cost estimation, *process models* comprising the product-related processes and activities of the downstream phases are useful [25]. For example, disassembly processes can be segmented in basic motions [26] or – much more aggregated – logistic activities may be described by the SCOR model [27]. Based on this, new factual cost knowledge is generated by *measuring and (statistically) analyzing* times and cost of different processes. Therewith, new methodological knowledge (time and cost calculation formulas [6]) as well as factual knowledge (standardized models, use cases and corresponding cost [24]) can be derived.
- Furthermore, knowledge generation in the use phase of machines is supported by the application of *condition monitoring*, i. e. the regular or continuous acquisition of current machine conditions. Based on this data, use- and maintenance-relevant knowledge about failures and their sources as well as the frequency of scheduled or unscheduled maintenance activities can be generated [28], [29].
- In the last phase of the already mentioned *target costing*, the calculated standard cost of the product and its components is compared to the target cost to control the accordance with the given cost limits. In case of a negative deviation, options for cost reduction have to be found [20]. Hence, new cost knowledge about the quality of cost estimations as well as cost drivers and their effects is generated.
- In addition to the upstream phases, customer requirements as cost relevant knowledge can be identified and generated by *analyzing customers' inquiries, complaints, negotiations, conversations* as part of sales/marketing activities [30].

The cost knowledge of internal experts can be elicited by interviews or monitoring their activities, whereas the knowledge of external knowledge carriers is less accessible. Firstly, physical and temporal distances impede direct communication to share knowledge [31], especially tacit experience. Secondly, since knowledge sharing takes place beyond corporate boundaries, communication barriers resulting from differences in previous knowledge and knowledge articulation as well as from fear of losing knowledge are high [2], [32]. The *cooperation* with different downstream knowledge carriers could diminish these problems. By collaboration with (important) suppliers, easier access to manufacturing knowledge, durability data for specific components as well as information about recyclability is conceivable. Within *open book accounting,* i. e. the exchange of cost data and calculation-related additional information, suppliers' cost information can be shared. Necessary prerequisites for the application of this method are "the expectation of cooperative behavior from the supply-chain partner and trust between those companies" ([33], p. 231). Selected customers can deliver condition-specific machine data and cost data from the use phase, whereas recycling/disposal companies provide knowledge about prices or the recyclability of materials. In order to stimulate the customers' and recycling/disposal companies' motivation for collaboration, different *incentives* (e. g., cost reduced service, integration in development, contracting) seem to be adequate [34].

For *knowledge application* in design processes, the cost knowledge generated in downstream phases has to be prepared and – as far as practicable – stored, e. g., in (relative) cost data bases and calculation formulas [6] as well as in PLM-systems [35]. Otherwise the utilization of the factual and methodological knowledge could fail.

5 Concluding Remarks

On the basis of a holistic cost knowledge management concept, methods for supporting the integration of cost knowledge from upstream and downstream phases into design decision-making are presented. Due to the restricted scope of the paper, the methods and their usage could not be deeply elaborated and discussed, respectively.

Further work should concentrate on the refinement and validation of the presented and other methods. Besides, specific methodological issues should be raised, concerning, e. g., the collaboration between different companies and the management of knowledge (from upstream and downstream phases) about revenues. Especially with regard to service processes, the interdependencies between a customer's cost and the company's revenues ask for an integrated cost and revenue knowledge management.

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Functional Shape Elements Integrating Design and Manufacturing Knowledge

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Abstract. In the aviation industry, engine components of different families, variants and versions are characterized by a high level of geometrical, functional and procedural similarities and offer a high potential for rationalization. The reuse of existing knowledge is enabled in product development by part families and features libraries. The classification, administration and retrieval of these parts and features are mainly based on geometric properties, while functional aspects are not considered sufficiently. Nevertheless, in engine design the functional attribute is crucial: Two geometry elements with a nearly identical shape may be applied for completely different functions. A flange serves for transmitting torque as well as for sealing against hot air. In this paper functional shape elements integrating knowledge from both design and manufacturing and the method for their definition are introduced and their application is presented exemplarily.

Keywords: functional shape, design reuse, knowledge integration, knowledge based engineering, CAD, PDM, PLM.

1 Introduction

To reuse valuable knowledge, new products are typically not designed from scratch but by modification of existing solutions. While in the area of mechanical engineering more than 80% of developments are based on reuse [13], for jet engines this number can be assumed to be even higher. In doing so, developments are very time-consuming due to multiple iterations between design and manufacturing. On the one hand components, their function and shape are well-known from past developments. On the other hand, the knowledge that engineers needed and created to develop optimal solutions is not sufficiently documented and stored.

To enable the reuse of knowledge for future developments, harmonization and definition of a template is necessary. Standard parts, standardized part families and

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customized part libraries are common and facilitate the reuse of frequently used geometry elements on a component level [6]. Feature Templates are also common and standard functionality of most professional CAD systems. They allow defining reusable geometry elements on a feature level, below the component or part level.

All these technologies have in common, that they are mainly geometry-based approaches: Classification, retrieval and reuse follows primarily geometric properties (e.g. standard screw). Although functional commonality is known to be the key for design reusability for a long time [4], additional information about the function of reusable elements is usually not provided. In the field of jet engines, in particular this attribute is crucial. Two geometry elements with a nearly identical shape may be applied for completely different functions: A flange serves for transmitting torque as well as for sealing against hot air. This example shows, that a classification of reusable elements based on only geometric properties is deficient. An extension by functional information is necessary to ensure the distinct classification, retrieval and reuse.

In this paper Functional Shape Elements (FSE) will be introduced, which can be interpreted as a unit of shape and intended function of the geometric element. Introductory, recent approaches and related work from science and industrial application will be listed in chapter 2. The method to define a FSE and developed tools supporting the method will be described in chapter 3. The concept of FSE has been successfully proofed by adapting to three different components and will be exemplarily presented in chapter 4. An outlook and a conclusion finish the paper in chapter 5.

2 Related Work

The approach described in this paper belongs to the wide field of knowledge-based engineering (KBE) [18]. KBE systems capture and reuse engineering knowledge about products and processes to solve design problems. The main goal of KBE - reducing costs and saving time in product development - can be achieved by automation of recurring tasks and the integration of different domains [2]. Further advantages of KBE are a transparent communication and information sharing. The storage of knowledge in a common database such as a Product Data Management (PDM) system allows reusability [17].

In this chapter a brief overview about related topics that have influenced the development of FSE from within KBE will be given: Part libraries, feature templates, design reuse solutions and knowledge integration.

2.1 Part Libraries and Feature Templates

Part libraries of standard parts and reusable feature templates are common knowledge-based engineering approaches. Part libraries are well-established in science and industry. They can contain predefined standard parts (like screws, bolts, etc.) and incorporate national standards as well as individually modeled geometry based on company standards. Developing methods for modeling and classifying these parts is still a matter of research [11] [16].

While part libraries offer reusing geometry on a component level, feature template technologies enable the definition of reusable geometry elements below the component level. Feature Templates are also known as User Defined Features (UDF) and can be defined as a set of attributes and constraints, which specify the overall shape. Feature templates are an aggregation of predefined CAD features and can be modeled with every established 3D-CAD system. They enable users to generate complex geometric elements and offer a favorable design environment. Besides shape information, features templates can also contain additional information, e. g. tolerances [5].

2.2 Design Reuse and Knowledge Integration

The integration of KBE and Product Lifecycle Management (PLM) enables the reuse of design solutions, sharing of documents and central storage of CAD files in a repository. But even with KBE methods it is difficult to get relevant knowledge for feature based modeling out of a PDM system [12]. Information about a models design parameters often cannot be viewed directly in the PDM system and updates of those parameters have to be done manually in the CAD environment [9]. Representation in PDM systems is mostly limited to geometry, although non-geometric information e.g. bills of materials or product requirements are available [15]. Pugliese, Colombo and Spurio claim that there is a strong demand for methods to retrieve knowledge from a PDM system and prepare it properly for KBE application [12].

Today several KBE methodologies are available: One of the most known is MOKA (Methodology and tools Oriented to Knowledge-based engineering Applications) [10] [14]. Other KBE methodologies are KOMPRESSA [8] and KNOMAD [3]. For more information about these approaches, the reader is referred to the sources above.

3 Design Approach

FSE are characterized by a defined shape and a unique function and integrate knowledge from both design and manufacturing. They can be interpreted as a geometric area of a component that fulfills a specified function of the entire part. In this paper, the geometric area is called a design zone and is, in terms of CAD technology, represented by an aggregation of features and design operations.

In the following, the method to define a FSE is described: Seven subsequent steps are necessary to ensure uniqueness of the intended function, to analyze, compare and merge different design approaches into one shape and to integrate knowledge: Component Variants and Versions; Function Analysis; FSE Identification; Capturing Design Rationale; Parameterization; Naming Convention; Modeling and Storing.

Supplementary, tools developed to adapt the method to component families and to define a FSE will also be explained. The tools and the seven steps of the method are shown in figure 1 and will be explained in detail in the following paragraphs.

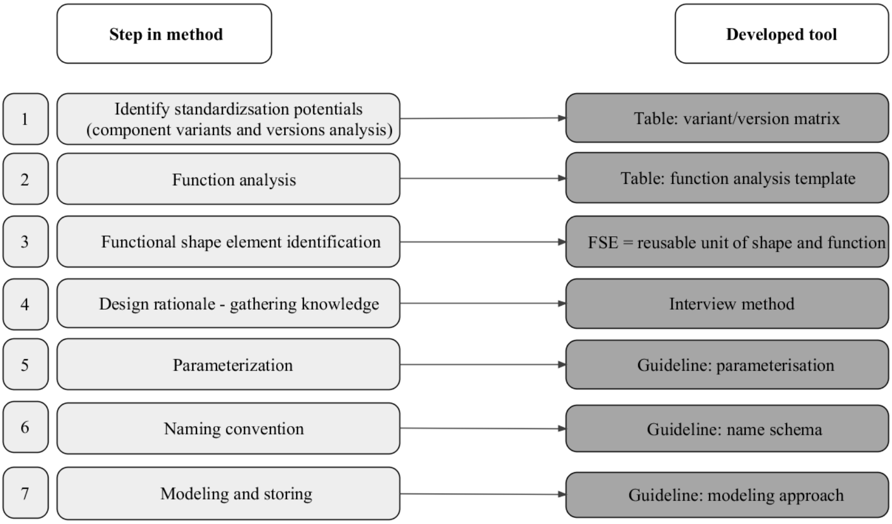

Fig. 1. Method and developed tools

3.1 Component Variants and Versions

The first step is to choose the component family which should be analyzed. In general it can be any component of an assembly containing function oriented design zones. Before using the method, the design zone has to be defined and analyzed. Therefore the design alternatives of the selected component family on which the method should be applied have to be collected and compared to each other. A template has been developed to collect the information about variants and versions (see figure 2). In these templates the different variants and versions for each component are mapped onto a matrix.

