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# A Knowledge-Based Approach for Integration of System Design Methodology and Documentation in Advanced Multi-Disciplinary NPD Projects

Thesis for the degree of Philosophiae Doctor

Trondheim, December 2014

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# Preface

This doctoral thesis has been submitted to the Norwegian University of Science and Technology (NTNU) for the degree of Philosophiae doctor (PhD). The work has been carried out in the period from October 2011 to October 2014 at the Department of Engineering Design and Materials (IPM) under the supervision of Professor Torgeir Welo (NTNU). The research has been funded by the Research Council of Norway together with FMC Kongsberg Subsea AS, Kongsberg Automotive AS, Kongsberg Defence and Aerospace AS, and Kongsberg Devotek AS in the KBD-project.

The thesis contains two parts. Part 1 is a summary report, introducing the research topic and building the coherent framework for the second part. Part 2 is a collection of papers, which represent the research content.

## Acknowledgements

At first, I would like to thank my supervisor Professor Torgeir Welo for his support, encouragement, and guidance. He has been very helpful in critically discussing and contributing to ideas, as well as supporting and encouraging me in improving my work. Additional thanks goes to the KBD-project group in Kongsberg, including Frode Island Bergan, Torfinn Tobiassen, Turid Rustand Olsen, Dag Espen Tegdal, Tom Ole Haukom, Simen Skiaker, Dag Bergsjö, and Eivind Fauskanger for opening their community for discussions and observations in an industrial project environment.

Further, I would like to thank Ulf Harlou and Lars Krogstie for research collaboration, and Cecilia Haskins for inspirations in research methodologies and systems engineering and for co-authoring one paper. I would also like to thank many colleagues at IPM, particularly Christer Elverum, with whom a shared my office for three years, Ivar Marthinusen, Jan Magnus Granheim Farstad, Fredrik Widerøe, Bjørg Granly, Jon Harald Grave, Knut Einar Aasland, Bjarne Stolpnessæter, Knud-Helmer Knudsen, and Martin Steinert and many more for encouraging and technical discussions.

A special thanks goes to my family for showing interest in my work and keeping my spirits high, as well as my friends for making my life outside work even more enjoyable and exiting, especially by many outdoor activities. Finally, a special thanks goes to Jeanett Rørvig for loving and encouraging me.

Trondheim, October 2014

Sören Ulonska

## Abstract

New product development (NPD) performance depends both on developing new knowledge as well as on leveraging existent knowledge inside an organization. In project-based NPD execution knowledge is often created without a clear reuse strategy and subsequently misplaced by storing it in project-related, disjointed knowledge repositories. Thus, valuable information is most likely not utilized and has limited value for organizational learning. One possible countermeasure is to establish a strategic, dynamic knowledge standard that spans all of an organization's projects and enables reuse of valuable knowledge with being simultaneously flexible to novelty and product evolution.

The goal of this work has been to investigate the deployment of strategies, tools and methodologies to capture, structure, and utilize valuable product engineering knowledge in order to establish a framework for implementing a strategic, knowledge-based approach, which can contribute to establish a dynamic knowledge standard. The research has been conducted in several learning cycles through a combination of literature reviews and case studies. The literature reviews, considering the fields of engineering design, systems engineering, lean product development, and knowledge management were directed towards theories, tools, methodologies, and processes that address knowledge-related engineering and management aspects. The case studies have been conducted in product engineering companies an industrial product engineering environment. All case companies develop knowledge-intensive, high-technology products in multi-disciplinary teams with project-based NPD execution.

Overall, the work has several outcomes. The first outcome is an exploration of the current knowledge transformation practices in the case companies, which revealed the needs for an engineering-driven framework for knowledge-based product development. Further, a product mapping methodology for evaluating the disjointed product portfolio is explored, providing a practical, qualitative way of transforming fragmented product variant information into visual overviews. The third outcome is an investigation of the role of A3-reports as potential documentation tool, discovering that A3-reports can contribute positively to reuse of company-internal documentation. Finally, a strategy to develop a structural knowledge standard, based on a modular architecture and a strategy to develop a declarative knowledge standard based on A3-reports and causal diagrams are investigated.

Although this work has substantially increased the body of knowledge towards the development of a dynamic knowledge standard, further research is required for implementation, including the establishment of an integrated (structural and declarative) dynamic knowledge standard as well as exploring adequate routines for product evolution.

## List of papers in main body (Appendix A)

The following papers constitute the main body of this research.

**Paper I**

**Need Finding for the Development of a Conceptional, Engineering- Driven Framework for Improved Product Documentation**
Sören Ulonska and Torgeir Welo
Presented at the Conference on Systems Engineering Research in Atlanta 2013
Procedia Computer Science no. 16 (0):423-432. DOI: 10.1016/j.procs.2013.01.044

**Paper II**

**On the use of a product portfolio map and variant maps as a tool to enable platform-based manufacturing strategies**
Sören Ulonska and Torgeir Welo
Submitted to a journal

**Paper III**

**A3-reports as tools for supporting organisational learning and knowledge reuse: A comparative survey-based study**
Sören Ulonska and Torgeir Welo
Submitted to a journal

**Paper IV**

**Strategies for implementing a dynamic knowledge standard in product engineering using structural representations and knowledge artifacts**
Sören Ulonska and Torgeir Welo
Submitted to a journal

## List of supplementary papers (Appendix B)

The following papers have been developed supplementary to the papers in the main body.

**<u>Paper V</u>**

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

Sören Ulonska and Torgeir Welo
Presented at CIRP Design Conference in Bochum 2013.
Proceedings of the 23rd CIRP Design Conference:11-21. Springer 2013
ISBN 978-3-642-30816-1.

**<u>Paper VI</u>**

**Keep Systems Engineering Simple to Get the Job Done**

Sören Ulonska, Cecilia Haskins, Oluf Roar Bjørset Tonning, and Itxaso Yuguero-Garmendia
Presented at 23rd Annual INCOSE International Symposium in Philadelphia 2013.

**<u>Paper VII</u>**

**On Knowledge-Based Development: How Documentation Practice Represents a Strategy for Closing Tolerance Engineering Loops**

Lars Krogstie, Sören Ulonska, Torgeir Welo, and Bjørn Andersen
Presented at CIRP Design Conference in Milano 2014.
Procedia CIRP, vol. 2:318-323. ISSN 2212-8271

**<u>Paper VIII</u>**

**Product Portfolio Map: A Visual Tool for Supporting Product Variant Discovery and Structuring**

Sören Ulonska and Torgeir Welo
Published in Advances in Manufacturing no. 2 (2):1-13. 2014
DOI: 10.1007/s40436-014-0077-y

# Contents

## List of abbreviations

| | |
|---|---|
| **CoA** | Case company A |
| **CoB** | Case company B |
| **CoC** | Case company C |
| **CoD** | Case company D |
| **CoE** | Case company E |
| **H1** | Hypothesis 1 |
| **H2** | Hypothesis 2 |
| **KBD** | Knowledge-based development |
| **KM** | Knowledge management |
| **LPD** | Lean product development |
| **MBSE** | Model-based systems engineering |
| **NPD** | New product development |
| **PLM** | Product life-cycle management |
| **POC** | Proof-of-concept |
| **R&D** | Research and development |
| **RQ** | Research question |
| **SE** | Systems engineering |

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# 1 Introduction

## 1.1 Background

Contemporary engineering companies operate in an environment of increasingly competitive global 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 (Carlile and Rebentisch 2003; Martin 2009; Welo 2011). The only permanent solution is to improve a firm's capability in inventing, developing, and producing innovative, new products that provide high value to the customers. In addition, products are becoming more complex and require multi-disciplinary efforts to design and produce, which increases the importance of effective knowledge exchange as a base for collective decision-making and risk mitigation. Thus, the need for developing innovative products together with the need to manage product complexity make knowledge a main pillar for value creation in many companies (Hitt *et al.* 2011).

New product development (NPD) performance depends not only on acquiring and developing new knowledge, but also on leveraging existent knowledge inside an organization (Lawson *et al.* 2009). The effective utilization of knowledge is a challenging task for many product engineering firms, especially for those with project-based NPD strategies (Ajmal and Koskinen 2008). Their business strategies essentially include offering incremental product innovation based on an existing product portfolio (Matta *et al.* 2000; Colosimo, Poggi, and Tolio 2002). Knowledge is often created without a clear strategy and is subsequently misplaced by storing it in project-related, disjointed knowledge repositories (Love, Fong, and Irani 2005). In this manner, it remains most likely unused (Jantunen 2005; Shaw and Edwards 2006). Recent research indicates that more than 50 % of all stored information in an organization is never even accessed (Shankar *et al.* 2012). As a consequence, resources are often used on repeated problem-solving and firefighting instead of product innovation (Kennedy, Sobek, and Kennedy 2013).

The minor amount of reused knowledge resembles a 'copy-and-paste' approach, where the preferred solutions from earlier customer-specific projects are adopted in new projects (Mortensen *et al.* 2008). Subsequently, they are reconfigured and reengineered to comply with new requirements, customer needs, rules and regulations, and the most recent state-of-the-art technology. This reuse strategy is usually more work-intensive than initially expected and increases cost and lead time (Kennedy, Sobek, and Kennedy 2013). Over time, this can result in an overall lack of organizational capability as illustrated in Figure 1-1.

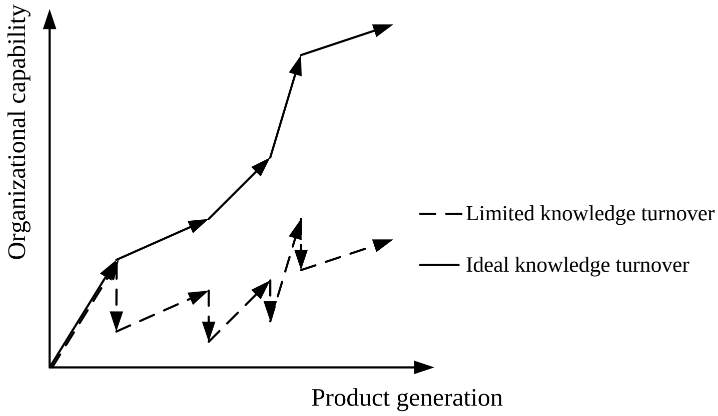


Figure 1-1: The increase of organizational capability over product generations

Each segment symbolizes one development project or product generation. The figure indicates two approaches with the same efficiency (same gradient of the segment) within a project, but differing in their success of knowledge transformation. The approach with effective knowledge transformation between the product generations achieves a significantly higher level of organizational capability after several, successively developed product generations.

## 1.2 Main goal

To address the described challenges product engineering companies need to implement strategies and tools to capture valuable knowledge, make it actionable for (re)use, and utilize it within and between projects (Ramesh and Tiwana 1999; Dunford 2000; Shaw and Edwards 2006; Nonaka *et al.* 2014).

The current situation resembles an unstructured and disjointed approach for knowledge reuse between the projects (Mortensen *et al.* 2008) as illustrated on the left Figure 1-2. One possible countermeasure to address the challenges described above is to establish a strategic knowledge standard that spans all projects of an organization; one that enables reuse of valuable knowledge on the one hand, but is dynamic and flexible enough to incorporate novelty on the other hand (Figure 1-2, right side). In this regard, some researchers (Sanchez 2004; America *et al.* 2011) apply the term *evolvability*, meaning the ability of a product system to actively respond to changes with predictable minimal effort and time. Ideally, during product development and project execution the knowledge standard evolves over time and organizational capability is increased (America *et al.* 2011). Kennedy, Harmon, and Minnock (2008) discuss a dynamic knowledge standard across different projects in every company, representing the knowledge value stream of the company. The dynamic knowledge standard may be used as a base for project execution, while new learning outcomes in the projects contribute to update the knowledge standard.

Further, a knowledge standard can support a group competence, linked through the standard (Czarniawska and Joerges 1996), and can become a basis for organizational learning by collaboratively utilizing existing knowledge as well as streamlining the creation of novel knowledge (Grant 1996; Liu *et al.* 2013).

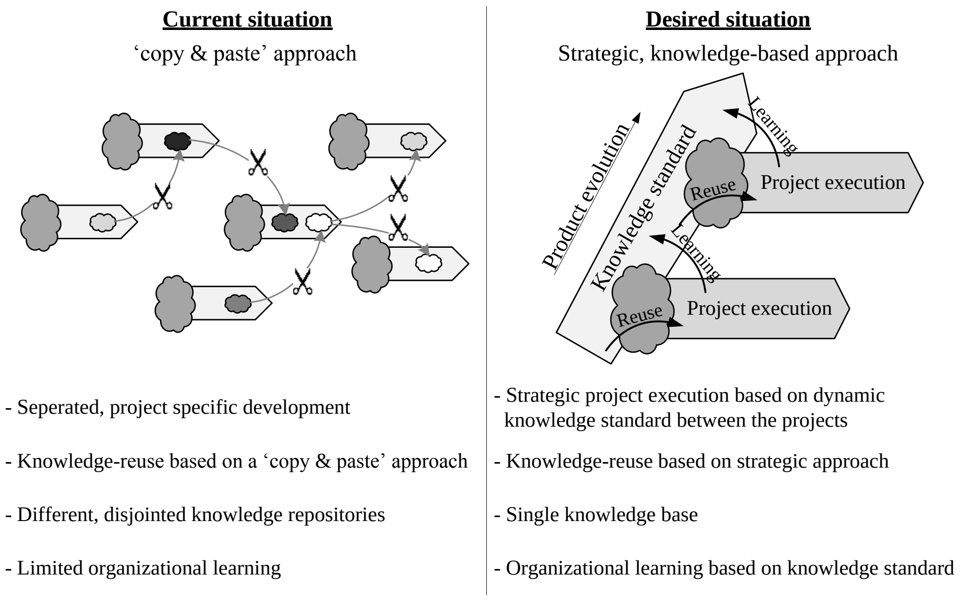


Figure 1-2: Current and desired knowledge reuse strategy

The overall goal of this thesis is to investigate the deployment of strategies, tools and methodologies to capture, structure, and utilize valuable product engineering knowledge in order to establish a framework for implementing a strategically-oriented, knowledge-based approach. More specific, a clear overview over the structural and declarative product knowledge within an existing product portfolio shall be provided in a single knowledge base as a base for a standardization strategy. In addition, proper tools for knowledge capture and reuse and a strategy for implementing the tools shall be investigated. The expected benefits are a more effective collaboration within and between teams and projects, less rework, and thus increased organizational learning.

## 1.3 Research scope

According to Chandrasegaran *et al.* (2013), the definitions and understanding of knowledge are dependent on the context and can be viewed from different perspectives. In order to refine the scope of this thesis, the focus is on organizational product engineering knowledge. Product engineering considers both design and manufacturing aspects of a product. It entails the activities of finding solutions to technical problems by applying insights from natural and engineering sciences, while at the same time respecting constraints and conditions (e.g., cost, producibility, quality, performance, reliability, serviceability, and user features) of a certain task (Pahl *et al.* 2007). Thus, product engineering knowledge covers the design parameters, concept choices, technologies, manufacturing processes, requirements, functionalities, principal components, etc., that are involved in the technical description. This includes also the architectural aspects (Wiig 1995) and the background knowledge (Sunnersjö 2010), which are necessary to realize engineering solutions, e.g., dependencies and principles in natural sciences.

Several researchers emphasize the role of knowledge in NPD and introduce the term *knowledge-based development* (KBD) (Grant 1996; Spender 1996). Product engineering knowledge in NPD is embedded and carried through multiple entities, including products, systems, tools, documents, routines, organizational culture, individuals, etc. Consequently, KBD is not a separate research field, but draws on theories, tools, methodologies, and processes from several areas that address knowledge-related engineering and management aspects. Engineering design, systems engineering (SE), lean product development (LPD), and knowledge management (KM) are the research fields that provide theoretical foundations that can be utilized for KBD. For the scope of this thesis KBD is defined as follows.

KBD entails practices to effectively

(1) support individual and organizational learning;
(2) transform (create, capture, store, represent, connect, and utilize) valuable product engineering knowledge;
(3) evolve existing product engineering knowledge by adapting it to new requirements, technological progress, changing markets, etc.

In general, KBD methodologies and tools can be divided into those that address *content-specific* and *context-specific* knowledge. Content-specific knowledge is declarative and fact-based, and can be documented into knowledge artifacts, meaning objects that convey transferable knowledge representations (Holsapple and Joshi 2001). Context-specific knowledge is the structure in which knowledge artifacts are interrelated at system level (Sanchez and Collins 2002; Jonassen, Beissner, and Yacci 2013).

## 1.4 Research design

The research design of this thesis is based on the assumption that the strategy presented in Figure 1-3 enables the implementation of the dynamic knowledge standard. Figure 1-3 refines the overall implementation strategy that is believed to be suitable to achieve the main goal as defined above. The initial situation (*step 1*) resembles a ‘copy & paste’ approach without a clear knowledge development and utilization strategy. In this step the product knowledge is distributed over many project-related knowledge repositories and may be dispersed, disjointed, or unknown. The entire product portfolio, product variants that have been developed in the past, and related knowledge may be unclear. Consequently, the action in *step 2* is to analyze the present product portfolio and its variants in order establish an overview of the entire product knowledge base in between the various repositories. The aim is to discover and structure the ‘unknown’ knowledge. In step 3, the identified products, their variants, and related knowledge are systemized into a comprehensive overview. This unifies the items that were distributed over many project-based knowledge sources into a single knowledge base and establishes a base for *step 4*. In step 4 the most successful solutions and variants are identified by comparison in the established overviews. They are the most promising solutions to be considered for the potential knowledge standard between the projects. Step 4 also includes the choice of adequate, standardizable documentation tools, which can be structural or declarative tools. *Step 5* introduces strategies to turn the identified, most successful solutions into structural and declarative product knowledge standards. Finally, these are integrated into a single strategic approach in *step 6*, representing the desired dynamic knowledge standard.

## 1.5 Research goals and objectives

To build up research evidence that supports the implementation of the main goal, this work has been divided into smaller learning cycles. The focus has been on the challenges that were believed most critical in the overall implementation strategy. Thus, the research has been structured into four research goals, distributed over the Papers I, II, III, and IV in the main body of this thesis. The particular goals of the separate papers can be linked to the overall implementation strategy as illustrated in Figure 1-3. In addition, Figure 1-4 relates the research objectives and goals. In the following the motivations for conducting the papers, including their goals and research objectives have been explained.

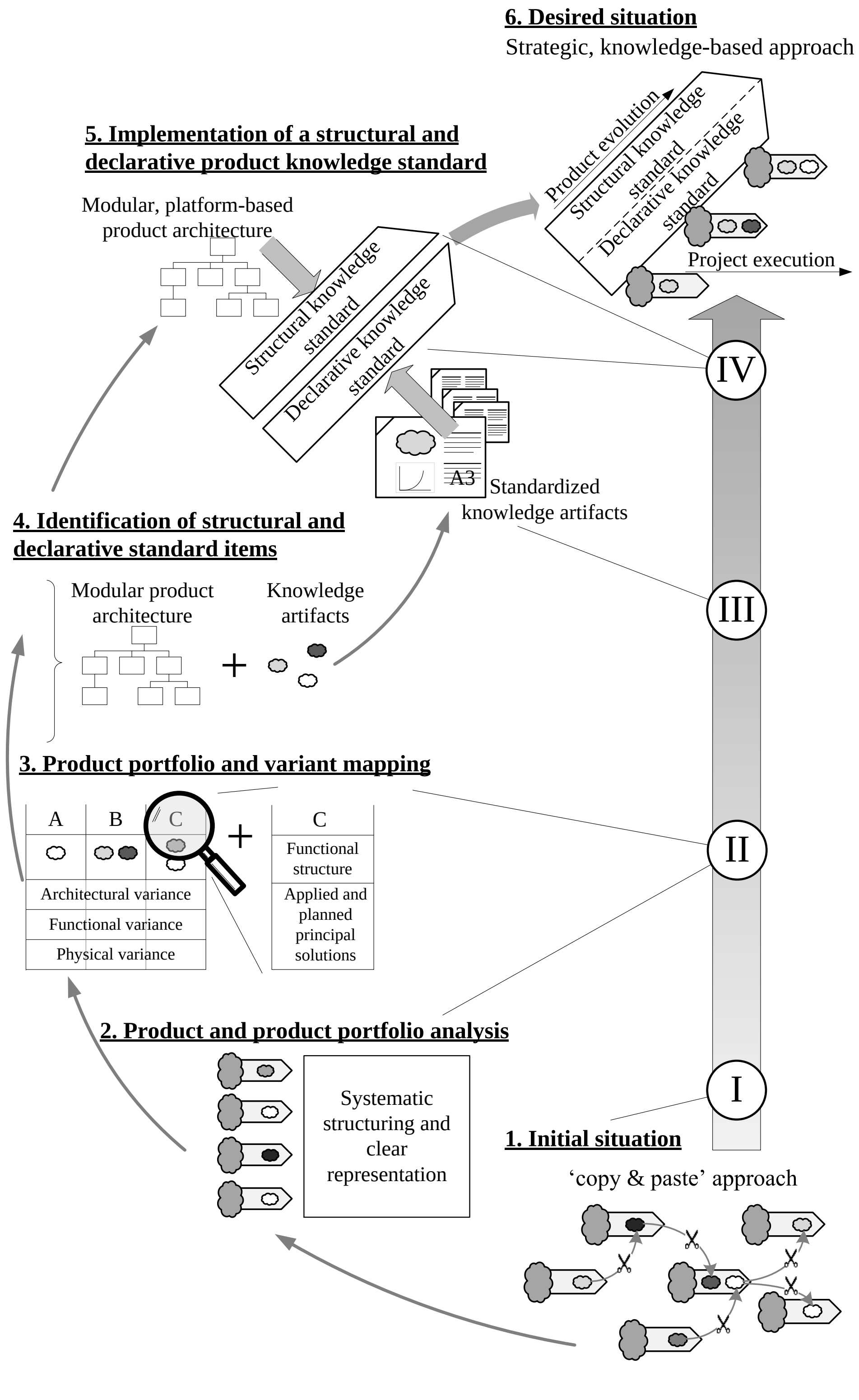


Figure 1-3: Overall implementation strategy

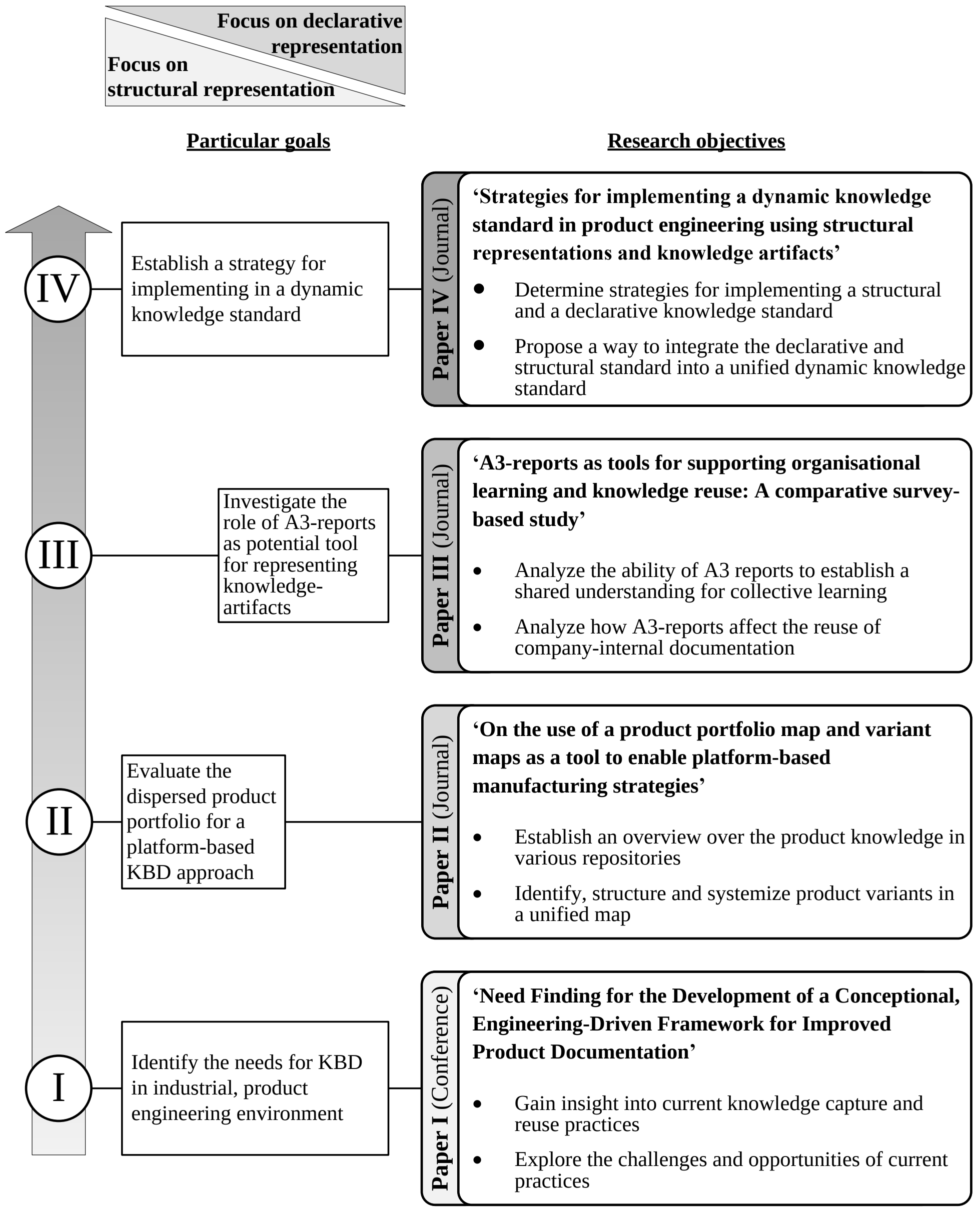


Figure 1-4: Overview of the research goals, objectives, and related papers

**Paper I** has the goal to identify the needs for KBD in industrial, product engineering environment and to document the initial situation. Hence, the objectives are to gain insight into current knowledge capture and reuse practices among engineering practitioners and to explore the challenges and opportunities of current practices. This research intends to analyze the initial situation and can therefore be related to step 1 in Figure 1-3. It covers both structural and declarative knowledge representations. The findings in Paper I reveal that engineers desire a single, hierarchical, traceable knowledge-base, related on the product model.

In this regard the platform-based, modular product architecture is one potential tool (Sanchez 2004). It may also serve to establish a structural standard between the projects and may allow the reuse of components, (sub)systems, and processes as well as correlated knowledge. Nevertheless, the successful implementation requires a thorough analysis of existing products to identify and understand all of the necessary product (variant)-related information (Meyer and Lehnerd 1997a; Harlou 2006). Thus, a prerequisite to apply methodologies for product architecture and platform establishment is that the input information about variants is explicit and clear.

**Paper II** aims to evaluate the dispersed product portfolio for a platform-based KBD approach. The objectives are to establish an overview of the product knowledge in various repositories and to identify, structure, and systemize product variants in a unified map. Accordingly, Paper II addresses the steps 2 and 3 in Figure 1-3 and has focus on structural knowledge presentations.

In addition to a structural knowledge description, effective knowledge transformation requires a simple yet precise and comprehensive presentation of knowledge in knowledge artifacts to enable clear interpretation by the receivers (Parry and Turner 2006). When providing adequate tools, a common organizational understanding can emerge and create a group competence to collaboratively produce, apply and reuse knowledge as a basis for organizational learning (Grant 1996; Liu *et al.* 2013). In this regard, so-called A3-reports are a potential tools for effectively representing the declarative knowledge (knowledge artifacts).