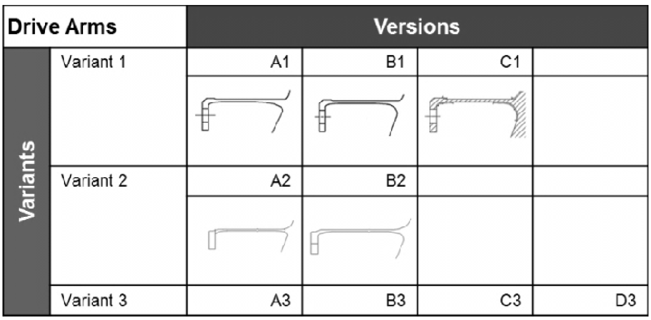

Fig. 2. Variants and versions template

This first step of the method is important for getting an overview of all components of the engines that fulfill same functions. Similarities or variations in engine design alternatives are pointed out and possibilities for rationalization are identified.

3.2 Function Analysis

In function analysis a detailed understanding of all variants and versions for the component family is necessary. Thereby it is possible to detect areas with similar design and similar function as well as areas with differing design and similar function. As the idea of FSE is to reuse knowledge and design rationale in further developments, understanding the functions of design zones and the rationale behind these is fundamental for their identification. To provide an overview of all the functions of the component, they have to be collected in a table. As in the previous step, a template for the function analysis has been developed. In this template it is checked whether a component implements a certain function or not.

Drive Arms		Products								
	Variants	Family A			Family B		Family C			
	Versions	100	200	300	100	200	100	200	500	1000
Functions	Transmit torque	1	0	0	1	0	0	1	1	0
	Transmit axial forces	1	0	0	0	0	0	0	1	1
	Attach shields	0	0	0	1	0	0	0	0	0
	Add stiffness	0	0	0	1	1	0	1	0	0
	Sealing	0	0	1	0	1	0	0	1	0

Fig. 3. Function analysis template

If it represents the function, the function is marked with a 1, if not with a 0. With this procedure it is possible to get a clear understanding of the functional variation and development within one component family. This understanding provides an indication about which geometric areas are relevant for the definition of FSE.

3.3 Functional Shape Element Identification

The next step is the identification of possible FSE. Therefore a schematic sketch is created from component designs that were collected in the template for variants and versions. By labeling design zones that fulfill important functions, those which appeared in function analysis can be assigned to geometry. The example of a high pressure compressor casing is illustrated in figure 4. All components typically provide at least one particular function which is important for the entire engine function. To define functional importance of an element and to assign it to a design zone, it is necessary to involve design and manufacturing engineers of the original component.

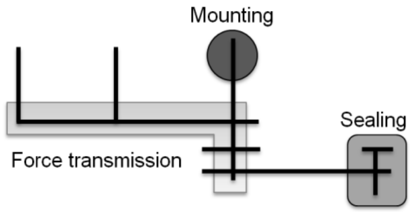

Fig. 4. FSE identification

3.4 Design Rationale – Gathering knowledge

After defining the FSE, all related components collected in the first step have to be analyzed to identify similarities and differences. Capturing design rationale [1] is a documentation of all decisions made during the design process and why these decisions have been drawn. In this step traditionally technical drawings of the FSE are collected from variants and versions template and compared to each other. If some differences in the design alternatives of different variants and versions appear, they are highlighted and discussed with responsible designers of this design zone. Design solutions are categorized into reasonable or not, whether a valid rationale for the variant exists or not. All design variants that are necessary should be represented in FSE to make sure, that all of these can be reused. Comparing all versions and variants of a FSE and the design rational behind is extensive work, but essential for the method.

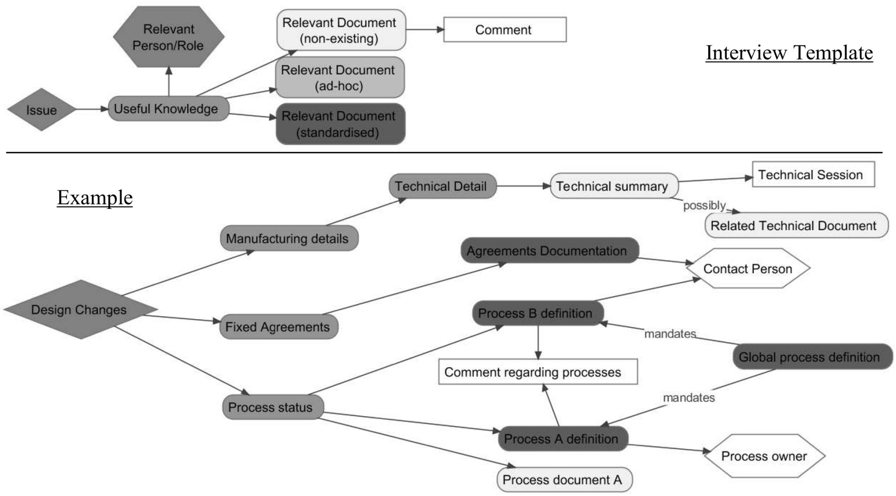

Fig. 5. Capturing knowledge from design and manufacturing

For capturing the design rationale an interview method has been developed. As identified knowledge needs to be represented and stored digitally and accessible, integrating knowledge into a FSE is only recommendable if it exists explicitly or can be transformed into a document. The interview method is based on the template shown in the upper left corner of figure 5. Starting with issues in past development projects, engineers from both design and manufacturing are being interviewed about, which information would have been useful to avoid similar future issues and how this information should be represented. For each interview, both documents and their relations among each other are documented graphically as a network. To highlight the relations between all relevant documents of the design and the manufacturing department, all networks are merged into one "knowledge map". An analysis of the identified documents and relations of this knowledge map provides a pool of documents, which contain knowledge required and which are already used by multiple engineers. The knowledge within this pool of documents is represented appropriately to be integrated into FSE.

3.5 Parameterization

As described in steps before, for a complete parameterization a close information exchange with designers of engine components is indispensable. In order to simplify the implementation of FSE, a robust and possibly established parameterization should be used. The designers must analyze all components of the component family which will be represented in the FSE including their parameterization. If the parameterization is not unique, a decision has to be made, which type of parameterization is more robust and universal. Parallel to establishing parameterization, working on the naming convention is required, because the labels which describe the parameters are a fundamental part of the convention.

3.6 Naming Convention

The naming convention covers all elements of the FSE: The considered component, the particular features and the labeling of parameters. To start, a naming for the FSE has to be defined. Therefore, names and labels designers used in the traditional design process should be taken into consideration. This allows an easier implementation of the new method in existing product development workflows, because familiar elements are included. For naming elements, a method was developed that supports a standard labeling for all parameters. The method for the parameter labeling is shown in figure 6.

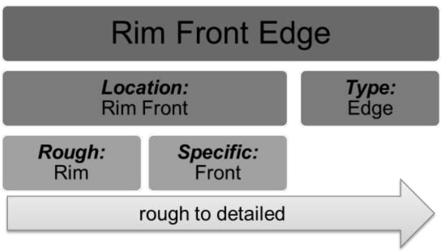

Fig. 6. Naming convention

The first part of the naming defines the location of the element. This element of the name consists of a rough definition, which is the naming of the FSE and a specification, which part of the feature is described. The second element characterizes the type of element, e.g. an edge. The labeling of the parameters is also based on this method and enlarged by a description of the dimension, e.g. FlangeFrontEdgeLength.

3.7 Modeling and Storing

Until step 7, the method was completely independent of any software. To complete the method and to model a FSE, User Defined Features (UDF) as part of the design software Siemens NX 7.5 can be used. To create a robust and sustainable library, best practice for UDF creation need to be defined. This was already described in an earlier publication on knowledge-driven design features [7].

FSE are stored in a PDM/PLM system such as Siemens Teamcenter 8.3. The hierarchical structure of the CAD reuse library allows a functional classification of FSE. Associating FSE to geometric elements of the product structure is enabled by the PDM structure Manager. While the CAD system offers only a view on the concrete used documents within the assembly structure, the PDM systems provides an independent and structured overview of all existing documents related to the product structure. The storing and classification structure of a FSE library in CAD and PDM can be seen in Figure 7.

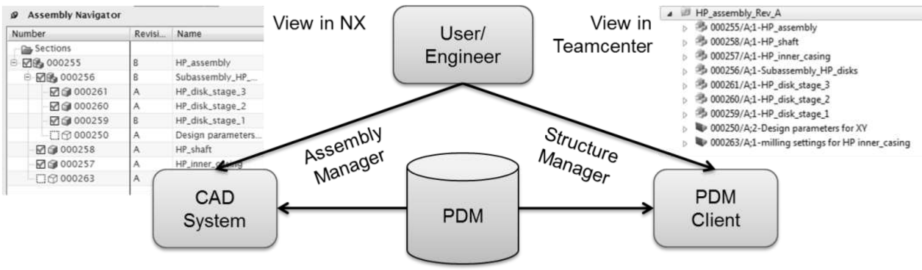

Fig. 7. FSE storing concept

4 Proof of Concept

To proof the concept of FSE, the methods to define FSE and the developed tools have been successfully adapted within showcases in the industry. Three different jet engine component families have been analyzed for adaption: Compressor and turbine disks, compressor casings, and combustor parts. Among these, high levels of similarities between part variants, versions and other parts could be identified. Expert knowledge has also been externalized and associated to the newly defined Functional Shape Elements. During the first six steps of the method, only standardized document types were generated and no specific software was required. For modeling the Functional

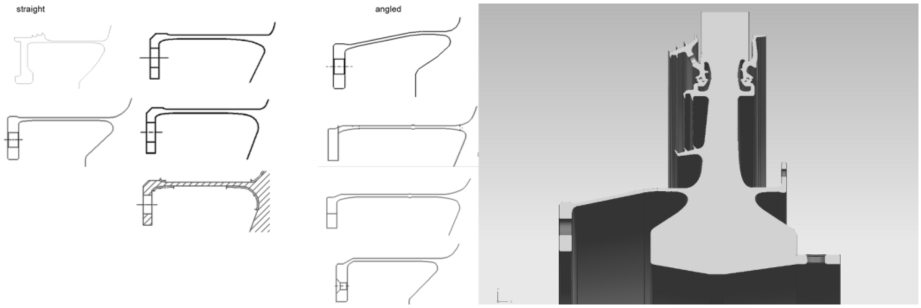

Fig. 8. Snapshots of an exemplary FSE definition

Shape Elements in step seven, NX 7.5 and Teamcenter 8.3, both software systems from Siemens PLM, were used.