**Paper III** focuses on the investigation of the role of A3-reports as potential tools for representing knowledge-artifacts. The objectives are to analyze the ability of A3-reports to establish a shared understanding for collective learning and to analyze how A3-reports affect the reuse of company-internal documentation. Accordingly, Paper III addresses parts of step 4 and step 5 in Figure 1-3, as these steps aim to contemplate appropriate types of standardizable knowledge artifacts for documenting declarative knowledge.

**Paper IV** has the goal to establish a strategy for implementing in a dynamic knowledge standard. Drawing from the former results both the platform-based modular product architecture for representing structural knowledge and the A3-reports for representing declarative knowledge are potential tools for implementing a dynamic knowledge standard. Literature provides many tools and methodologies for representation standardization of both (Jiao, Simpson, and Siddique 2007; Mortensen *et al.* 2008; Schuh *et al.* 2008). However, to utilize the tools properly and turn those from a "shelf ware" to a strategic base for KBD adequate strategies need to be developed and deployed. Thus, the objectives of Paper IV are to determine strategies for implementing a structural and a declarative knowledge standard and to propose a way to integrate the declarative and structural standard into a unified dynamic knowledge standard. This paper is linked step 5 in Figure 1-3 and proposes a way to establish step 6. It considers both structural and declarative knowledge representation.

The particular research strategies and results are presented in four research papers in the main body of this thesis in **Appendix A**. In addition, supplementary research papers that either contribute to support the research in papers I-IV or might have some overlap are presented in **Appendix B**. Studies on the deployment of a modular product architecture and product platform (step 4 in Figure 1-3) have not been conducted within the scope of this work, because they are extensively described in literature (Gershenson, Prasad, and Zhang 2003; Jiao, Simpson, and Siddique 2007).

## 1.6 Structure of this thesis

This thesis has been structured as follows.

**Chapter 2** sets the theoretical background of KBD. It reviews key definitions, methodologies, and tools in the research fields engineering design, LPD, SE and KM.

**Chapter 3** presents the overall research design, applied research methods, and the studied cases.

**Chapter 4** summarizes the most important results derived from the papers.

**Chapter 5** presents the overall conclusion of the thesis. Further, it suggests potential areas for further work.

**Appendix A** contains the papers I-IV that contribute to the main body of this thesis.

**Appendix B** contains the supplementary papers that have been developed in this PhD work.

# 2 Theoretical foundations

## 2.1 Cornerstones of KBD

### 2.1.1 General

Chapter 1 introduced KBD as a field that draws on theories, tools, methodologies, and processes from engineering design, systems engineering (SE), lean product development (LPD), and knowledge management (KM). Figure 2-1 illustrates these fields as the cornerstones of KBD, and introduces aspects that are considered relevant for knowledge-related engineering and management aspects. This chapter discusses the aspects of these fields that are the focus of this thesis briefly with the goals to:

(1) Refine the scope of KBD;
(2) Review the key definitions of knowlege;
(3) Establish the foundations of this research;
(4) Review relevant tools and methodologies for product and knowledge standardization and representation.

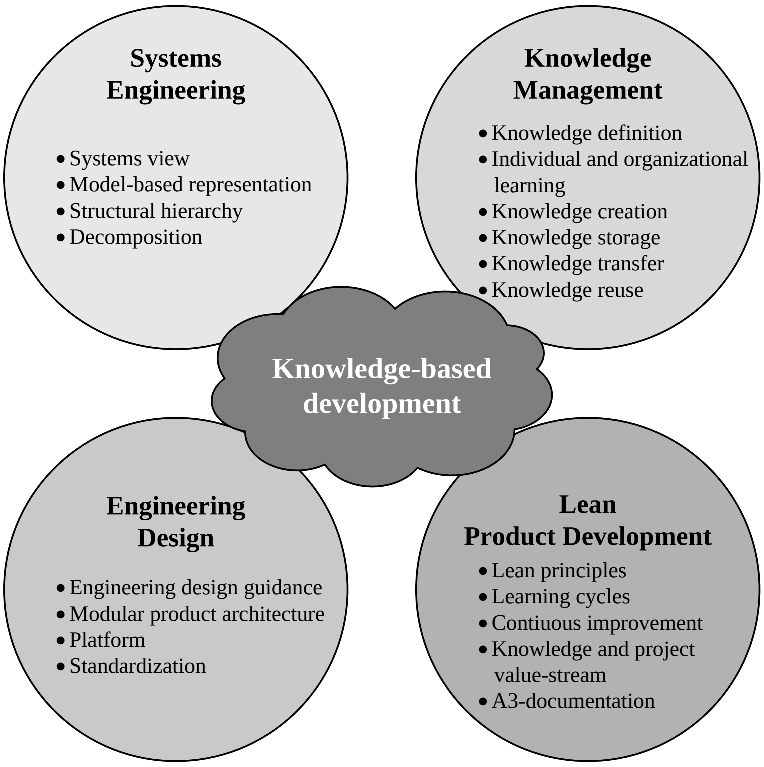


Figure 2-1: Cornerstones of knowledge-based development

### 2.1.2 KBD in engineering design

*Engineering design* methodologies (VDI2221 1993; Roth 2000; Ulrich and Eppinger 2004; Pahl *et al.* 2007) provide guidance to engineers for how to develop, engineer, and design technical products, while allowing flexibility, creativity, and variety at the same time.

The engineering design process (VDI2221 1993) begins with a clear definition of the task and continues with abstracting the problem by establishing functional structures and diverging in the number of solution possibilities as principal layouts and concepts. After a number of evaluations, the process converges and a product is designed, elaborating all technical details. Important outcomes are the requirement list, functional structure, principal layout, and the detailed solution, as well as the architecture in which all are interrelated. Engineering design provides also tools and methodologies to decompose products and develop product architectures and platforms (Stone, Wood, and Crawford 2000; Jiao, Simpson, and Siddique 2007). This is important with reference to standardization and building a knowledge standard.

### 2.1.3 KBD in systems engineering

According to Kossiakoff *et al.* (2011), a *system* can be defined as a set of interrelated components working together towards some common objective. Haskins (2011b) refers to *systems engineering* as a perspective, process, and profession. Focusing on the perspective, Ramo (2004) defines SE as a discipline that concentrates on the design and application of the whole system as distinct from the parts, involving to take into account all facets and relate them to social and technical aspects. Eisner (2008) describes SE as an iterative process of top-down synthesis, development, and operation of real-world system that intends to satisfy the full range of requirements for the system. INCOSE defines the profession of SE as follows: “SE an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.”

Thus, SE is an enabler to solve problems of increasing complex and multi-disciplinary products with the goal to meet the user needs and mitigate risks by supporting all product life cycle processes (Haskins 2011b). For the purpose of KBD, SE contributes with techniques to manage complexity, e.g., by product and systems decompositions as well as visual modelling, e.g., model-based systems engineering (MBSE).

### 2.1.4 KBD in lean product development

LPD has its origin in lean manufacturing (Toyota Production System), starting with the Lean Automotive Factory and evolving into the Lean Factory with emphasis on cost reduction, quality improvement, and delivery (Womack, Jones, and Roos 2007). Based on an excessive study of the Toyota Production and Development System, Morgan and Liker (2006) introduced 13 principles for LPD within the dimensions of process, technology, and people.

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 and willing to pay for (Mascitelli 2007). While waste is easy to detect in manufacturing (visible, physical objects), separating value from waste is more difficult in product development since the work-product is information and may be cognitive. Thus, 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). Type 2 waste is pure waste that does not create any value (e.g. defects, waiting, underutilization of people).

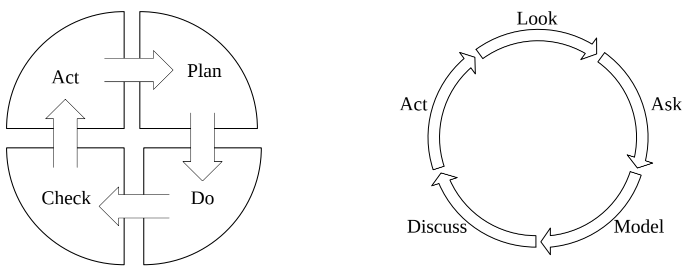


Figure 2-2: PDCA cycle and LAMDA cycle

An essential element of the lean philosophy (Morgan and Liker 2006) is continuous improvement of products and processes. Based on the Deming-Cycle (Deming 1986) the lean literature recommends to do learning iterations continuously in small steps. In this regard the lean literature introduces the PDCA-cycle (Plan, Do, Check, Act) (Kennedy 2010) or LAMDA-cycle (Look, Ask, Model, Discuss, Act) (Ward 2002), Figure 2-2. The ultimate goal is to achieve a perfect solution by following a learning-spiral with each cycle closer to the target than the previous one (Morgan and Liker 2006). Although these iterations could be considered waste at micro-process level, they are necessary to maximize the value of the overall outcome seen in a system perspective (Mascitelli 2007). In addition, capturing and improving (and thus reusing) knowledge in the learning cycle is a source of organizational learning, providing strategic value for the company (Hines, Holweg, and Rich 2004).

### 2.1.5 KBD in knowledge management

According to Von Krogh (1998) KM refers to identifying and leveraging the collective knowledge in an organization to help the organization to compete. Wiig (1997) summarizes the objectives of KM as (1) making the enterprise act as intelligently as possible to secure its viability and overall success, and (2) realizing the best value of its knowledge assets. KM aims to maximize a company's knowledge-related effectiveness by monitoring knowledge-related activities, creating and maintaining a knowledge infrastructure, renewing knowledge assets and using knowledge assets to realize their value. Central aspects are the social and cognitive aspects (Nonaka, Toyama, and Konno 2000). Important aspects in relation KBD are the transformation of knowledge for learning and knowledge exchange. Alavi and Leidner (2001) summarize knowledge transformation processes into (1) creation, (2) storage, (3) transfer, and (4) application.

### 2.1.6 Concluding remarks

The development of products and product systems takes is initiation in engineering design. LPD is an enabler to make knowledge creation more effective and efficient. SE support engineers to consider engineering problems iteratively from a systems perspective, managing multidisciplinary problem solving, wholeness, and socio-technical aspects. In addition, KM adds social and cognitive aspects of knowledge transformation. According to Lindlöf, Söderberg, and Persson (2012) the four fields provide different tools and methodologies, but are complementary to each other. They can be applied to the same problem at the same time. However, this does not mean that they cannot be applied separately.

## 2.2 Knowledge definition and classification

### 2.2.1 Product engineering knowledge

In this thesis, the term *product engineering knowledge* is applied as an 'umbrella' for the knowledge developed in all engineering disciplines that are essential in the development of a product, with main focus on engineering design, production, and systems engineering. Hence, the engineering design knowledge, including design parameters, concept choices, functionalities, principal components, etc., is extended by adding knowledge about manufacturing processes, producibility, quality, performance, reliability, serviceability, and user features as well as architectural aspects (Wiig 1995) and background knowledge from natural sciences (Sunnersjö 2010).

However, knowledge can not just be related to products, because it is processed between individuals. Having the goal to address KBD practices in companies raises the question: *What is knowledge?* In this regard, common definitions of knowledge have been reviewed. Further, they have been classified for the purpose of this thesis.

### 2.2.2 Knowledge hierarchy

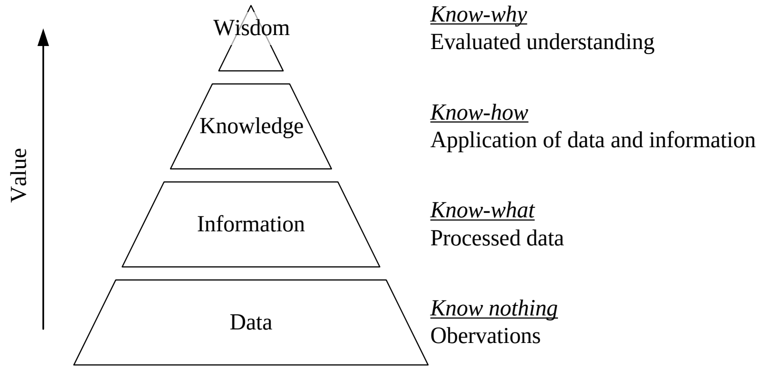


Figure 2-3: Knowledge hierarchy (adapted from Ackoff (1989) and Rowley (2007))

Literature provides many definitions of knowledge. For example Schubert, Lincke, and Schmid (1998) describe knowledge as ‘understanding gained through experience’ and ‘the sum of what has been perceived, discovered, or learnt’. Other references have other definitions of knowledge or knowledge perspectives, such as knowledge as a state of mind, object, process, capability, etc. A common model in the KM literature is the wisdom hierarchy (Ackoff 1989), defining and contextualizing *data*, *information*, *knowledge*, and *wisdom* in a hierarchical order (Figure 2-3). *Data* are defined as symbols that represent properties of objects, events and their environment and they are a product of observation (Rowley 2007). *Information* is processed data, descriptions, or instructions. It is converted into *knowledge*, when it is processed in the minds of individuals, combining information with understanding and know-how. On the other hand, knowledge becomes information once it is articulated, documented, or presented (Alavi and Leidner 2001). *Wisdom* requires judgment of knowledge and can thus add value by putting knowledge into a context.

### 2.2.3 Knowledge classification

#### *2.2.3.1 Knowledge model*

To refine knowledge for the purpose of this thesis, a knowledge model has been adapted from Chandrasegaran *et al.* (2013) (Figure 2-4). It classifies knowledge into the following main dimensions: (1) conversion, (2) representation, and (3) standardization, which will be discussed in the following. In addition, it relates the foci of the papers I-IV to the model.