In figure 8 two work results of the FSE definition of a flange for transmitting torque are shown: On the left side, a result from step 1 is illustrated. Different variants and versions of flanges with the same function (transmitting torque) but different shapes are listed. On the right side, the complete result of the definition process after step 7 is visualized. An exemplary disk modeled by using FSE as user defined features with NX 7.5 is demonstrated. Several flanges are used, while each represents a particular design zone. The model in the figure consists only of FSE. This shows that the entire modeling of a disk with several functions can be achieved by using only FSE.

5 Conclusion and Outlook

In this paper an approach for defining Functional Shape Elements integrating knowledge from design and manufacturing has been introduced. In common part and feature libraries, classification, retrieval and reuse of reusable library elements are mostly based on geometric properties. The here described Functional Shape Elements represent a reusable element integrating knowledge from design and manufacturing and provide not just geometric shape, but also functional information. The definition process for Functional Shape Elements consists of seven subsequent steps and is the main core of this paper. The method has been successfully adapted to exemplary component families in industry.

The approach is of a conceptual nature and until step 6 independent from any CAD/PDM software. This generic character of the method leads to a possible application in different industries and IT infrastructures. Nevertheless, extensive work is necessary to implement the method, in particular during the analysis phase.

Future research will concentrate on further integration of design and manufacturing knowledge. Furthermore, the applicability of the method to other engineering sectors with different requirements such as automotive is planned.

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Decision-Making Support for Sustainable Product Development

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Abstract. This research focuses on the conceptual design of a Knowledge-based Engineering (KBE) System. A concept for the KBE System and its requirements are described and an outlook of the KBE structure is provided. The KBE System supports design engineers to better understand the impacts of their design decisions on the entire product/system lifecycle. The following points are addressed: Clarification of the evaluation criteria for sustainability assessment, concept development for the KBE System and establishment of a comprehensive knowledge base.

Keywords: sustainability, environmental assessment, decision making, sustainable product design, knowledge-based systems.

1 Introduction

Addressing the problem of global distributed and limited resources, engineers have to develop solutions which consider the entire lifecycle of a product and make reference to the environmental and social impacts. Products and services which ensure a high standard of living are tied to the use of natural resources which are limited available and unevenly distributed [1]. In order to cope with the challenges of an overload of sustainability and lifecycle information the support of KBE Systems during the design phase seems to be necessary. KBE systems should combine the collective knowledge of engineers and designers as well as sociologists and ecologists. That way, product design could contribute significantly to minimize the negative impact on the environment and the society. This paper proposes the aspects of sustainability context areas which support the designer in making decisions based on either:

- Economical Sustainability (e.g. market success and investment efficiency),
- Environmental Sustainability (e.g. ecological footprint) or
- Social Sustainability (e.g. Customer use value and societal value).

The engagements between the context areas are discussed against the background of the decision-making process in the conceptual design stage. Design decisions and their impact on the lifecycle could be shown. Additionally, the paper presents an

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ontology approach following the CommonKADS methodology [2]. The paper presents the current work on the development of a KBE System that supports sustainable product development. The system is designed to make statements about the sustainability of design decisions. The following points are addressed:

- Clarification of the evaluation criteria for the sustainability assessment
- Concept development for the knowledge-based system
- Establishment of a comprehensive knowledge base

2 Problem Statement

To assess a product in terms of sustainability the question arises how the issue of sustainability can be made convenient and controllable for the designer. "Clearly, technology designers need more concrete targets then just sustainability. What do you do when you are working on ceramics, aircraft, communication protocols, skyscrapers and you want to contribute to sustainable development?" [3] In the course of time a variety of environmental factors have emerged which can be quantified. The most prominent examples are the assessment of CO_2 emissions and water pollution. Based on these two factors other factors can be derived which have a direct impact on the sustainability of a product/system, i.e. the consumption of fresh water during production can be measured, the pollutants emitted during the use phase and the fuel consumption for any transportation have an impact on product's sustainability. However, extensive sustainable assessment like Life Cycle Assessment (LCA) is not suited for industrial practice of product creation and hence does not lead to more sustainable products. For this widely acknowledged problem three major drivers can be identified:

- LCA is too extensive to conduct thus it cannot be done comprehensively for a large number of different products. Therefore most products will never be covered.
- The value of LCA is questionable due to massive uncertainty of the analysis, in particular regarding the impact assessment. The aforementioned effort has to be seen in combination with weak results in an unfavorable cost-value-ratio.
- The amount and specificity of information generated by an LCA cannot be used by the designer, i.e. applied in his daily decisions. Hence even well conducted LCA rarely influence design decisions and therewith the product's characteristics.

To cope with the challenge, certain governmental and non-governmental organizations have published databases which list different sustainability indicators of different states, e.g. the Japanese National Institute for Environmental Research [4]. Based on these data a team of German and Japanese scientists has elaborated 32 factors for sustainability which are directly related to the product lifecycle (Table 1) and can be influenced by the designer [5]. Most of the criteria only state formulations like "the less / the more better" since not all factors are determined to an absolute minimum or maximum. The sustainability of products can therefore not be assessed absolute compared to an LCA approach. At this point the lifecycle's stakeholders have to define the sustainability goal in terms of the sustainability context areas.

Table 1. Selection of officially accepted sustainability indicators [5]

Category	Subcategory	Indicator	Country	Year
Ecological	Recycling	Amount of recycled and reused wastes	Mexico	2000
Ecological	Chemicals	Hazardous chemicals, quantity	Sweden	2006
Economical	Material Use	Energy and raw materials productivity	Germany	2002
Economical	Transportation	Traffic related emissions	Austria	2002
Social	Family	Frequency of interaction with family and friends	New Zealand	2002
…	…	…	…	…

In order to allow an assessment in accordance with the indicators it is necessary to provide additional knowledge about a number of topics in the form of databases on the system. These are addressed in Table 2.

Table 2. Knowledge areas for sustainability assessment

Topic	Brief description	Example
Environmental influences	Impact of processes and materials on the environment	Linking of CO2 emissions and global warming
Manufacturing method	Contains the knowledge about the amount of work involved, the process as well as the used tooling of the single manufacturing methods	Mill consumes energy, leave filings and coolants
Working conditions	Different terms of working conditions and their effect on the environment	Monotonous, heavy work is harmful to health
Utilization model	Contains knowledge about different application purposes of products	An engine is pursued with petrol to drive a vehicle
Method for recycling	Types of recycling	Waste glass is melted under energy application and recycled
Local knowledge	Knowledge about working conditions and infrastructure	Transport by rail in Germany
Knowledge of material	Knowledge of various material properties	Carbon can be completely recycled

Since the stakeholders of each lifecycle phase have certain expectation, needs or requirements the main question for the designer is how to design sustainable products/systems if the impacts on the lifecycle remain uncertain (Figure 1).

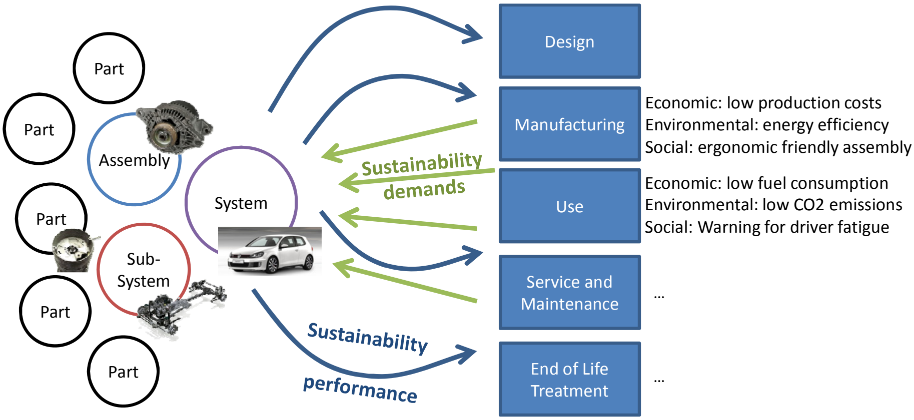

Fig. 1. Relation between Sustainability demands and Sustainability performance

3 Goal and Scope

To improve the described situation, an effective support of the designer is required. He has to be enabled to make decisions towards more sustainable products/systems within his given working environment under certain constraints (systems, resources, knowledge). The goal is the establishment of an assessment method which has the potential to have an impact on products/systems towards less environmental harmful characteristics. While aiming on this aspect a reduction of accuracy of the assessment has to be accepted. Given the required input data and manpower, the method can be adopted and used for other products as well.