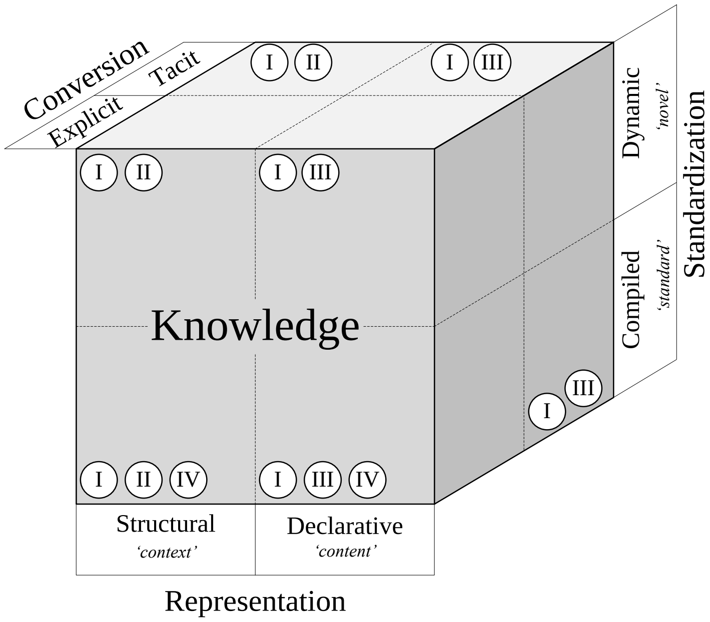

Figure 2-4: Classification of knowledge (adapted from Chandrasegaran *et al.* (2013))

#### *2.2.3.2 Individual and organizational knowledge*

A fundamental issue in KM is the distinction between *individual* and *organizational* knowledge. Individual knowledge can be defined as the sum of what has been perceived, discovered, or learned by individuals within an organization (Schubert, Lincke, and Schmid 1998). According to Løwendahl, Revang, and Fosstenløkken (2001) individual knowledge can be classified into (1) *information-based* (task-related and objective), (2) *experience-based* (subjective, and tacit), and (3) *personal* knowledge (talents, aptitudes, intuitions).

Organizational knowledge exists between, rather than within individuals. Nonaka and Takeuchi (1995) argue that it is created through interactions of individuals at various levels within an organization. Lam (2000) claims that organizational learning refers to the way in which knowledge is shared among members of the organization, but takes place inside an individual's head (Simon 1991).

#### *2.2.3.3 Tacit and explicit knowledge*

Polanyi (1966) introduces the *tacit* aspect of knowledge. Tacit knowledge is personal know-how, craft, and skill, and thus hard to formalize and communicate because it is deeply rooted in individual actions, commitment and involvement into a specific, individual context. *Explicit* knowledge on the other hand is embedded in documents, repositories, structures, and routines.

Løwendahl, Revang, and Fosstenløkken (2001) argue that only information-based, individual knowledge can be made explicit and transferred by knowledge sharing systems, while experience-based knowledge need to be transferred by interpersonal interaction. Personal knowledge, including talents and intuitions, cannot be made explicit. One could assume that tacit knowledge is more valuable than explicit knowledge due to the fact that not all tacit knowledge can be converted. However, Alavi and Leidner (2001) and Haas and Hansen (2007) argue that explicit knowledge is essential for true knowledge exchange, because it can physically be transferred, when it is expressed in such a manner that it is interpretable by the receivers (Parry and Turner 2006). Only information that can be actively processed in the mind of an individual—through processes of reflection and learning—is valuable (Alavi and Leidner 2001). Consequently, explicit knowledge is an enabler for organizational learning and knowledge creation.

#### *2.2.3.4 Structural, declarative, and procedural knowledge*

Chandrasegaran *et al.* (2013) divide the explicit representation of knowledge into *context* and *content*. According to Jonassen, Beissner, and Yacci (2013) the context is represented by *structural* knowledge, and the content by *declarative* knowledge. In addition, *procedural* knowledge represents the tacit dimension.

Ryle (2009) defines declarative knowledge as fact-based, object-specific knowledge, which can be summarized below the term *know-what*. Holsapple and Joshi (2001) summarize declarative knowledge documentations (e.g. memos, short documents, or a long reports) into *knowledge artifacts*. These are explicit objects that capture explicit knowledge. In terms of product engineering, knowledge artifacts can represent detailed product and process knowledge as well as technological background knowledge.

According to Diekhoff (1983), *structural* knowledge describes the interrelation of knowledge artifacts. Jonassen, Beissner, and Yacci (2013) claim that structural knowledge provides the conceptual basis for the *know-why* because it provides the receivers a context to understand declarative knowledge.

#### *2.2.3.5 Compiled and dynamic knowledge*

Knowledge can be classified into *compiled* and *dynamic* knowledge (Chandrasegaran *et al.* 2013). Compiled knowledge is knowledge that is gained from previous problem-solving, learning, and product development attempts that can be turned into rules, best practices, and standards. Accordingly, it is knowledge that may become part of a knowledge standard.

Dynamic knowledge is the knowledge that is necessary to generate new knowledge. It is not compilable, because it is novel and may be unstable or unassured. Nonaka, Toyama, and Konno (2000) see dynamic knowledge as an important driver for the organizational learning process. Due to the fact that it is more flexible, it may help to adapt or upgrade the knowledge standards.

Many researchers, e.g., March (1991) and Schein (2010) discuss the balance of compiled (standardizable) knowledge and dynamic (novel) knowledge, including advantages and disadvantages of knowledge reuse. Sanchez (2004) argues that a clear knowledge standard, based on compiled knowledge, may enable a base for combination of knowledge artifacts and support creation of new knowledge. On the other hand Sveiby (1997) argues that knowledge becomes static when compiled. Consequently, establishing a knowledge standard may decelerate knowledge creation and innovation. Also Huysman and de Wit (2004) experienced that a too high focus on capturing and reusing explicit knowledge may result in dependency of the retrieved documents instead of taking advantage of individual expertise. As a consequence, dynamic and individual knowledge may be overlooked. In addition, Huysman and de Wit (2004) discover that compiled documents quickly may become outdated. In this regard, March (1991) and Hedberg and Wolff (2001) recommend to find an adequate balance between stable, compiled standards and dynamic change.

## 2.3 Social and cognitive aspects of knowledge transformation

### 2.3.1 General

Knowledge is processed in individuals and therefore dependent on social and cognitive aspects. Hence, the social and cognitive aspects of organizational learning and knowledge transformation have been reviewed.

Pentland (1995) discusses the cognitive and social nature of organizational knowledge and its embodiment in the individual and organizational practices. The conversion between individual into organizational knowledge, or vice-versa, is related to cognitive and social aspects. It consists of a continuous and dynamic set of knowledge transformation processes between individuals, groups, and physical structures and knowledge artifacts. According to Alavi and Leidner (2001), they can be summarized into (1) creation, (2) storage, (3) transfer, and (4) application of knowledge. Further, Alavi and Leidner (2001) argue that all four processes are necessary for effective organizational KM because the knowledge transformation processes are not independent of each other but intertwined.

### 2.3.2 Knowledge creation

According to Pentland (1995) the creation of organizational knowledge involves developing new knowledge or replacing existing knowledge. Nonaka (1994) discusses the conversion of tacit to explicit knowledge as a central aspect in knowledge creation. To illustrate knowledge creation, Nonaka, Toyama, and Konno (2000) established the SECI-model (Figure 2-5). It begins with the *socialization* (developing own tacit knowledge), followed by the *externalization* (turning tacit knowledge into explicit knowledge), the *combination* (sharing and transferring explicit knowledge), and finally the *internalization* (turning explicit into tacit knowledge). In the socialization phase, tacit knowledge is passed on between individuals through processes of observation, imitation, and practice. In the externalization phase the tacit knowledge is articulated into explicit knowledge, which makes it possible to share it with others. Explicit knowledge can be made independent from the context and be connected in new settings in the combination phase. Finally, in the internalization phase, the explicit knowledge is converted into new tacit knowledge. When it is internalized, it broadens the tacit knowledge base.

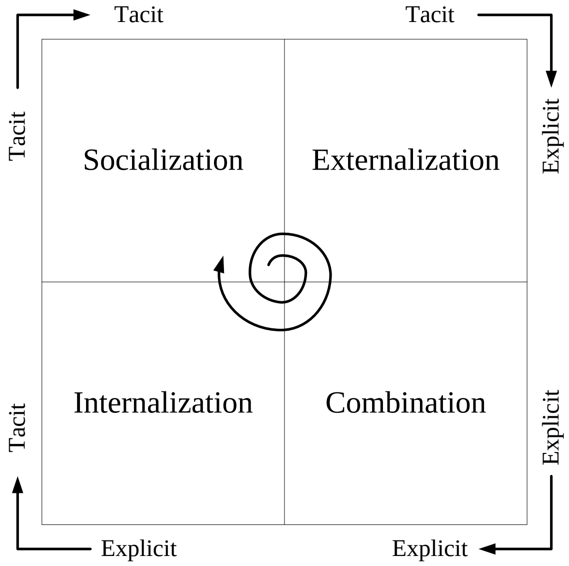


Figure 2-5: The SECI Process (adopted from Nonaka, Toyama, and Konno (2000))

### 2.3.3 Knowledge storage

Alavi and Leidner (2001) argue that knowledge storage and retrieval are important issues of organizational KM. Stein and Zwass (1995) refer to an organizational memory as the means by which knowledge from the past, experience, and events influence present organizational activities. Researchers detect both positive and negative influences of the organizational memory. An advantage is that a memory helps store and utilize valuable solutions from the past and can avoid rework and repeated problem solving (Wilkins and Bristow 1987). On the other hand it can rise a stable consistent organization that is resistant to change (Denison and Mishra 1995). Thus, as a counterpart to organizational learning, researchers also discuss organizational forgetting (Argote, Beckman, and Epple 1990).

Several researchers argue that a good infrastructure is essential for effective knowledge capture, storage, and reuse. Shankar *et al.* (2012), Piorkowski *et al.* (2012) and Sanchez and Collins (2002) argue that the structure for knowledge storage has to be well-organised to support easy accessablility and searchability. Nonaka, Toyama, and Konno (2000) consider the structure of system-wide knowledge also as an enabler for dynamic knowledge creation and development with the capability of creating shared understanding. Further, Czarniawska and Joerges (1996) argue that a knowledge standard can support group competence, linked through the standard, and can thus become a basis for organizational learning by collaboratively utilizing existing knowledge, as well as streamlining the creation of novel knowledge (Grant 1996; Liu *et al.* 2013).

### 2.3.4 Knowledge transfer

According to Nonaka, Toyama, and Konno (2000) a prerequisite for knowledge transfer is a *shared understanding* between individuals. For the purpose of this thesis we define shared understanding as suggested by America *et al.* (2011); shared understanding implies that individuals within a team, project, or company think of the various aspects of systems in the same terms. This involves that individuals do not keep knowledge in their heads but make it explicit; e.g., by using common tools, visualizations, and discussions. This does not mean that everybody needs to know everything about a system, but integrates special knowledge (Grant 1996). Further, Nonaka, Toyama, and Konno (2000) and (Lam 2000) argue that knowledge transfer requires a knowledge-sharing atmosphere in an organization. According to Hansen, Nohria, and Tierney (1999) and Snowden and Boone (2007), leaders play an important role in this regard. Beside the organizational prerequisites, knowledge transfer requires adequate transfer media that are accepted by the employees (Von Krogh 1998; Cai *et al.* 2012; Shankar *et al.* 2012).

Gupta and Govindarajan (2000) summarize knowledge transfer to five points that influence the knowledge flow in organizations. These are (1) perceived value of the source unit's knowledge, (2) the willingness of the source to share knowledge, (3) existence and richness of transmission channels, (4) the willingness of the receiver to acquire knowledge from the source, and (5) the ability of the receiver to utilize the knowledge.

### 2.3.5 Knowledge application

Grant (1996) argues that clear and effective organisational routines, directives and self-containted task teams are crucial to allow and support knowledge reuse. According to Shankar *et al.* (2012), the routines need to be aligned with the documentation storage systems to enable smooth information flow. Further, to enable multi-disciplinary knowledge application and (re)use of stored information, Piorkowski *et al.* (2012) recommend to support transparency of system dependencies by leveraging interconnection of stored information, which makes it easier for individuals to find information. Tan *et al.* (2009) identify a number of reusable knowledge artifacts that are applicable in multiple contexts, including *standard designs*, *process knowledge*, *'best practices'*, and *'lessons-learned'*. Also, in application of knowledge, a shared understanding is important to enable discovery and application of the desired information.

## 2.4 Product and product knowledge standardization

### 2.4.1 General

Standardization approaches in engineering design usually take their initiation in modular product architectures an platforms, as well as product families, reference architectures, modules, etc. (Jiao, Simpson, and Siddique 2007). Thus, they play an important role in establishing a dynamic knowledge standard, especially with regard to the representation of structural knowledge.

### 2.4.2 Product architectures

Ulrich (1995) introduces the *product architecture* in engineering design. He defines the essential elements of a product architecture, including (1) the arrangement of *functional elements*, (2) the mapping of *functional elements* to *physical components*, and (3) the specification of *interfaces* between the components. The abstract functional elements are arranged in functional structures, which decompose, connect, and relate sub-functions with flows of energy, material, and information (Pahl *et al.* 2007). The physical components are the specific design features and parts of a product. To identify the elements in a product architecture, Ulrich (1995) recommends the decomposition of the system. Sudjianto and Otto (2001) propose to apply the functional structure as a basis for modularization.

The decomposed, independent building blocks within the product architectural are defined as *modules* (Stone, Wood, and Crawford 2000; Muffatto and Roveda 2002). In this regard, Pahl *et al.* (2007) summarize some central definitions:

- *Modularity* is the degree of purposeful structuring of the product architecture.
- *Modularization* is the purposeful structuring of a product in order to increase its modularity. The aim is to optimize an existing product architecture to meet product requirements.
- *Modules* are units that can be described functionally and physically and are essentially independent.