4 Other Approaches (Examples)

The complexity, and hence lavishness, of (product) assessment procedures is a common problem, in particular if the information is required in industrial product development processes as temporal resources are increasingly scarce due to accelerated innovation cycles. Various methods attempt to address the aforementioned problem by reducing the extent of analysis of the environmental impact of systems. This reduction of complexity is achieved by different approaches, which can be allocated into the following categories (examples given):

- Reduction of scope (i.e. the considered lifecycle phases) in full LCA approaches:
  - Cradle-to-grave: from resource extraction (cradle) via primary use to disposal (grave), which excludes recycling or remanufacturing and additional use phases
  - Cradle-to-gate: from resource extraction to the factory gate
  - Gate-to-gate: production phase within the factory
- Reduction of detail in full LCA approaches
- Reduction to a single factor:

- Energy:
  - LCEA: Life-Cycle Energy Analysis
  - KEA/KEV: Cumulated energy consumption (Kumulierter Energie Aufwand/Verbrauch) [6]
- Material:
  - MIPS: Material Input Per Service unit [7]
  - Carbon Footprint CO2 or hazardous substances
- Specification on single industries or product classes:
  - GREET Model: Greenhouse gases, Regulated Emissions, and Energy use in Transportation
  - Well-to-Wheel: Assessment of energy efficiency in vehicles
- Simplified environmental evaluation [6]
  - MET-Matrix: Material, Energy and Toxic substances in- and output
  - Eco-Compass by DOW Europe
  - Eco-Estimator by Philips

5 Knowledge-Based Approach

5.1 Goal and Concept

The major function of the KBE System is the classification of the various properties and characteristics of a product (which can be a either a single part or a system) with respect to its sustainability. The environmental and social impacts over the entire lifecycle are considered. For this purpose, the system should ideally access to databases to gather information about the sustainability context areas, i.e. manufacturing processes and equipment and the re-use purposes. Furthermore, the system evaluates both the designer's intention and the stakeholder's needs and requirements. It is clear that the necessary databases achieve a volume which must inevitably lead to a restriction of the evaluation space. It is likely that computing power can be saved if the user of the system already provides information about the manufacturing processes, the purpose of use and the envisaged type of recycling/re-use. Additionally, the same product/system can have different effect on its sustainability due to different methods of processing and assembly in different countries. The KBE System's inputs and outputs are the following:

- Input
  - CAD model (properties) and material characteristics
  - Production site/location, location of use and recycling
  - Design intention (sustainability context areas)
  - Databases (knowledge areas for sustainability assessment, cp. Table 2)

- Output
  - Sustainability assessment of manufacturing, use phase and recycling
  - Combined sustainability assessment

Figure 2 provides an overview of the major functions of the KBE System and its inputs and outputs. The system is designed modular. There exists a modular inference machine for each assessment (manufacturing, use, recycling) and one for the combined assessment. Modules can be expanded if necessary and replaced. Furthermore, the modules are designed to deal with any amount of information on each assessment. Therefore, the system repeats the evaluation steps for an arbitrary number of information. Subsequently, the results of all assessments are allocated.

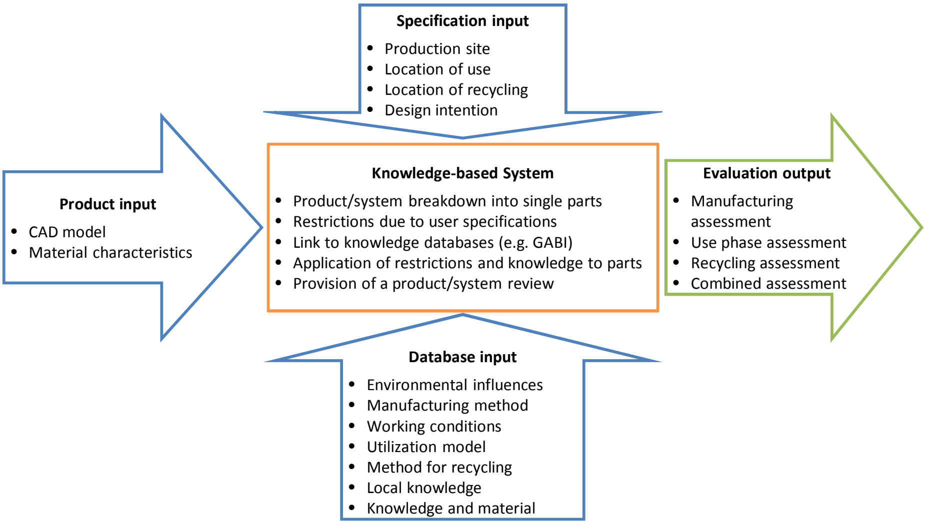

Fig. 2. Major function of the Knowledge-based System

5.2 Task-Level Definition

The highest stage of a KBE System is represented by the so-called task level. In this discipline-unspecific level a general statement about the task of the system is taken. It can be distinguished from six areas of responsibility of a system [2]. In addition, there are a number of solution-generating task types. These serve, i.e. to perform planning tasks or to develop models. The concept of knowledge engineering affords that the task definitions are done independently. Since the KBE System evaluates an object with respect to a superior goal implementation the following three steps have to be succeeded (see also Figure 3):

1. The system assigns properties of the object to corresponding instances of classes
2. The object is evaluated against the assigned instances and its inherent properties
3. The object is evaluated in terms of individual assessment results

To complete the first step the application of the task "classifying" is repeated until all classes of an object are assigned to an instance. The task of the second step consists of evaluating the object on the basis of data from the knowledge-base (Knowledge areas for sustainability assessment, Table 2). Within the third step the results of step two are allocated and an overall result is presented.

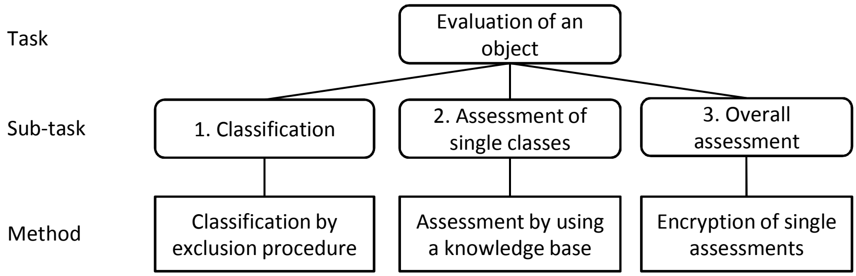

Fig. 3. Task definition and performance (three step approach)

The CAD model and the other inputs (cp. Figure 2) are entered into the KBE System. Based on that, the system assigns an instance per class to the model. Figure 4 provides an example for the classes and its instances. The modular design of the system allows adding any other classes.

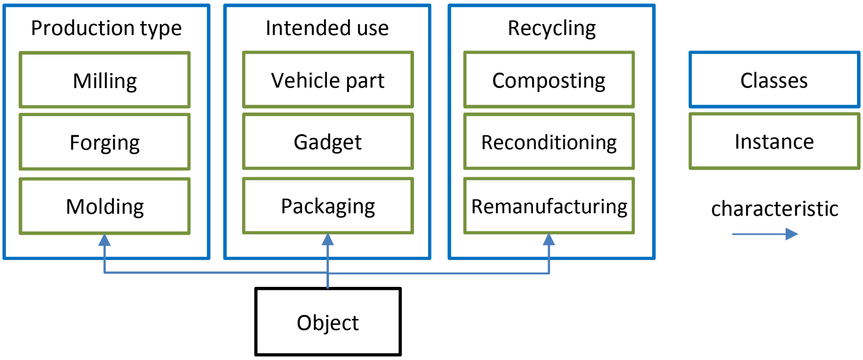

Fig. 4. Example of the classification principle for the KBE System

5.3 Knowledge-Base

The knowledge base is the basic element of every KBE System. Once the overall objectives of the system are defined the knowledge structure has to be defined in a way it can be processed in a KBE System. Initially, an abstract object contains all relevant and available information which is required to assess the object. The presentation of the proposed concept which includes the relationships between the different objects as well is based on the notation of CommonKADS [2]. Figure 5 provides an overview of the necessary environment (relevant knowledge areas) for sustainability assessment.

The state of the art provides the evaluation criteria (sustainability indicators) based on environmental impact models and health effects. Additionally, the ideal values of the evaluation criteria have to be defined. The data from the CAD model provide all necessary parameters to simulate the corresponding processes. Another important issue for sustainability evaluation is the country of origin. The production site

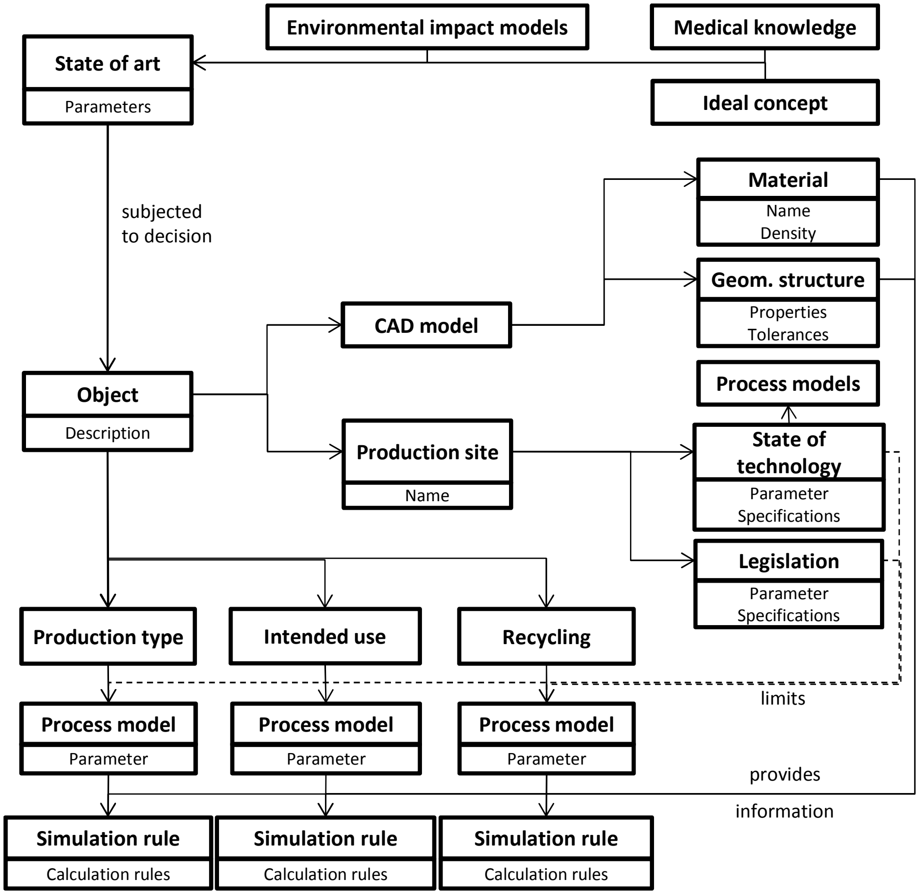

Fig. 5. Environment (relevant knowledge areas) for sustainability assessment

determines the available technology and defines its processes. Furthermore, the production site is crucial for the applied legislation. Legal obligations regarding working conditions, i.e. maximum lifting loads, as well as environmental protection play a major role. That way, the same process has unlike characteristics in different countries, e.g. an air filter protection is mandatory in country A whereas the costs for emissions are lower in country B. Both the legislation and the state of technology limit the processes for production, use and recycling. The KBE System can, in turn, assign process models to production, use and recycling. That way, the process models can be simulated and evaluated against the pre-defined ideal concept.

The state of art delivers comparative data to the system thus the system is enabled to assess the impact of individual process parameters. The description of this knowledge is a challenge due to the fact that there are no defined guidelines to make various health parameters, environmental impacts and other important indicators for sustainability comparable. Combined LCSA (Life-Cycle Sustainability Assessment, consisting of Life-Cycle Assessment, Life-Cycle Costing and Social Life-Cycle Assessment) approaches are already in focus of other research [8]. In fact, it can be assumed that there exists another KBE System or database which provides information about the relationships between the different indicators.

The KBE System of this research could request to the state of art "10kg of CO2 are emitted" and would receive a corresponding value of sustainability from the database in response. At the same time, the state of art has to be given an ideal value for each parameter to allow the formation of a decision. The database has knowledge about the effect for each parameter in terms of a sustainability value. This effect is related to a denomination which indicates the amount the sustainability value draws. To take up the example of the CO2 emissions, the following information has to be stored in the database: CO2 impact is 4.2 per 1.0kg. According to the state of knowledge ideal values for all parameters have to be stored. Moreover, it is necessary to provide a possibility to break down the individual impacts of resources to each of the parameters. Since the average energy mix in different countries varies widely it is necessary to define this knowledge in conjunction with the country. The system can resolve a query of the type "3kg iron are processed" into "40kWh energy are consumed" and it concludes at the same time " 25kg of CO2 are produced + 0.0002g nuclear waste have to be discharged". These two parameters can be evaluated by the system and a statement about the sustainability of iron production can be made according to the current CAD model, either if it is a single part or an assembly (system).

6 Conclusions and Outlook

This research presents the current progress on the development of a KBE System that supports decision-making for sustainable product development. The following points are addressed within the paper:

- Clarification of the evaluation criteria for the sustainability assessment
- Concept development for the knowledge-based system
- Establishment of a comprehensive knowledge base

The next steps are:

- Establishment of the inference levels
- Implementation of the KBE System
- Integration of the KBE System into a PLM (Product-Lifecycle Management) System
- Integration of existing databases (sustainability indicators and data)
- Application and testing within industry

One of the important steps is to define the inference levels. At this level the tasks of the KBE System are broken down to the individual logical units of the solution process. That way, the inference structure represents the determined linking of knowledge with each task level at the knowledge-base. Based on this research an application for a PLM system will be developed. PLM systems are a core component of the system landscape in product development environments and represent a standard for industrial applications such as in the automotive or aerospace industry. The application includes the development of a Virtual Database approach, which is extended by the KBE System ontology as a data model. This allows the modeling of logical statements (e.g. rules) and the use of logical query languages (e.g. SPARQL). With the help of the application design engineers will be assisted to develop sustainable and energy-efficient products/services.

The engineer's primary task in industry is still not to design sustainable products/systems. For now his dominant assignment is designing products which ensure a high return on investment. Thus no matter how well the support for the designer will be, his priorities still are not in favor of sustainable products. In order to give to the sustainability dimension an appropriate, i.e. manageable place and weight, engineering IT systems like PLM systems should be adopted to support to the multidimensional nature of engineering decisions.

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Industry Requirements for an Assistant System Supporting Energy-Efficient Product Development in the Automotive Supply Industry

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Abstract. Today the development of energy-efficient products throughout their entire lifecycle is more than a major issue for environmental and economic concerns, it also represents a high business potential for companies.

Unfortunately, a complete integration of energy-efficiency aspects into industrial product development practice has not been achieved yet. This is partly due to a lack of simple methods and tools for the evaluation of energy-efficiency and costs of design alternatives, as well as checking their compliance with regulatory constraints. A possible solution to this problem is an assistant system adapted to the designer's working environment. This paper describes the main requirements in the automotive supply industry for such an IT support.

The requirements list was first obtained from an analysis of industrial and research publications and the most relevant regulations related to the energy-efficiency of products. This list was then weighted, extended, and validated through interviews with design experts from the industry.

Keywords: Assistant system, product development, energy-efficiency.

1 Introduction

In economics, efficiency is defined as achieving maximum output from a given level of resources (input) used to carry out an activity [1]. In this context, energy is considered a resource, contrary to the concept used in physics: energy can be "created" or "lost". The term energy-efficiency comprises the attainment of maximum useful output from a given energy input, or the use of minimum energy input to obtain a given useful output. A social view of energy-efficiency may consider energy savings to be an efficiency gain, e.g. when taking the stairs instead of using an elevator. A more technical view may consider savings as conservation rather than efficiency improvement. Today the development of energy-efficient products throughout their entire lifecycle is an important issue for environmental and economic concerns. This is mainly motivated by the following drivers:

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Ecological Drivers. Nowadays, climate change is the most important environmental problem, where greenhouse emissions take the most crucial role [2]. Energy-related emissions are responsible for an important part of these emissions [3]. 80% of future environmental impacts of a product are defined in the product development lifecycle phase [4]. According to the International Energy Agency (IEA), the increase of energy-efficiency will play an equivalent role for climate protection as the sum of renewable energies and other environmentally friendly measures [3].

Economic Drivers. Especially over the last ten years, energy prices have been increasing considerably [3]. According to the European Commission (EC), energy-efficiency is the most cost-effective and fastest way to increase security of the energy supply needed for economic growth in the European Union [5]. Furthermore, energy-efficient products represent a high business potential for companies. On the one hand, companies can achieve important savings by improving the energy-efficiency of their products in the different product lifecycle stages. According to a study in German companies, 80% of product costs are defined in the product development stage [6]. On the other hand, companies achieve a greener image. Energy-efficiency and savings benefit the economy as a whole, the public sector, businesses, and private individuals [5] [7].

Legislative Drivers. As the result of environmentally friendly governmental policies, an important number of standards (norms, labels, guidelines, etc.) related to the energy-efficiency of products have been developed or are under development all over the world [4] [5] [8].

Unfortunately, a complete integration of energy-efficiency aspects into industrial product development practice has not been achieved yet (cf. chap. 2.1). Figure 1 outlines the main stages for the development of an assistant system supporting energy-efficient product development. The assistant system first and foremost focuses on the requirements of the automotive supply industry.

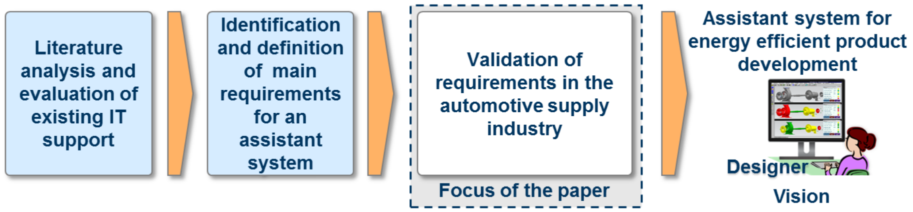

Fig. 1. First steps towards an assistant system supporting energy-efficient product development in the automotive supply industry

The requirements for the assistant system have been defined in three main steps. First a detailed literature analysis has been carried out (cf. chap. 2.1). Based on the analysis, a list of main preliminary requirements has been defined (cf. chap. 2.2). The main preliminary requirements have then been validated through a survey in the automotive supply industry (cf. chap. 3).

2 Preliminary Requirements

2.1 Literature Analysis

This chapter summarizes the results of an analysis of industrial and research publications. The detailed analysis has been presented by the authors in a previous publication [9]. The goal of the analysis was to determinate a list of preliminary requirements for IT support environmentally friendly product development with special regard to energy efficiency.

Environmentally friendly engineering IT support proposes nowadays the major solutions for the development of energy-efficient products. This type of IT support can be divided into two main categories [9]: Eco design specific IT tools and environmentally friendly modules in general purpose software such as specific modules in Enterprise Resource Planning (ERP) systems, Computer Aided Design (CAD) software, or Product Lifecycle Management (PLM) software. Specific eco design IT support presents one or more facets of which the most important are: the definition of strategies, the analysis of product alternatives, the management of specific data, the compliance with standards, and e-learning.

Approaches for strategy definition consider energy efficiency and are interesting for early design stages [7] [10] [11]. Unfortunately, IT support in this area does not sufficiently exchange information with other systems [9]. The amount of time and efforts needed for collecting information is considerable.

In spite of important progress in the field of IT support for environmental assessment, there is a lack of solutions that support designers in finding and substantiating solutions after the assessment [9]. Life Cycle Assessment (LCA) software today represents the most comprehensive support for energy-efficient product development, even if it is not specific for design [9].

It is important for a reliable energy efficiency assessment to access and collect quality data from appropriate sources [12]. Unfortunately, there is currently a lack of solutions for the integration of different systems such as CAD, ERP, PLM etc. [9]. Furthermore there is a need for solutions for automated and permanent updating of data [12] [9].

With regard to compliance checking of products with regulatory constraints, current IT solutions are focused on integrating norms, labels etc. into databases. The most advanced solutions are proposed by LCA software [13]. Furthermore, some current research projects deal with the facilitation of the use of standards [8] [14]. Unfortunately, support in verifying compliance of the design alternatives is still poor [9].

IT solutions that support eco design learning (e-learning) are rare and very limited. The most advanced support in this area is LCA academic software [9].

The most used IT support in product development practice is commercial general purpose engineering software (CAD, ERP, PLM etc.). It thus generates a high potential support for the development of energy-efficient products. At present, however, it does not sufficiently deal with energy efficiency aspects [9] [15].

To enable the designer to consider energy efficiency aspects throughout the entire lifecycle of a product, CAD software is capable of providing useful information aside from material, volume, and geometric data [16]. Currently, some CAD modules provide relatively simple proposals e.g. concerning material choice [17]. Other solutions comprise giving advice about different design alternatives in various scenarios via dashboards [18].

Since data of items and manufacturing processes is often handled in industrial ERP appliances, it represents an important source of product energy-efficiency data. In the early 1990s, first ideas came up to integrate LCA software into ERP software. Today, this is carried out only partially as a result of research projects [9].

Due to the fact that PLM solutions facilitate the collection of information with the support of authoring systems (CAD, CAE, CAM and office systems) [19], it represents a high potential support for the development of energy-efficient products [9]. Unfortunately, the management of energy data is currently not sufficiently integrated into PLM environments. Furthermore, like other IT solutions, most of the data has to be integrated manually and the quality of the results depends on the accuracy of the database [9].