Modules can be classified according to the functional and physical independence of its components. A component is considered completely independent if it performs exactly one sub-function. Then, the relationship between function and component is unambiguous. In terms of modularization this offers advantages, for example, the possibility to develop, test, upgrade or change modules independently from the rest (Holland 1992). It should be noticed, however, that the objective of product modularization is not the maximization of modularity—which would unnecessarily increase interfaces—but optimization of the opportunities to meet different objectives.

### 2.4.3 Product platform

Harlou (2006) classifies the modules into *standard* modules and *customer-specific design* modules. Standard modules are common modules that comply with several product variants of the product architecture. According to Mortensen *et al.* (2008), they can be reused over time within several product configurations. Thus, s*tandardization* is characterized by reusing similar or equal modules. Dynamic, customer-specific design units are elements that are different across the variants and are consequently not reused. Meyer and Lehnerd (1997a) introduce the *product platform* as a set of subsystems and interfaces that form a common structure from which a stream of derivate products can be efficiently developed and produced. Thus, the standard modules in the architecture can become a platform across several product deliveries. According to Holland (1992) modules can evolve independently from the platform and be substituted by upgrades when desired.

### 2.4.4 Extending product standardization to knowledge standardization

Robertson and Ulrich (1998) extend the use of the modular product architecture by assigning knowledge about common product technologies, production methods, etc., to the modules. Thus, knowledge related to the modules can be classified in the same way as the module classification. According to Sanchez and Mahoney (1996), s*tandardized* knowledge is the compiled knowledge that is linked to standard designs, standard functions, and standard modules that are reused over time. This can include both standard structural knowledge as well as standard knowledge artifacts. Hence, knowledge artifacts can get a modular character while structural knowledge can get a platform character, equally to the related modular, platform-based product model.

### 2.4.5 Pitfalls in product architecture design

Even though the implementation of a product architecture can have many advantages for a company there are also some pitfalls. The establishment of a successful architecture requires the alignment of technical architecture (product and production aspects), market (customers) and business goals (Mortensen, Harlou, and Haug 2008). According to Cloutier *et al.* (2010) the business architecture and customer context are often missing in practice. Consequently, the technical architectures represent often solutions for unspecified problems in unspecified contexts. Another challenge may be that they are misaligned (Hansen, Mortensen, and Hvam 2012).

One common mistake in product architecture modelling is a coordination deficit. According to (Gokpinar, Hopp, and Iravani 2010) especially subsystems with intermediate centrality show a mismatch between organizational attention and interconnectivity. Usually the highly central sub-systems receive substantial attention because they are obviously complex. The subsystems with very low complexity require little effort and are thus unlikely to be under attended. As a consequence the product quality may be influenced negatively (Sosa, Gargiulo, and Rowles 2007).

A further pitfall may be unmatched team interactions because the system boundaries may prevent the identification of interfaces (Sosa, Eppinger, and Rowles 2004). Also, the communication of different teams that need to address the same interfaces can be challenging (Sosa, Eppinger, and Rowles 2004).

According to (Mortensen, Harlou, and Haug 2008) decision making in the early phases of concept development of a product system is important for company performance, benefits in functional areas, maintenance and quality. In this regard (Hansen *et al.* 2012) discusses factors for the success of architectural initiatives. Cloutier *et al.* 2010 recommed a reference architecture as a means to incorporate an organization’s vision and strategy for the future.

## 2.5 Enablers for representation of products and product knowledge

In order to implement a dynamic knowledge standard, adequate representation is essential to enable individuals to create a shared understanding. Many tools can support the explicit representation of product engineering knowledge, e.g., by using pictorial, symbolic, virtual, or algorithmic approaches (Owen and Horváth 2002).

Both structural and declarative representations are necessary to cover the context and content of knowledge. Holsapple and Joshi (2001) and Ameri and Dutta (2005) argue that structural knowledge—although small in volume—has high value for the company because it can easily be accessed, mined and used as a cognitive structure for finding the desired knowledge artifact. Also Sanchez and Collins (2002), Piorkowski *et al.* (2012) and Shankar *et al.* (2012) discuss the importance of structural knowledge and see advantages in supporting easy accessablility and searchability of knowledge artifacts. Consequently, knowledge artifacts can easily be combined with help of a structural knowledge representation, e.g., by product architectures or computational support systems (Chandrasegaran *et al.* 2013).

### 2.5.1 Structural representation

In product engineering structural knowledge is represented by functional structures, causal diagrams, product architectures, etc. Kruchten *et al.* (2005) include design decisions, assumptions, context, and other factors that together determine why a particular solution is designed the way it is into structural knowledge.

Examples for structural, context representation various architectural modelling techniques (Mortensen *et al.* 2000; Jiao, Simpson, and Siddique 2007; Bruun, Mortensen, and Harlou 2013), model-based systems engineering (MBSE) approaches (Friedenthal, Moore, and Steiner 2012; Singh and Muller 2013), or strategies for utilizing product life cycle management (PLM) systems (Baughey 2011; Bruun and Mortensen 2012; Zancul 2012; Urwin and Young 2013). The quantitative methods include approaches for product customization (Ruohonen, Riihimaa, and Makipaa 2006; Bruun and Mortensen 2012), product-process relations mapping (Schuh *et al.* 2008), or product KM support (Folkard *et al.* 2012).

#### *2.5.1.1 Model-based systems engineering (MBSE)*

MBSE is a potential method from SE theory. Friedenthal, Moore, and Steiner (2012) define MBSE as a method that implements parts of the SE processes visually and produces a systems model as its primary outcome. It documents the SE effort through models, diagrams, and hierarchies, following strict rules. Thus, when clear rules are defined and followed, it can establish a structural modelling standard. A *system model* represents a system and its elements. Baughey (2011) introduces the requirements, functions, principal layout, and physical details as most important structures for a systems model in product engineering.

Haskins (2011a) argues that MBSE can improve knowledge capture and reuse and that it can improve the capacity to teach and learn SE, integrate new team members, minimize knowledge loss, and establish shared mental models.

#### *2.5.1.2 PLM systems*

Saaksvuori and Immonen (2005) define PLM as a systematic concept for the integrated management of all product related information and processes through the entire life-cycle of a product from the idea to the disposal. The aim is to enable a clear value creation chain. PLM supports the knowledge transformation processes by enabling knowledge creation, supporting individual learning and organizational learning, improving knowledge access and making available more channels of communication throughout the project life cycle (Folkard *et al.* 2012).

### 2.5.2 Declarative representation

Saad *et al.* (2013) provide an overview of tools for effective representation of declarative knowledge. Among them are A3-reports (Sobek and Smalley 2008), ‘8 disciplines’ method (Arnott and Pervan 2008), problem analysis flowcharts (Sproull and Sproull 2001), root-cause analyses (Mahto and Kumar 2008), and 5-Whys (Sproull and Sproull 2001). All are created on the base of a standardized template with high focus on visualization and can thus serve as standardizable knowledge artifacts.

A challenge regarding the representation and standardization of knowledge artifacts is that they often describe one specific problem, design, or activity, and are lacking a common structure, documentation rules and overall reuse strategy for applying them new projects (Fikes and Farquhar 1999; Lee and Suh 2008; Li, Raskin, and Ramani 2008).

#### *2.5.2.1 A3-reports*

A main focus of this thesis is on A3-reports. These are one-page reports, named after the paper size format used. The main objectives of the A3-docuementation process are to guide the author in presenting the product development problem, issue, or standard logically and objectively from a systems viewpoint (Sobek and Smalley 2008). The A3-reports document information and knowledge as a part of the individual learning process, while forcing the author to express condensed information clearly and visually. Each idea, status, proposal, and learning cycle is documented in a separate report—including the goals, processes, solutions, and risk elements—summarizing the information briefly and precisely in a predefined, standardized pattern (Shook 2009).

## 2.6 Product and systems evolution

In order to identify a dynamic knowledge standard, product and systems evolution is a central topic in both engineering design, LPD, and SE. According to America *et al.* (2011) *evolvability* is the ability of a product (system) to actively respond to changes with predictable minimal effort and time.

Based on engineering design theory, Sanchez (2004) proposes to apply the product architecture as a base for product evolution, where the architecture represents structural knowledge. Declarative knowledge is linked to the architecture in form ‘modules’, which can be changed and upgraded independent of each other. In contrary, knowledge modules can be linked to an updated structural standard.

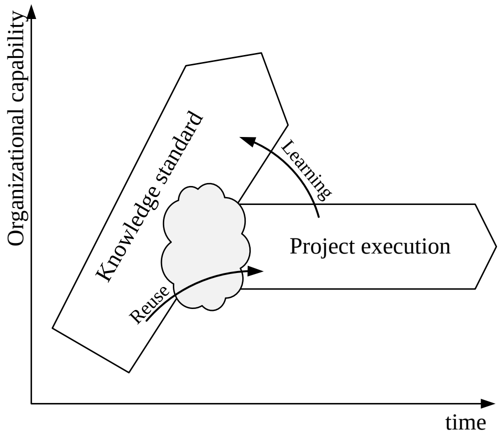


Figure 2-6: Model of knowledge and product value stream (adapted from Kennedy, Harmon, and Minnock (2008))

In LPD literature Kennedy, Harmon, and Minnock (2008) discuss a dynamic knowledge standard across different projects in every company, representing the knowledge value stream of a company (Figure 2-6). Also, Shook (2008) recommends a mental model consisting of two value streams (knowledge standard and project execution) as a fundamental framework. In this model, the knowledge standard is used as a base for project execution, while new learning outcomes in the projects contribute to maintain and update the knowledge standard. Ideally, during product development and project execution the knowledge standard evolves over time and organizational capability is increased (America *et al.* 2011). Further, a knowledge standard can support group competence, linked through the standard (Czarniawska and Joerges 1996), and can thus become a basis for organizational learning by collaboratively utilizing existing knowledge as well as streamlining the creation of novel knowledge (Grant 1996; Liu *et al.* 2013).

Also, SE discusses the evolution of products and systems. Sage and Cuppan (2001) address evolution in the theory ‘systems of systems’ and argue that systems should be evolutionary. A system of systems is never fully formed or complete but grows and evolves over time by modifying, adding, and removing structures, functions, and purposes as experience with the grows.

# 3 Research methods

## 3.1 Overview of the research design

This chapter introduces the research methods, which have been applied in the appended papers, from a superior view. In addition, it presents the industrial case companies. An overview of the research methods in the four main learning cycles, containing the focus of the accordant literature review, selected data collection method, and selected cases, is provided in Table 3-1.

The general research strategy in each learning cycle was as follows. Adhering to the overall implementation strategy presented in Figure 1-3, several challenges and accordantly different research questions (RQ) emerged. In order to address the identified challenges, a literature review was conducted to identify potential theories, tools, and methodologies to solve the problem. On this base, new approaches to bridge potential research gaps have been developed and tested in case studies.

Table 3-1: Overview of the applied methods and selected cases

| Paper | Focus of literature review | Main data collection method | Selected cases |
|---|---|---|---|
| **I** | • Knowledge definition<br>• KBD fundamentals in engineering design, LPD, and SE | Semi-structured interviews | CoA<br>CoB<br>CoC<br>CoD |
| **II** | • Product architectures<br>• Platforms<br>• Product modelling | Proof-of-concept demonstrator | CoE |
| **III** | • Knowledge creation<br>• Knowledge storage<br>• Knowledge utilization<br>• Knowledge reuse<br>• A3-reports | Survey | CoA<br>CoB<br>CoC<br>CoD |
| **IV** | • Knowledge classification<br>• Representation tools<br>• Standardization tools | Semi-structured interviews | CoA<br>CoB |

## 3.2 Applied research methods

### 3.2.1 Literature reviews

Webster and Watson (2002) argue that the review of prior, relevant literature is an essential feature of any academic project. Further, they state that “an effective review creates a firm foundation for advancing knowledge. It facilitates theory development, closes areas where a plethora of research exists, and uncovers area where research is needed”.

Ridley (2012) condenses three key elements of a literature review, recommending the following:

(1) Situate the research focus within the context of the wider academic community in the field;
(2) Critically review the relevant literature;
(3) Identify potential gaps within that literature that the research will attempt to address.

In this research, literature reviews have been conducted in all papers. They have followed the recommendations of Hart (1998), Webster and Watson (2002), and Levy and Ellis (2006). They provide guidelines for effectively identifying input, processing information, and structuring output of literature reviews.

### 3.2.2 Case studies

Eisenhardt (1989) describes case studies as a research strategy, which focuses on the understanding of the dynamics, present in single settings. According to Yin (2014), case studies help to investigate contemporary phenomena holistically and meaningfully in their real-world context. They are applicable for research topics that address ‘*how*’ or ‘*why*’ questions, in contexts where the behavior of the participants cannot be manipulated. According to Schramm (1971), they can illuminate a set of decisions and explain why they were taken, how they were implemented and with what result. Typically, case studies combine several data collection methods, such as observations, interviews, and questionnaires (Eisenhardt 1989). The application of case studies as main source for data collection provides the benefit that data have a high industry relevance.

Eisenhardt (1989) elaborates on the strengths of case studies. She argues that case studies can generate novel theories and that the emergent theories are likely to be testable with constructs that can be readily measured, and hypotheses that can be proven. A third strength is that the resultant theory is likely to be empirically valid.

Eisenhardt (1989) also discusses some weaknesses, among them risk that the intensive use of empirical evidence can yield theories which are overly complex. Further, the theories built on case studies may be narrow and idiosyncratic. In addition, Yin (2014) states that a common concern about case studies is that the findings are made on a single example and may consequently be difficult to generalize. In this regard, Yin (2014) argues that the goal of case studies is to expand and generalize theories analytically and not to extrapolate statistical probabilities.

The quality of case study research is commonly measured on the basis of four tests: (1) construct validity, (2) internal validity, (3) external validity, and (4) reliability (Yin 2014). The construct validity concerns the identification of correct operational measures for the studied concepts. Internal validity concerns causal relationships and is influenced by the external validity concerns the extent to which the findings can be generalized. Reliability concerns whether the operations of a study can be repeated with the same result.