2.2 Preliminary Requirements Definition

Based on the literature analysis in chap. 2.1, a list of preliminary requirements for an assistant system supporting the development of energy-efficient products has been defined. The most important functional requirements are:

- Automatically collect information from different systems (e.g. CAD, PDM/PLM, ERP, etc.).
- Constantly and automatically update relevant databases for energy and cost assessment, as well as for compliance checking.
- Support simple visualization of the results (e.g. markup of critical elements in 3D models).
- Allow a simple comparison of the states of the design alternatives before and after changes.
- Automatically search and recommend useful alternatives.
- Include an e-learning module.
- Perform compliance checking of the design alternatives with regulatory constraints.

In addition to the above functional requirements, the following main general requirements are included in the list:

- Consider the entire product lifecycle of a product.
- Always evaluate the energy-efficiency of design alternatives in relation to costs.
- Extend the assistant system to cover other design aspects like safety.
- The system should be user-friendly.
- Integration into an existing IT tool (e.g. CAD, PDM/PLM, ERP, etc.).

In order to verify whether the above-mentioned main functional and general preliminary requirements coincide with the real needs in current industrial product development practice, a survey has been conducted in the automotive supply industry. The central questions were:

- How important are the requirements to the designers?
- What are the particular requirements regarding an assistant system to support energy-efficient product development in the automotive supply industry?

3 Requirements Validation

3.1 Validation Approach

The approach used for the validation of the preliminary requirements (cf. chap. 2.2) has been carried out in two main stages:

Development of a Survey Concept. In order to answer the central questions mentioned in chap. 2.2, a survey based on a list of more detailed questions (questionnaire) for design experts from the automotive supply industry has been chosen as the most suitable way to validate the requirements. The two main advantages of this type of survey are: it allows a statistical analysis of the results, and it can be carried out both by personal interviews and online. The questionnaire was first drawn up in cooperation with a selected group of design experts from the automotive supply industry. The questions dealt among others with the following topics: the weighting of the preliminary requirements, consideration of regulations related to energy-efficiency (including labels and methods from norms and guidelines), the consideration of the lifecycle, and the consideration of specific product features and characteristics with regard to energy-efficiency aspects and costs.

Execution of the Survey. The survey was carried out through personal in-depth and online interviews. In the second instance, in order to optimize its distribution and evaluation, the questionnaire was transferred to a PHP Surveyor browser-based survey tool. The completed questionnaires were evaluated via SPSS software. The survey was carried out with a large multinational company at several sites in Germany. The company is one of the major global players in the automotive supply industry. This supplier was chosen because of her large product range, presence in the global market, and her environmentally friendly policies (including energy-efficiency policies). For these reasons, the current results of the survey can be considered representative for the automotive supply industry. A total of **138 experts** from the different company sites on product development weighted, extended, and commented the preliminary requirements list. About one fifth of them submitted their opinions and comments via personal interviews, and the rest participated in the online survey. Approximately 70% of the experts were experienced designers, 30% of which top managers. The results of the survey will be described and analyzed in the following chapters.

3.2 Main General Findings

One of the most important topics of the survey was the question: Into which kind of software should the assistant system be integrated? The results confirm with the consent of approx. one third of the experts that the integration into CAD software is the most favored option. Nevertheless, PLM/PDM software is almost at the same level of desirability. An unexpected result was that around 25% of the interviewees prefer an assistant as independent software. Another interesting result was that energy-efficiency claims the sixth priority position among the aspects to be considered during product development, just after function assurance, costs, quality, manufacturability, and safety, and before transportation, maintenance, recycling, and others.

Depending on their characteristics, products may present important differences, even within the same company. It is a very ambitious project to develop an assistant system compatible with existing general purpose software (CAD, PLM, etc.) and capable of automatically collecting real and virtual data for energy-efficiency and cost assessment, and congenial to all types of products. The assistant system should first and foremost serve as a calculation tool. The assessment should consider at least the perspectives of the company and those of her customers.

Compliance checking of design alternatives with regulatory constraints (laws, standards, labels, etc.) is an important requirement but difficult to implement. In part this is due to the same reasons mentioned in the previous paragraph, and also as regulatory constraints are specific to each individual country, company (e.g. internal standards), and product.

To solve the problems mentioned in the last two paragraphs, prior to its first utilization, the assistant system would require configuration according to the specific processes of the company and the specific characteristics and constraints of the product or product family to be analyzed. This can be accomplished by developing adequate IT solutions to create models of products and product-related processes for the calculations. The models should be based on real and virtual data which require permanent updating.

3.3 Final Weighted Requirements List

One of the most important survey topics was the weighting of the requirements. The industrial experts on product development were asked to classify the preliminary requirements according to their degree of importance. For this particular item, the survey concept has been developed to allow experts to add requirements and give feedback. The most common comments included:

User friendliness is the most important requirement. The system should include e.g. a simple visualization of the results such as by color marking the critical parts of a product with different components within a CAD model.

The system should always evaluate the energy-efficiency of design alternatives in relation to costs, first and foremost, from a company perspective, then from a customer perspective. These two perspectives are particularly important for the automotive supply industry since their primary focus is on the energy-efficiency of the final vehicle.

With regard to the consideration of the different lifecycle phases, the production and the use phases have almost the same relevance, and they are the most important stages to be considered. The disposal/recycle phase has less relevance. An unexpected result of the survey was that the last place of importance was attributed to the procurement phase. In conclusion, the below table summarizes the weighting, opinions and comments made by industrial experts:

Table 1. Final weighted requirements list

	Requirements	Priority according to	
		Experienced designers	Design managers
functional	Automatically collect information from different systems (e.g. CAD, PDM/PLM, ERP, etc.).	2	3
	Constantly and automatically update relevant databases for energy and cost assessment, as well as for a compliance checking.	2	2
	Support simple visualization of the results (e.g. markup of critical elements in 3D models).	2	2
	Allow a simple comparison of the states of the design alternatives before and after changes.	2	1
	Automatically search and recommend useful alternatives.	2	2
	Include an e-learning module.	3	2
	Perform compliance checking of the design alternatives with regulatory constraints.	2	2
general	Consider the “procurement” product lifecycle phase.	4	2
	Consider the “production” product lifecycle phase.	2	1
	Consider the “use” product lifecycle phase.	2	1
	Consider the “disposal/recycle” product life-cycle phase.	2	3
	Always evaluate the energy-efficiency of design alternatives in relation to costs.	1	1
	Extend the assistant system to cover other de-sign aspects like safety.	4	4
	The system should be user-friendly	1	1
	Integration into an existing IT tool (e.g. CAD, PLM/PDM, ERP)	3	2

(1: highest priority, 4: lowest priority)

4 Outlook

The results presented in the paper in hand concern the automotive supply industry exclusively. In order to extend the number of opinions provided by industrial experts from other branches, the interviews will be continued in the context of a study, the focus of which will be the evaluation of the state of integration of energy-efficiency aspects into product development practice.

Considering the final requirements list and its weighting (cf. chap. 3), the development of a prototype for the assistant system has started. It will be focused on a rough assessment for early product development stages of mass products. The general concept consists of the following modules:

Data Integration Platform for Energy and Cost Assessment. The platform collects and process information from different software such as CAD, ERP, and PLM. This concerns real and virtual lifecycle data of previous product generations (including processes), similar or alternative products and alternative materials, or product-related processes, as well as information about regulatory constraints. The data will be stored in a common database and permanently updated.

Assessment of Design Alternatives. The main tasks of this module are energy-efficiency and cost assessment of the current design alternatives. This will be supported by methods such as Cumulative Energy Demand (CED) and Life Cycle Costing (LCC). Its second task is a compliance checking of the design solutions with regulatory constraints.

Frontend. The current idea is to present the assessment results in a CAD environment. Critical elements will be marked in 3D models with different colors. Detailed information based on adapted indicators will be available in special windows.

Figure 2 below provides a general overview of the concept for the assistant system.

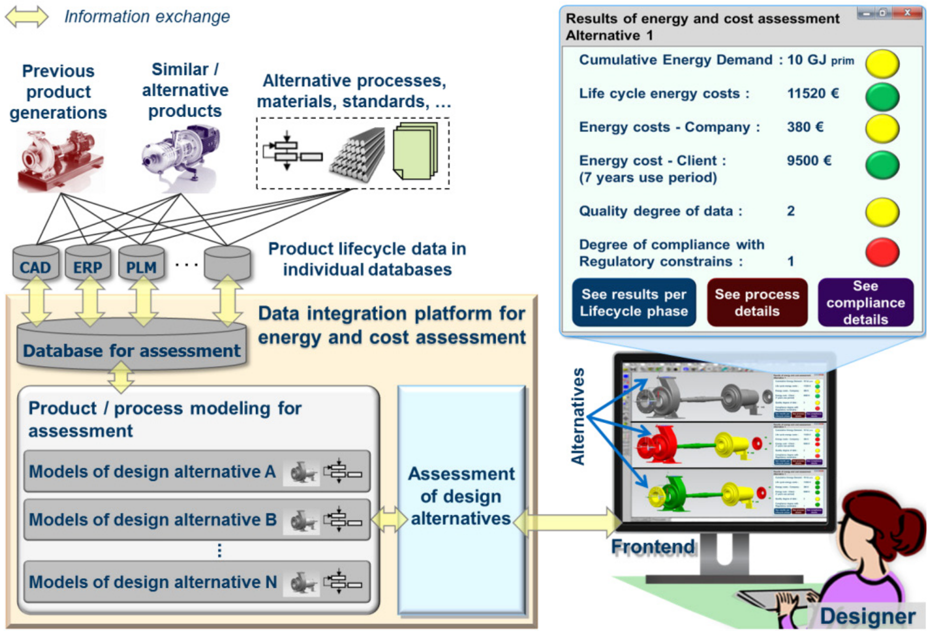

Fig. 2. General overview of the assistant system concept

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Early System Simulation to Support EcoDesign of Vehicle Concepts

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Abstract. Environmental restrictions request new – potentially revolutionary – mobility concepts which simultaneously address both user requirements and efficiency aspects. Early system simulation within the development process is able to support new development projects on the conceptual level. In an overall effort to support ecodesign as early as possible in the development process, this paper introduces a process model for ecodesign-oriented product development which focuses on these specific aspects. Special focus is set on the use of modeling and simulation in the conceptual design phase to evaluate and compare the energy efficiency and lifecycle assessment on the example of vehicle concepts.