In this research, case studies have been applied to collect data from real-world KBD applications in industry. The case studies follow the recommendations, regarding the planning, design, preparation, data collection, and analysis made by Yin (2014).

### 3.2.3 Semi-structured interviews

Interviewing people provides insights in their way to address problems, opinions and thoughts. Thus, collected data are based on qualitative measures. Compared to quantitative methods, semi-structured interviews allow the interviewer to better adjust to unexpected answers (Hove and Anda 2005).

Mitchell and Jolley (2012) identify three types of interviews. Among them are unstructured, structured, and semi-structured interviews. In unstructured interviews the interviewer suggests the questions, having just a few specific questions on mind. They are vulnerable to the interviewer bias and collected information may be too disorganized for analysis. Structured interviews repeat the same specific questions for every interviewee (Seaman 1999). Semi-structured interviews are a combination of both and begin with a core of standard questions, from which basis the interviewer may deepen or expand any question.

Semi-structured interviews are a resource demanding data collection method, requiring systematically and carefully planning since the way in which they are conducted as well as the selection of interviewees may influence and even limit the results (Hove and Anda 2005). In addition, results may be limited by the interviewer when relevant topic are not followed up further.

In some of the appended papers, the research method of semi-structured interviews has been applied. Hove and Anda (2005) provide a guide for advising researchers in how to plan and conduct semi-structures interviews. These recommendations have been used as a base for planning, conducting, and analyzing the interviews conducted in the appended papers.

### 3.2.4 Proof-of-concept demonstrator

The proof-of-concept demonstrator (POC) (Mankins 1995) allows the realization of a certain method or idea to demonstrate its feasibility and has the potential of being used. Its goal is to test, analyze, and validate the main characteristics of a certain concept or methodology in a specific example in order to proof that it is generizable. In Paper II, the method of a POC has been applied.

### 3.2.5 Survey

In Paper III, a survey approach was chosen to collect data. An advantage of surveys is that they help to gather information from a large sample with less effort than other techniques. Researchers distinguish between exploratory, confirmatory, and descriptive surveys (Malhotra and Grover 1998.

Forza (2002) provides a set of recommendations to develop and conduct a survey. The method includes the establishment of hypotheses in relation to the theoretical context, pilot testing, data collection, and analysis. Hypothesis testing is conducted relative to a set of carefully selected statements, which are to be ranked by the surveyees. Hence, the approach serves to support or refuse the hypotheses based on the statistical data collected from the surveyees. Common sources for inaccuracy and research bias in survey research, according to Krosnick (1999), are sampling errors, measurement errors, statistical conclusions errors, and internal validity errors.

The confirmatory survey conducted in Paper III was designed according to the methodological structure and processes proposed by Forza (2002).

## 3.3 Introduction of the case companies

In order to conduct the case studies from an assortment of product manufacturing companies, five different case companies have been selected, all with an R&D hub in Norway. The companies belong to different industry sectors, including automotive, defence, subsea, product development full service provider (without manufacturing responsibility), and mast systems. All companies develop knowledge-intensive, high-technology products in multi-disciplinary teams. With product innovation being the main pillar for value creation, all the companies have a strong focus on continuously improving their KBD performance.

Although all four companies develop advanced products, there are major differences between the companies, as illustrated in Figure 3-1. It arranges the companies according to their relative project (value related to uniqueness of outcome) and process (value related to consistency of outcome) focus. The companies embody a variety of organizational focus that cover a wide spectrum from process and mass-production-orientated firms to entrepreneurial focused firms, and firms developing ‘one-of-a-kind’ products.

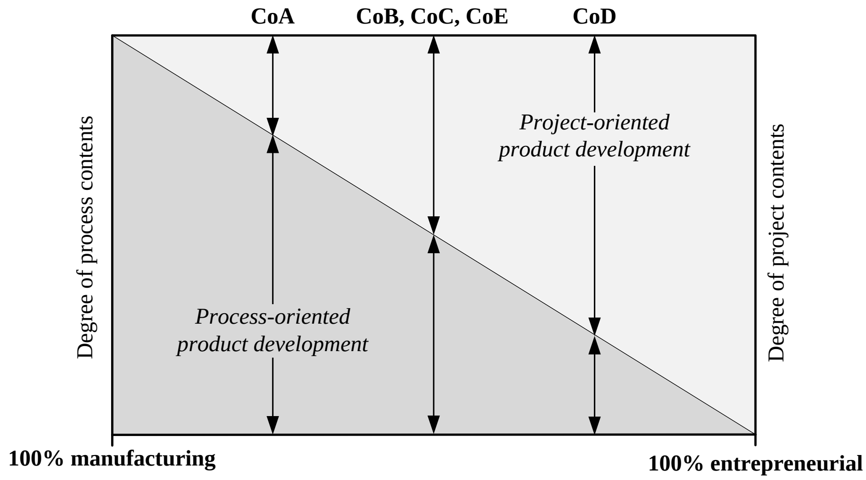


Figure 3-1: Product development focus of case companies

Table 3-2: Case sample overview

| Co | Products | Operation | Products/year | Employees | Main KBD focus |
|---|---|---|---|---|---|
| **A** | Automotive parts | • Global production<br>• Global development<br>• Global customers | 50,000 to several millions | 10,000 | • A3-documentation<br>• Visual relations |
| **B** | Defence, space, and aerospace products | • National development<br>• National production<br>• Global customers | 100 | 450 | • MBSE<br>• Modular product architecture |
| **C** | Subsea products for petroleum industry | • Global production<br>• Global development<br>• Global customers | 2-6 of one kind (ca 100 a year) | 11,500 | • Standardization |
| **D** | Consultancy and systems development | • Production at customers' locations<br>• National development<br>• Global customers | 1 to several millions (project dependent) | 100 | • A3-documentation<br>• reuse of knowledge in new context |
| **E** | Mast systems for road traffic and aviation | • National development<br>• Global production<br>• Global customers | Several thousands | 50 | • Standardization |

Table 3-2 provides an overview of the companies and their specific foci in KBD implementation. Company A (CoA) is an automotive Tier 1 supplier that produces parts and subsystems at high volumes. Its NPD process is of repetitive nature between the different product development programs, resembling somewhat the characteristics of a manufacturing process. Company B (CoB) develops and produces high tech defence, space, and aerospace products (e.g. missiles), capturing knowledge in long reports as required by governmental restrictions. Company C (CoC) develops and produces low volume, engineer-to-order products for the offshore subsea and petroleum industry. The NPD strategy of Company D (CoD) includes developing unique products for a variety of manufacturing customers. CoD's main competence is project and engineering management, without taking product manufacturing ownership. CoD designs and develops different types of advanced products for a variety of customers who manufacture and distribute the products in different market places. The products of company E (CoE) include customized, lightweight aluminum mast systems for road traffic and aviation applications.

## 3.4 Limitations

A general limitation is that the ability of the researcher to see the world in new ways, is dependent on the way s/he is educated, and may just be biased (Kuhn 2012). More specifically related to this research, the focus of this research has been limited by the overall implementation strategy presented in Figure 1-3. Research directions, literature reviews, and RQs have been developed within this scope.

Further, the cases have been selected from a specific context, which introduces some challenges to the validation of the research. All case companies are situated in Norway and operate in a product engineering environment. Consequently, this may limit the generalization ability over to other working cultures in other countries or in other companies. The applied research methods have some limitations as discussed in the accordant sections.

Further, the methods developed and tested in the case studies are limited to single, rather simple, examples. Although developed in an industrial context, they do not cover the full complexity. A more authentic evaluation and validation of the methods may be an issue for further work to make them applicable in a broader context.

# 4 Results

## 4.1 General

This chapter provides a brief overview of the research approaches and results obtained in the four learning cycles. The detailed elaboration of the research questions, specific research design, and discussion are subject of the appended papers I-IV.

## 4.2 Paper I – Need finding

*'Need Finding for the Development of a Conceptional, Engineering-Driven Framework for Improved Product Documentation'*

### 4.2.1 Research approach

The objectives of Paper I were to gain insight into current knowledge capture and reuse practices in industry, to explore the challenges of current practices, and to identify the needs for improved knowledge-based development (KBD) performance in order to establish a conceptional framework for KBD. The research approach incorporates a literature review based on strategies from engineering design methodology, model-based systems engineering (MBSE), and lean product development (LPD). In-depth data from engineering practitioners in CoA, CoB, CoC, and CoD have been collected by a case study, conducting using semi-structured interviews. Questions were related to project execution practices, knowledge capture and storage, main challenges and opportunities for improvements, as well as needs for an engineering-friendly KBD knowledge storage system.

### 4.2.2 Results

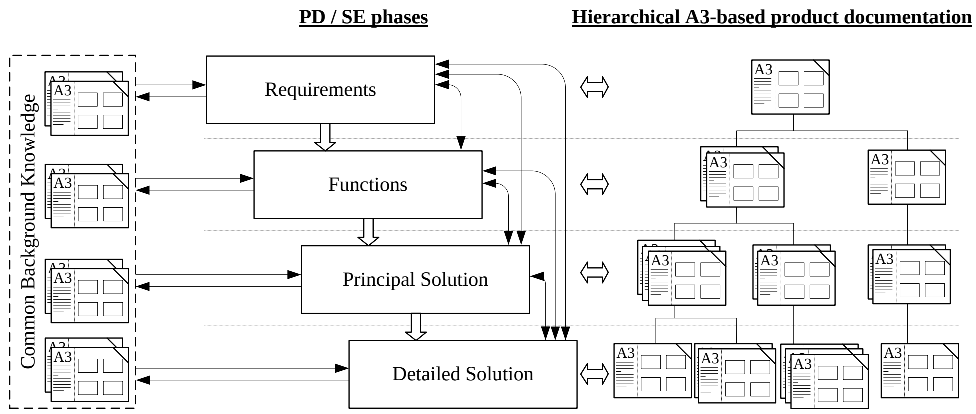


Figure 4-1: Conceptional model for KBD

The results of the need finding could be summarized into a set of propositions, which address the aspects product development, project communication, and product documentation. Based on the propositions, requirements for an engineering-driven KBD approach could be derived. They are summarized in a conceptional model (Figure 4-1). It links documentation, for example, in form of A3-reports, to the product architecture, combining strategies from product design methodology, MBSE, and LPD into a knowledge standard between the projects. The product architecture should be structured according to the steps of systematic engineering design processes, including the layers of requirements, functions, principal layout, detailed solution, and their linkages. All aspects of the product life-cycle need to be included in the development, including knowledge collected from former projects, experiences, literature, and other internal and external sources. The KBD structure needs to be flexible to dynamic changes imposed from the product environment. In summary, the KBD model should describe a holistic system, integrating all life cycle phases, showing dependencies between sub-systems, and make it possible to quickly grasp a product and its dependencies from different perspectives.

## 4.3 Paper II – Product portfolio and variant mapping

*'On the use of a product portfolio map and variant maps as a tool to enable platform-based manufacturing strategies'*

### 4.3.1 Research approach

Paper II takes its initiation in disjointed knowledge repositories and structural representation. It directs towards the conceptual model elaborated in Paper I. However, to be able to build a knowledge-base for KBD, the input for the knowledge base needs to be detected. Hence, the objectives of Paper II were to establish an overview of the product knowledge in various repositories and to identify, structure, and systemize product variants in a unified map. The desired outcome is illustrated in Figure 4-2.

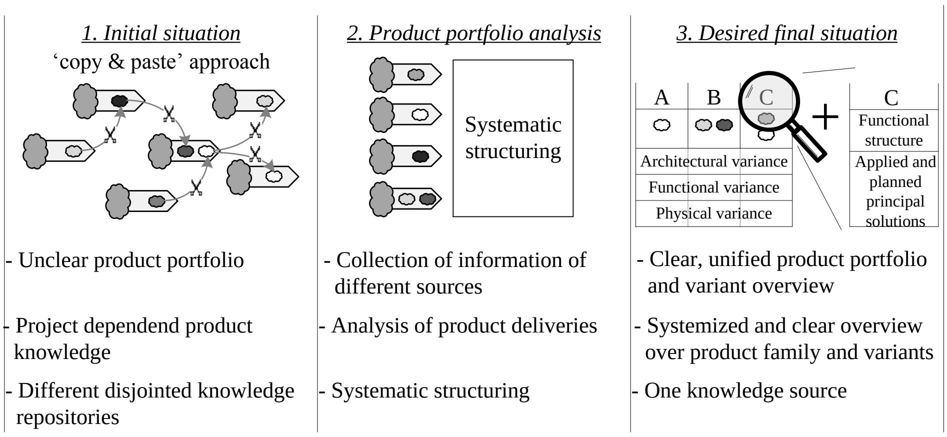


Figure 4-2: Desired outcome of Paper II

Based on a literature review on product modelling, product architectures, and product platforms as well as on experiences in the case CoE, a method to systemize a dispersed product portfolio into a unified, transparent overview has been developed. A real-world proof of concept (POC) demonstrator case has been defined to verify the proposed modelling approach when applied to the unstructured product portfolio of CoE.

### 4.3.2 Results

For the evaluation of the cross-variant product family a *product portfolio map* has been developed. Its layout is demonstrated in Figure 4-3. Building on the results of the literature review and the case study, it identifies variants from different sources and structures and systemizes them in parallel at different abstraction levels, including architectural, functional, and physical variance. In addition, the details of the variants have been identified by decomposing them into functional and physical building blocks, followed by structuring and systemizing them into *variant maps* (Figure 4-3, right side). They include both present solutions as well as those which are subjects of current development. Rough estimates of the development risk are also indicated in the variant map.

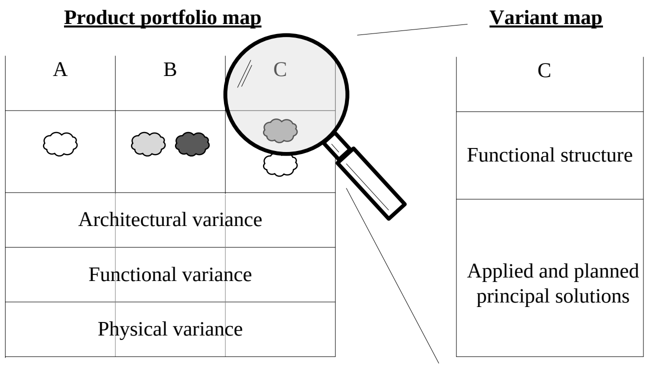


Figure 4-3: Layout of product portfolio map and variant map

Both maps combined can map the entire principal, architectural, functional, and physical variance across a number of products while making scattered product variant information more explicit. This enables the comparison of the functional, principal, or physical variants in parallel at the cross-variant (product family) level and for each variant. It also provides the capability to show systems that span the variants within the product family. The maps collect information into a single-source repository, presuming that both maps are applied together as one tool.

## 4.4 Paper III – Experiences with A3-documentation

*'A3-reports as tools for supporting organizational learning and knowledge reuse: A comparative survey-based study'*

### 4.4.1 Research approach

In addition to a structural knowledge description, effective knowledge transformation requires a simple yet precise and comprehensive presentation of knowledge in knowledge artifacts to enable clear interpretation by the receivers (Parry and Turner 2006). In this regard, A3-reports are a potential tool for representing the declarative knowledge (knowledge artifacts) effectively in a standardized form.

The objectives of Paper III were to determine how A3-documentation compared to other documentation types may affect (1) the ability to establish a shared platform of understanding for collective learning, and (2) reuse of company-internal documentation. Data have been collected by a survey, conducted in the case companies CoA, CoB, CoC, and CoD. Based on a literature review on knowledge transformation processes a conceptual theoretical (Figure 4-4) and two hypotheses have been developed. The following hypotheses (H1 and H2) have been explored in the survey:

*H1: A3-documentation can contribute positively in establishing a shared understanding as a basis for (improved) organizational learning.*

*H2: A3-documentation has a positive impact on the reuse of internal information within the company.*

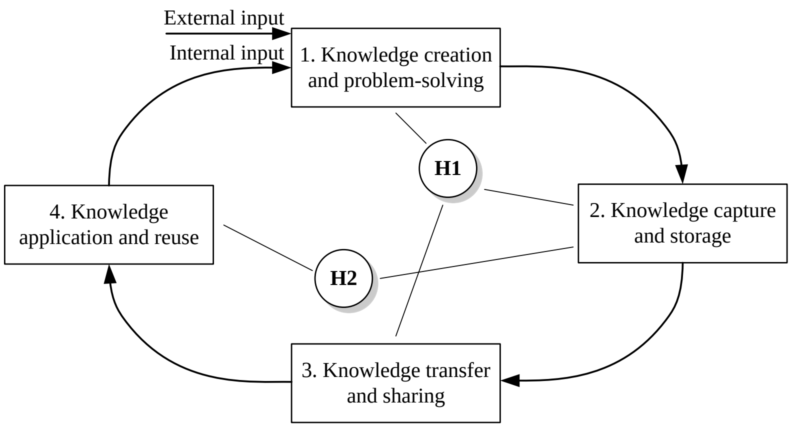


Figure 4-4: Conceptual theoretical model for hypotheses development

The establishment of a shared understanding (H1) could not be measured directly, because it affects many knowledge transformation aspects. It involves that individuals think of the various aspects of systems in the same terms within a team, project, or company. Thus, survey statements have been related to four main aspects that were identified to be central in establishing a shared understanding. Among them were learning, visualization, discussion, and systems understanding.

In order to measure if A3-users are more likely than non-A3-users to reuse internal documentation (H2), survey statements have been formulated related to the preferred information source, acceptance of the tool, trust the documented content, and utilization of the information in new contexts. This included finding the right information for the right context, processing follow-up actions and avoiding to repeat former mistakes by consulting the lessons learned.

The survey statements have been developed in relation to the conceptual theoretical model and the literature review. The results were analyzed by applying statistical methods.

### 4.4.2 Results

#### *4.4.2.1 Establishing a shared understanding by A3-documentation*

The survey results prove that A3-documenation contributes positively to creating a shared understanding by improving the perceived learning and visualization capabilities. However, in the survey statements related to discussion aspects and systems understanding, no clear direction can be measured. Consequently, no general conclusion can be drawn as to whether A3-reports contribute positively in establishing a shared understanding. Hence, H1 remains unsupported.

#### *4.4.2.2 Reuse of documentation*

The survey results demonstrate that A3-reports have a positive impact on the reuse of company-internal information, although no evidence is found that this reduces repeated (same) problem-solving. Thus, H2 is supported. The main constraints for knowledge reuse between different projects turn out to be the lack of effective storage systems and searching possibilities.

## 4.5 Paper IV – Strategic implementation of a dynamic knowledge standard

*'Strategies for implementing a dynamic knowledge standard in product engineering using structural representations and knowledge artifacts'*

### 4.5.1 Research approach

Drawing from the former results both the platform-based, modular product architecture as approach for representing structural knowledge and the A3-reports as approach for representing declarative knowledge are potential tools for implementing a dynamic knowledge standard.

Product representation and standardization methodologies do offer potential tools for implementing a dynamic knowledge standard. However, they do not provide detailed strategies for how to utilize the tools to establish the standard. Thus, the objectives of Paper IV were to determine adequate strategies for implementing a structural and a declarative knowledge standard, and to propose an integrated model that combines the strengths of both.

Based on a literature review that defined and classified organizational product engineering knowledge, analyzed knowledge representation and standardization approaches as well as a case study in two industrial companies (CoA and CoB) strategies to determine adequate strategies have been developed.

### 4.5.2 Results

#### *4.5.2.1 Structural knowledge standard*

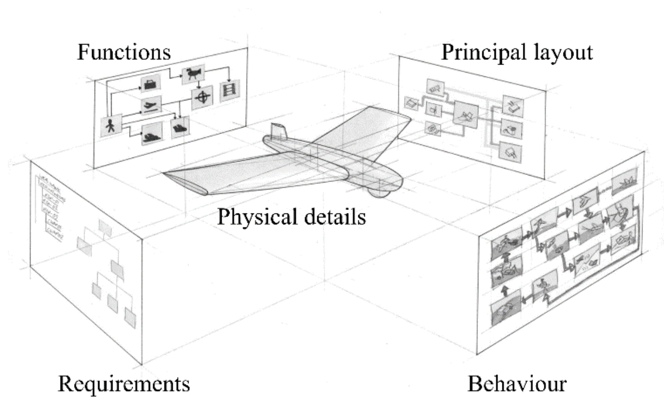


Figure 4-5: Product views and standardization levels of the structural knowledge standard

The results present an implementation strategy for a structural knowledge standard based on an architectural decomposition of the product and a visual presentation in a MBSE approach. The structural standard is founded on different product views as illustrated in Figure 4-5. The implementation strategy consists of six main steps including (1) identification of the requirements, (2) definition of the behavior, (3) identification of main functions, (4) finding principal solutions, and (5) developing concepts, identifying the best concept and (6) elaborating details. The model includes several decomposition levels. Thus, the implementation steps need to be followed iteratively both between the development steps and between the decomposition levels. Further, strict rules for engineering execution and a strong support of systems engineers are necessary for implementation.

#### 4.5.2.2 Declarative knowledge standard

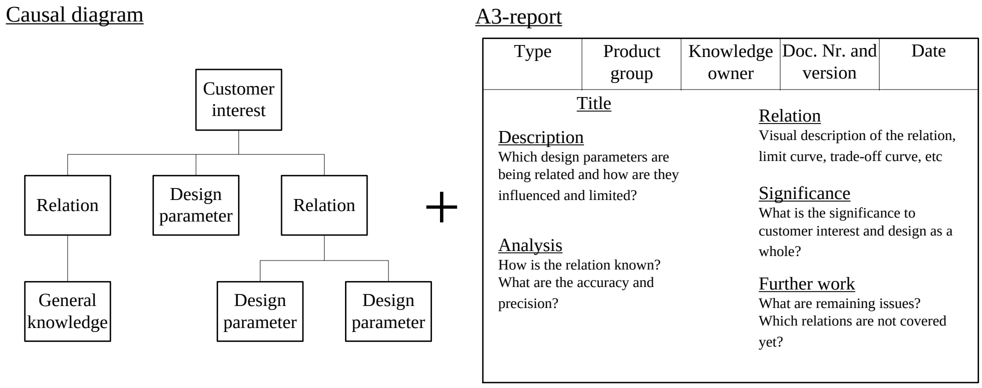


Figure 4-6: Causal diagram and A3-reports in for the declarative knowledge standard

The strategy for the declarative knowledge standard was implemented by combining A3-documentation and causal diagrams (Figure 4-6**)**. The A3-reports are linked to the causal diagram. Both the causal elements and the A3-reports are categorized equally into customer interests, relationships, design parameters, and general knowledge. Knowledge artifacts (A3-reports) and elements in the causal diagram have a one-to-one relation, which enables each knowledge artifact to be represented in its causal interrelation. The implementation strategy is based on a standardization of problem-solving A3-reports in the project of knowledge owners. The tasks of the knowledge owner are to assure the documentation quality and maintain a certain number of standardized A3-reports. Thus, the combination of causal diagrams and standardized A3-reports forms the knowledge standard, where the A3-report describes the content of a certain knowledge artifact and the causal diagram assigns it according to its causal context.

### *4.5.2.3 Proposed integrated approach*

A weakness of the causal diagram is that it less flexible towards changes other than the modular product architecture and upgrades. In addition, a weakness of the pure structural knowledge standard is that it does not consider the knowledge content. Thus, a modular product architecture as a structural base for interrelating the declarative A3-reports has been proposed for an integrated model (Figure 4-7).

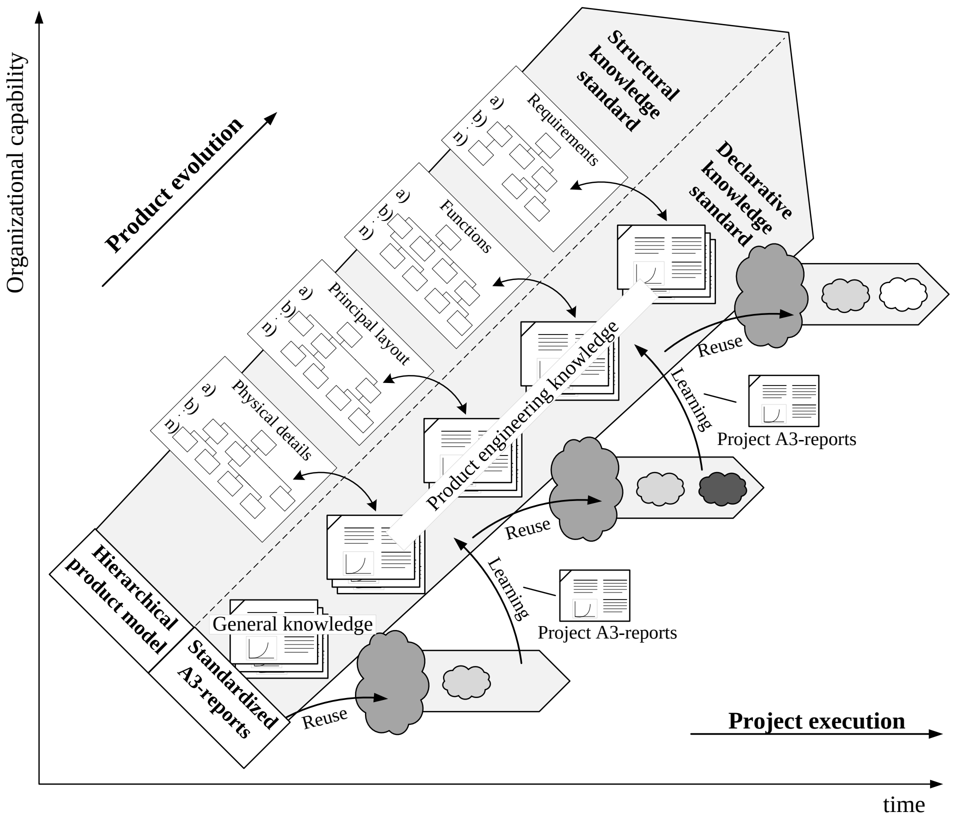


Figure 4-7: Integration of examined approaches

The structural part consists of a hierarchic product model with a modular product architecture entailing a requirement, functions, principal layout and physical details layer. All layers can be decomposed in sub-systems, sub-functions, etc., and be interconnected both within and between the layers. The main contents of the declarative standard are standardized A3-reports. They are linked to the structural elements in in each structural layer. Thus, the A3-reposts need to be classified into different A3-types according to the architectural layers and the interrelations or design decisions at nodes in the structure. When the A3-reports are linked to the modular product architecture, they can get a modular character as 'knowledge-artifact modules', which can be changed and upgraded in the structure, independently of the rest. In addition, A3 reports for general knowledge are necessary; ones that are independent of the structure.

In the project execution phase the knowledge standard serves as knowledge base, where the structure helps to find the desired information and the A3-reports provide a fast and clear overview of the specific content. By solving new problems and developing new knowledge in the project execution, the standard can be upgraded.