Keywords: ecodesign, system simulation, vehicle concepts, simulation-based ecodesign.

1 Introduction

Today environmental restrictions have become a very important aspect in product development – especially in the vehicle industry. Hence there are a lot of activities regarding environment-oriented design (ecodesign) in general and new mobility and drive concepts in particular, leading to completely new designs for automobiles and other vehicles.

As a consequence the traditional evolutionary development process from one car model to the next is not sufficient anymore to create new revolutionary concepts and to evaluate these early in the process. It is well known, however, that – especially in projects with new development character – the early phases are of outstanding importance for the product's success regarding cost, quality and environmental impact. The use of modeling and simulation has proven to be an appropriate tool for early evaluation since it allows system optimization long before any hardware is detailed or even produced.

Today, a lot of effort is spent on the energetic optimization of vehicle concepts. There are various aspects to be considered – e.g. finding the optimal size and operational strategy for an electric motor of a hybrid drivetrain.

In an overall effort to support ecodesign as early as possible in the design process, this paper introduces a process model for ecodesign-oriented product development

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which focusses on the specific aspects mentioned. Special focus has been set on the use of modeling and simulation in the conceptual design to evaluate and compare the energy efficiency and lifecycle assessment.

This paper is structured as follows. Chapter 2 describes the background regarding simulation-based product development on the one hand and ecodesign concepts on the other hand and derives needs for action regarding the integration of both fields. Then, chapter 3 introduces a concept for simulation-based ecodesign, providing also use cases for its application. A prototypical realization illustrates the power of the presented approach. After a discussion, chapter 4 draws conclusions and provides an outlook on future work.

2 Background

Simulation-based product development and ecodesign provide the background of the work presented in this paper. In both areas, new approaches are being developed and discussed. Thus integration of both fields requires further attention.

2.1 Simulation-Based Product Development

Product development generally follows process frameworks which guide through company-specific or generic process steps and milestones from the first ideas to a production-ready product design. Especially in academic process frameworks such as [1] and [2], modeling and simulation does not play the significant role that it deserves regarding the huge potentials it offers for efficient and effective product development [3]. Thus a new process model has been developed by the authors that positions modeling and simulation in the core of the engineering environment of the innovation and the product creation process, see Figure 1.

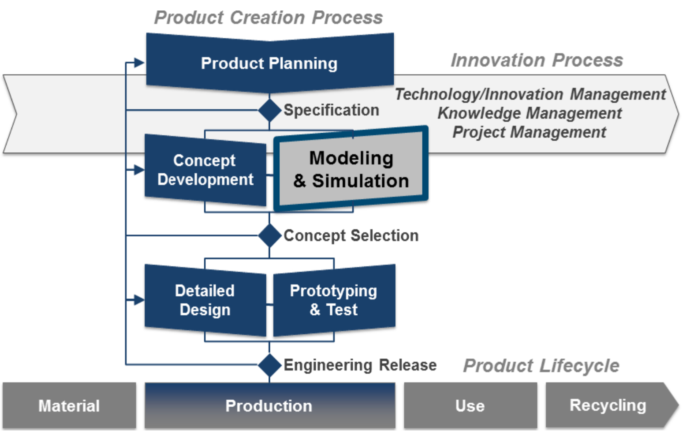

Fig. 1. Modeling and simulation within product development

Especially in new development type projects, early system simulation can play a predominant role to accelerate the knowledge buildup and to increase early concept maturity.

Typically simulations are kept on system level in this early stage of the process. The main purpose is to gain information about the overall system behavior. And since design parameters are still very vague during conceptual design, simulation results cannot be as exact as during detailed design. Hence it is mainly used to compare different concepts in order to find the best solution. Those simulations mainly concentrate on the compatibility of different partial solutions and on the generation and refinement of dimensioning criteria. Suitable tools for that purpose are domain-spanning system level environments like Modelica [4] based programs. The use of Modelica is further elaborated on in section 3.3.

Ecological criteria and especially lifecycle aspects are difficult to be considered systematically during the choice of a vehicle concept. Only in later phases when the basic concept is clear, simulations are used to estimate the energy consumption. For this purpose modeling is done on a high level of detail. Hence respective tools are highly specialized and as a consequence require a lot of effort for modeling of the system. An example of such a tool is AVL Cruise [5].

For the purpose of very early simulation with an ecodesign focus, it is essential to cover a broad range of different vehicle concepts – i.e. from battery electric cars to combustion cars and the corresponding hybrid variants. The properties of interest in this case might be the best compromise between the vehicle size – corresponding to the weight – and the required power or expected range. In order to get information about the entire lifecycle and the holistic environmental impact, it is not sufficient to merely simulate the energy consumption during the utilization. Instead it is important to also consider production and recycling of the entire vehicle.

2.2 EcoDesign

With environmental aspects exponentially gaining in importance, ecodesign has come up as a prominent subdiscipline of engineering design. Having now become internationally standardized, ecodesign is defined as the “integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout the lifecycle” [6]. Ecodesign research and activities are underway in multiple directions – see Figure 2. Besides laying the strategic grounds, methods are being developed to support transparency regarding environmental effects, environment-oriented process models are being proposed, methods and tools set up, e.g. [7], and implementation concepts for ecodesign approaches developed, e.g. [8], [9]. In the context of this paper, especially transparency methods, process models and supporting tools are relevant.

Transparency Methods. A multitude of transparency methods has been developed to support the analysis and assessment of environmental effects of products. Prominent examples in this context are the cumulative energy demand analysis (KEA) [10], which focusses on calculating the energy consumption along the entire lifecycle, the

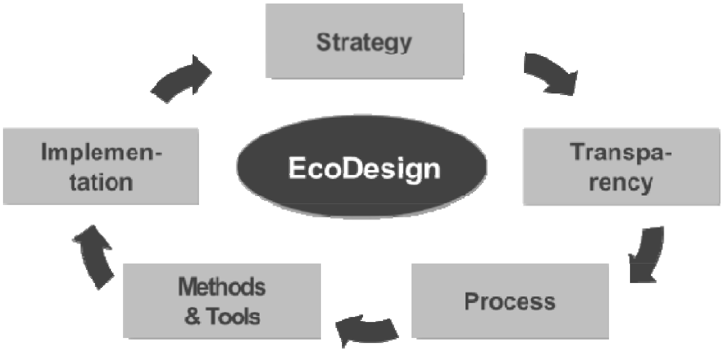

Fig. 2. Dimensions of ecodesign

global warming potential (GWP) assessment [11], which addresses lifecycle greenhouse gas emissions, and the lifecycle assessment (LCA) [12], which focusses on the holistic analysis and assessment of all environmental aspects. However, for simplification purposes – both effort- and marketing-driven – practical application is often reduced to the utilization phase of the lifecycle.

Process Models. Process models such as ISO/TR 14062 [13] focus on the integration of environment oriented methods into the product development process. They provide guidance on which method and approach to apply in which process step, with assessment methods playing an important role. Birkhofer [14] e.g. proposes detailed environmental assessment already in the specification and early conceptual phase, though based on the analysis of a feasible reference product.

Supporting Tools. With analysis and assessment methods – such as the lifecycle assessment – requiring comprehensive data and complex calculations, IT tools have been developed to support this process. Generally, these tools are applied reactively in later design or lifecycle phases and used as a basis for design iterations. Modeling and simulation tools offer comprehensive and powerful techniques along the product development process, see section 2.1. Specialized tools for vehicle development such as AVL Cruise offer modeling and simulation functions for driving performance and energy consumption estimations for the use phase of the lifecycle. Due to their complexity, they are mainly applied for detailed drivetrain optimizations based on comprehensive vehicle models. More hands-on tools such as Ecodesign Pilot [15] support the analysis and improvement of existing products by providing generic environment-related guidance.

2.3 Needs for Action

Although diverse approaches and tools exist to support either modeling and simulation or environment-conscious design, no integrated concept is available for simulation-based ecodesign, which requires early system development and lifecycle oriented simulation support on a high conceptual level. On the example of mobility, the European Union sets broad goals of 60-80% energy savings over the next few decades [16], leading to the demand for revolutionary new vehicle concepts. The traditional evolutionary development process from one car model to the next is not able to cope with these new circumstances anymore. Especially early phases are of high importance for projects with new development character since those predetermine further process steps and design decisions. In order to choose the right concept, modeling and simulation offer great potential to compare concepts without information about the detailed design.

Thus, in the following chapter, a conceptual framework for simulation-based ecodesign will be presented. It has to be supported by efficient and effective modeling and simulation techniques, which allow concept assessments on a lifecycle basis in very early development stages.

3 Concept

The early phases of product development are characterized by uncertainties in specifications and concepts and immaturities in solution principles. The main goal is to increase the maturity as fast as possible based on fast but sound concept evaluations. For this, modeling and simulation offer the techniques which will subsequently be applied to the example of vehicle concepts – in a broad understanding from human-powered bicycles to light electric vehicles to traditional combustion engine cars.

3.1 Simulation-Based EcoDesign

Modeling and simulating early product concepts – especially when targeting revolutionary solutions – requires keeping the decision space as wide and open as possible until sound information is gained to discard inferior concepts. Figure 3 shows an exemplary functional structure for mobility products with solution principles including the whole variety from human power to fuel and electric power, of car body alternatives and utilization modes. If modeling and simulation shall be used in this early phase, it has to be holistic and open enough to cover this variety of options.

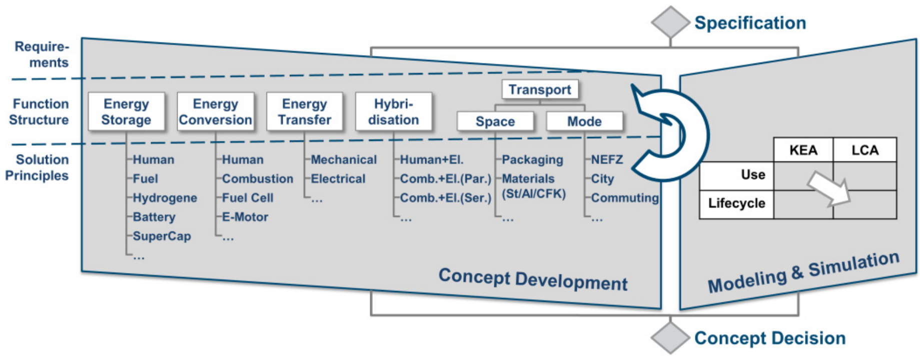

Fig. 3. Concept development and simulation of vehicle concepts (detailed excerpt of process depicted in figure 1)

In a first step the – generally still rough – requirements from the specification are mapped to a functional structure. Open question in the specification might be to which extent recuperation should be applied in electric drives or what the tradeoff should be between material selection and lightweight requirements. Then, depending on the requirements, valid solution principles are selected for further investigation.

Already at this level, a model can be built up to run first simulations. The simulation depth depends on the desired information – shall only the use phase be optimized or the entire lifecycle, and shall energy be in focus (KEA) or a holistic view on environmental impacts (LCA), see figure 3. This modeling and simulation step has to be efficient to enable multiple iterations, so that the specification becomes more and more solid and the solution principles more and more sound, until a certain level of maturity is reached to allow for a sound concept decision.

It becomes obvious that methods and tools which are currently available for lifecycle analysis and system simulation are too complex to allow for this process. Therefore those are not consistently applied in product development, especially not proactively and not in small or medium-sized companies.

Hence, in order to realize the presented concept, a prototypical tool has been set up to cover the requirements mentioned on a high enough level to be fast and efficient in its application, and on a deep enough level to allow assessments with sufficient breath of scope and exactness of results. Exemplary use cases and the functionality of the tool will be described in the following chapter.

3.2 Use Cases

The possible applications of the concept presented here and the modeling and simulation tool are manifold. In the following, examples will be given to demonstrate the power of early system simulation if applied to vehicle concepts.

Simulation of energy consumption during the utilization phase can support engineers in finding the best combination for a hybrid drive – e.g. finding the best ratio of human and electric power in a human power hybrid vehicle (e. g. e-bike) under consideration of different utility conditions and driving cycles, or determining the best-sized electric motor for hybridizing a combustion drivetrain based on the resulting total efficiency. Also, the model can support determining the best strategy for recuperation and driving strategies, e.g. for automatic transmission.

Simulation of energy consumption over the lifecycle can help judge the use of lightweight materials, assuming energy being the major environmental impact of their application. Trading off the potentially far higher production energy of, e.g., CFRP or aluminum designs against the higher energy consumption during the use phase of higher-weight steel designs may lead to “energetic mileage break-even points” for the use of alternative materials.

If environmental effects other than energy cannot be neglected, the described inclusion of simplified LCA estimations will empower the simulation even more towards a holistic environmental assessment on early conceptual level. An example could be the evaluation of different battery types also based on the emissions and toxicity during their production and recycling.

3.3 Prototypical Realization

In the specific case of vehicle concepts, a physical model has been developed for this purpose based on the object-oriented modeling language Modelica. It is suitable to describe the interdisciplinary interaction between electrical and mechanical components. Furthermore the individual modeled objects can be easily connected, replaced or extended. In this specific case SimulationX [17] has been used because it offers a comprehensive library with standardized models for most of the components used in a vehicle.

The model is built up modularly and has a separate graphical user interface so that the user can choose the mobility and drive concept and can easily parameterize the model without going into detail of the model itself. If some parameters are still unknown at this time, the user can select preset values from literature or similar products. Currently the model contains all aspects of the utilization phase. Hence the user can choose any vehicle concept from a bicycle up to a full-size car as well as different types of drive from human powered to electric drives to combustion engines and numerous hybrid combinations. Furthermore, the various energy sources like human power, battery, petrol, fuel cell or solar panel are implemented, too. The simulation can be started directly from the user interface based on the driving resistance which depends, among other things, on the driving cycle – which can be individually defined by the user. The results – e.g. energy consumption or the recuperated energy – are also illustrated in the user interface and can be stored in a separate file, e.g. for use in Microsoft Excel. Until now the model has been validated with data provided by several automobile manufactures. The deviation of the results is below five percent which is very satisfactory considering the simplifications which had to be done to make the model applicable in early phases.

As already mentioned, the model currently only contains the energy needs during utilization. Two system boundaries exist in here: tank-to-wheel (TTW) considers the energy just within the vehicle itself whereas well-to-wheel (WTW) includes the energy flow from the primary energy source, too. Presently the simulation is being extended in order to describe the complete product lifecycle of a vehicle, beginning with the production up to the recycling. Therefore for the materials used in an automobile, an average value for the energy needed in the production and recycling phase is predefined. Combined with the lifetime of the vehicle, the total energy need for the entire lifecycle can be simulated.

Figure 4 illustrates the structure of a model for a parallel hybrid vehicle as an example. The different modules are connected via signals. The vehicle is built up starting from the driving resistance to the wheel and the energy converters to the chemical and electrical energy storage. Each module in this energy flow reduces the efficiency of the overall system.

The comparison of the calculated efficiencies and CO_2 emissions between different vehicle concepts is shown in Figure 5, as an example for the results from the simulation. The two system boundaries TTW and WTW are listed separately. Electric vehicles emit no carbon dioxide during driving. However in the energy mix the traditional power production causes CO_2 emissions. The high mean energy effort for food production results in an efficiency factor of about 24 percent [18], based on data of a European country. Hence the carbon dioxide emissions for the bicycle are relatively high considering the WTW view. Therefore the usage of human muscles leads to higher energy consumption than electric drive systems. A conventional car with an internal combustion engine produces the highest emissions, which are not solely caused by the higher mass. The engine often works in the part-load range where the efficiency is very low. In contrast, electric drive systems are not as sensitive concerning the load factor.

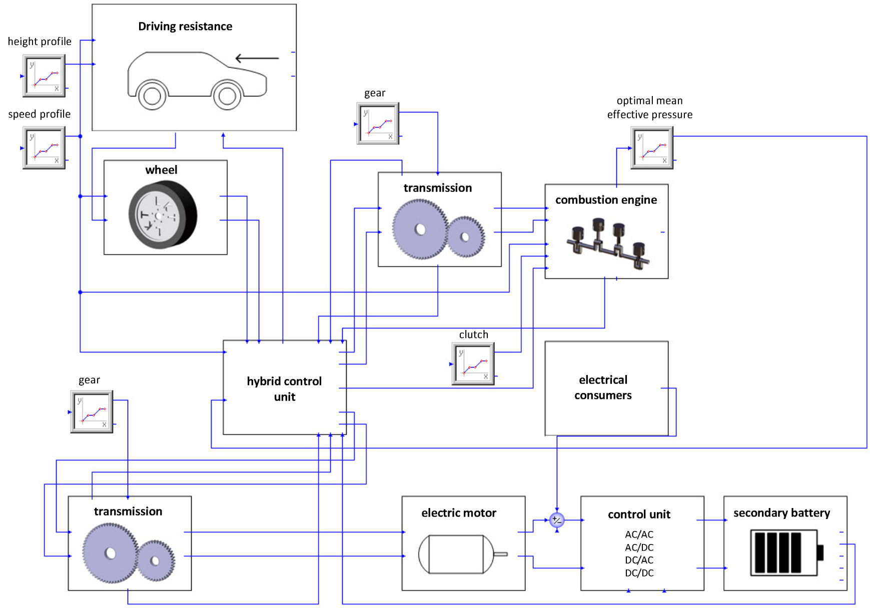

Fig. 4. Structure of the parallel hybrid model

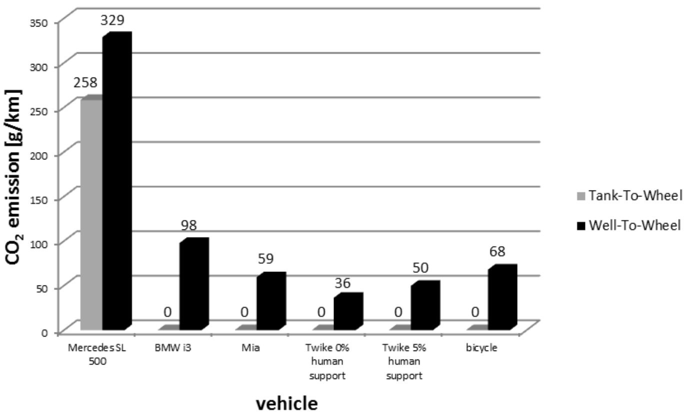

Fig. 5. Comparison of the CO_2 emissions for different types of vehicles (human power estimations based on European nutrition averages)

4 Discussion and Conclusion

The concept presented here proposes a process model that features a deep integration of modeling and simulation techniques into the early conceptual phases of new development style projects. Postulating that environment-conscious design demands unconventional, potentially revolutionary solution principles and solutions based on a wide solution space, early system simulation can offer important support for conceptual decisions – if set up sufficiently open and comprehensive to allow for sound assessments, yet simple enough to allow for fast assessments.

The tool presented here offers simple but powerful support for environment-oriented analysis and assessment on the example of vehicle concepts and thereby fulfills the criteria mentioned. It is obvious that conceptual models as the one presented here are limited regarding the product range they are able to cover. The example, however, shows that it is possible to set up a model to run evaluations across the entire spectrum of mobility products with reasonable effort, but results keep accurate enough at this stage of the development process.

Thus, concept and tool together enable the process model for simulation-based ecodesign as laid out in figures 1 and 3.

With the approach presented in this paper focusing on early conceptual design, its applicability may be limited for detailed simulation and optimization tasks in later phases. Here, more detailed models and commercial software for both energy simulation and lifecycle analysis may deliver more accurate results. The applicability may also be limited for other than new development type projects, where solution principles and potentially even physical realizations are already set from the early phases.

Further work will extend the model and tool as described in chapter 3.2 and 3.3. With the concept already existing, it will be possible to balance the environmental impacts in the utilization phase with the entire lifecycle and to trade off energy against other environmental effects before important conceptual courses are set, and long before any physical prototype hardware is created. In another ongoing activity, the model will be integrated into a driving simulator which is currently being developed by a partner institute. In this way it will be possible to optimize driving strategies and to train drivers in a virtual environment without physical prototypes.

To summarize, ecodesign is a field that calls for innovative concepts which have to be thoroughly analyzed and assessed already in early, conceptually immature process phases. A simulation-based process as presented in this paper, supported by pragmatic simulation solutions, can offer highly valuable support to reach early concept maturity as a basis for sound concept decisions.

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