# 5 Conclusions and suggestions for further work

## 5.1 Overall conclusions

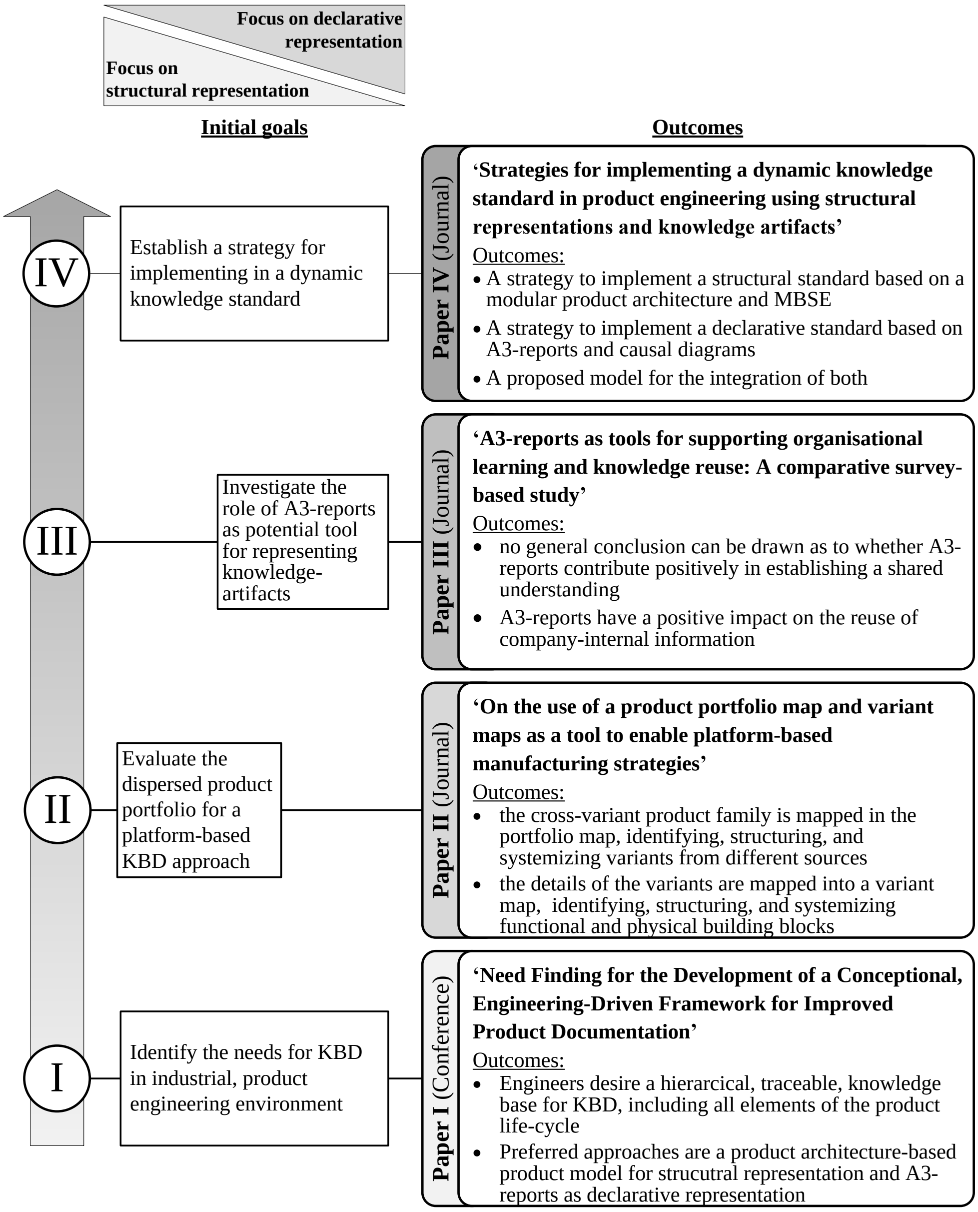


Figure 5-1: Overview of the overall outcomes

The overall goal of this thesis was to investigate the deployment of strategies, tools and methodologies to capture, structure, and utilize valuable product engineering knowledge in order to establish a framework for implementing the strategic, knowledge-based approach. Following the overall implementation strategy in Figure 1-3, outcomes for the different steps have been developed in the learning cycles with the specific goals and objectives in the Papers I-IV. Figure 5-1 presents an overview of the outcomes related to the initial goals. It closes the loop in relation to Figure 1-4, presenting the inputs of this research.

In particular, the following outcomes have been achieved in investigating strategies, tools and methodologies to capture, structure, and utilize valuable product engineering knowledge.

**Paper I** explores the current knowledge transformation practices in the case companies and reveled the needs for an engineering-driven KBD framework. The identified situation is similar to the situation described by other researchers (Bradfield and Gao 2007; Ben-Arieh, Easton, and Choubey 2009; Agard and Bassetto 2012; Shankar *et al.* 2012). It shows that engineering companies that develop advanced products in multi-disciplinary new product development (NPD) teams, have difficulties in managing, communicating, and (re)using knowledge in and between NPD projects. Further, it reveals that engineers desire a hierarchic, traceable knowledge base for KBD.

**Paper II** investigates methodologies for evaluating the dispersed product portfolio in a project-based NPD environment. The product mapping methodology, consisting of a portfolio map and a variant map, provides a practical and qualitative way of transforming fragmented product variant information into visual overviews, making it clearer and thus revealing and unifying data from spread sources. The example of the POC demonstrator has shown the ability of the methodology to map the dispersed product portfolio. On base of the maps, a modular product architecture and product platform may be evaluated and developed. For the latter, many methods are described in literature (Gershenson, Prasad, and Zhang 2003; Jiao, Simpson, and Siddique 2007).

**Paper III** investigates the role of A3-reports in KBD. The A3-reports turn out to be suitable knowledge artifacts for increasing reuse of information, but no evidence as to whether they can improve a shared understanding could be measured.

**Paper IV** intends to establish a strategy for implementing a dynamic knowledge standard. The outcomes are a strategy to develop structural standard based on a modular architecture and MBSE, as well as a strategy to develop a declarative standard based on A3-reports and causal diagrams. The final proposal is a model for product evolution that integrates the modular product architecture and A3-reports. Collectively, they may serve as dynamic knowledge standard of a company.

## 5.2 Suggestions for further work

The research areas of KBD are vast and hold many potential areas for future work. This section seeks to highlight a few potential areas in the establishment of a framework for implementing the strategic, knowledge-based approach for NPD. Regarding the case studies a concern is to provide stronger evidence for introduced approaches for a more solid validation.

Paper IV closes with the proposal of a model for an integrated structural and declarative approach (Figure 4-7). The knowledge strategies introduced in this paper are limited to the establishment of different standards and do not contain strong evidences for how to maintain and evolve them. Hence, the implementation of the proposed integrated standard as well as maintaining and evolving it remain issues for further exploration.

Another concern for further work is that A3-reports may not be suitable as the single tool for documenting knowledge artifacts. In some cases, A3-reports may be too compact to document a complex task. In addition, customers or governmental institutions may require detailed reports. In other cases, the use of A3-reports may be too extensive. Thus, there may be a need for other (standardizable) knowledge artifact types, both for long reports and brief memos.

An additional concern suggest for further work is studying inhibitors for an information overflow. Routines to keep the structures simple and to limit the content to the subjects that are considered most relevant need to be explored.

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# Appendix A – Main papers

# Paper I

## Need Finding for the Development of a Conceptional, Engineering- Driven Framework for Improved Product Documentation

Sören Ulonska and Torgeir Welo
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# Need Finding for the Development of a Conceptional, Engineering-Driven Framework for Improved Product Documentation

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**Abstract**

Engineering companies that develop advanced products in multi-disciplinary new product development (NPD) teams, have difficulties in managing, communicating, and (re)using knowledge in and between NPD projects. Information is lost due to team dynamics, inappropriate documentation and methods, resulting in unnecessary design iterations, repeated problem-solving, lack of effectiveness and value, and low financial performance. It is, therefore, desirable to develop a documentation model that can be integrated into different engineering processes and used to effectively communicate product information within a single project and between projects, combining strategies from product design methodology, model-based systems engineering, and lean development. It is necessary to combine the most recent product (systems) engineering methods with the understanding of problems and needs in industrial environments where they shall be applied. This paper presents results of need finding in four companies using a semi-structured interview approach to gain insight into problems associated with product documentation. The findings are turned into a conceptual engineering-driven product documentation framework, which links documentation to the product architecture using knowledge-brief (A3) type documentation strategies from lean execution environments.
*Keywords*: Model-Based Systems Engineering; Lean; Knowledge Capture and Re-use; Industry Study; Project Communication

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## 1. Introduction

Nowadays, engineering companies operate more and more globally in increasingly competitive markets. Outsourcing of production and algorithmic engineering tasks [1] 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. Companies need to launch new products earlier than their competitors—before new technology emerges or the market changes. Increasing complexity and multi-disciplinarity of products, in combination with increasing need for effective, fast, and lean development, make it necessary to establish a broad knowledge-base for engineers [2]. A knowledge-base is essential for (lean) development and continuous improvement, decision support, and risk mitigation. It reduces dependencies of knowledge and experiences of individuals, making knowledge an asset within the company. Tools for knowledge creation, storage, transfer, and application will aid the analysis, optimization, and combination of solutions, requiring engineers to coordinate the inputs from many specialists in advanced, multi-disciplinary projects.
Experiences from industry companies (as to be seen in a case study in this paper) show that engineers have difficulties to manage, communicate, and (re)use knowledge in and within new product development (NPD) projects. Apparently, PDM/PLM tools do not support the process of knowledge capturing, reuse well enough. Much knowledge is generated in product development (PD), but it is challenging to capture and reuse this knowledge, leading to increased costs, lead time, and resources for repeated problem solving due to a lack of organizational learning as illustrated in Fig.1. Each segment symbolizes one development project or PD generation. With a new segment a new project generation begins. Although teams in both organizations work with same efficiency (same gradient of the segment), the one without capability to transfer knowledge between generations ('DNA') achieves a significantly lower level of capability over time. Knowledge serves as a source for competitive advantage when it can be used in a way that increases effectiveness [3].

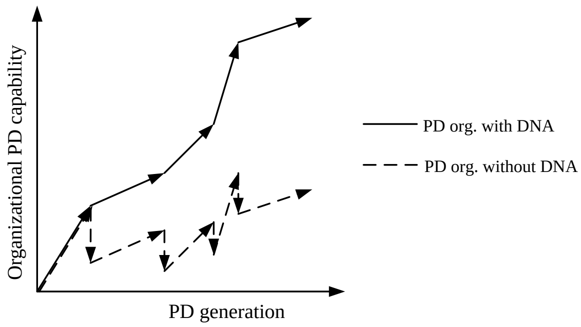


Fig. 1. The role of documentation as DNA in Product Development

PD, Systems Engineering (SE) and Lean Product Development (LPD) are different approaches that provide engineers with methodologies and guidelines to help develop products (considering organizational challenges). To address challenges of modern, competitive product engineering, a combination of all three disciplines is necessary to develop advanced high-technology products, including creativity, lean practices, and systematic risk mitigation on component and system level. Thus, all of them need to be considered for providing an effective approach for knowledge-based development (KBD). It is assumed that today's systems and routines to document and reuse knowledge are not satisfactory for many organizations. Knowledge stays with individuals (tacit knowledge [4]) and not within the company as such, leading to repeated problem-solving and lack of organizational effectiveness.

In the present paper, a conceptual framework for a KBD documentation model for making knowledge re-use in engineering easier—in and within NPD projects—will be proposed. Although PLM/PDM systems are used and organizational routines are defined, important knowledge is not transferred in an adequate way. Knowledge is often kept 'tacit' by individuals or stored in reports that are project specific. The framework shall build a base to solve this challenge, by making product and knowledge structuring more engineering-friendly. To relate the findings in the literature to experiences from industrial practice, semi-structured interviews have been conducted with 21 engineering experts from four high-technology companies in the industrial cluster Kongsberg, Norway, combining two sources of knowledge on today's documentation and communication practices and identifying possibilities for improvements. More specifically, a brief review of PD, LPD and SE literature, combined with results from semi-structured interviews, build a basis for developing a framework enabling better knowledge transfer. The documentation framework proposed is an engineering-focused way of documenting product information, ensuring continuous capture and reuse of knowledge and easily accessible, structured documentation. The focus is on the technical aspects (product engineering) of the three methodologies. The goal of this paper is to explore needs for such a knowledge-based framework for PD, one that would possibly enable 'genes' to be transmitted and evolved between 'project generations'. As a starting point, it was decided to establish a set of research questions in order to understand today's situation as a basis for development of a suitable approach:

- How, and to what extent, do engineers and engineering companies capture, store and reuse (individual and organizational) knowledge in and within product development projects?
- How, and to what extent, do engineering companies structure their product development ideas and what is the basis for decisions undertaken?
- How can knowledge be documented to make it more traceable and understandable as well as accessible for engineers working in multi-disciplinary product development projects?

## 2. The Nature of Knowledge and Knowledge Management

Before the framework for a knowledge base is introduced, a short discussion around the nature of 'knowledge' and 'knowledge management' (KM) will be made. These topics are important to keep in mind when aiming to create a framework for KBD. When defining knowledge, one has to distinguish between data, information, and knowledge. Data is raw numbers and facts, information is processed data, and knowledge is authenticated information [5]. Another definition describes knowledge as 'understanding gained through experience' and is the sum of what has been perceived, discovered, or learnt [6]. Other references have other definitions of knowledge or knowledge perspectives, such as knowledge as a state of mind, object, process, capability, etc. However, all definitions have in common the fact that knowledge is individual and must be expressed in such a manner that it is interpretable by the receivers. Only information that can be actively processed in the mind of an individual—through a process of reflection, enlightment, and learning—can be useful [4]. Knowledge is not just content or structure of information, but it is possessed in the mind of individuals—the product engineers in the case of this paper. Thus, engineering team members should share a certain knowledge base to have the same view and same understanding of a problem [4].

One challenge associated with knowledge capture, storage, retrieval, and transfer is that knowledge is explicated in two dimensions: tacit and explicit [7]. Tacit knowledge includes an individual's belief, viewpoint, paradigm, or concrete know-how, craft, and skill. Explicit knowledge, on the other hand is, articulated and communicated between individuals. One could assume that tacit knowledge is more valuable than explicit knowledge due to the fact that not all tacit knowledge can be transferred into explicit knowledge in an adequate way, meaning that the probability of having knowledge gaps and losses is high. Nevertheless, explicit knowledge is important, too, since it can extend an individual's tacit knowledge. Only explicit knowledge can be transferred and retrieved, such that both dimensions are essential [4] for true knowledge exchange.

Considering a knowledge system, it should be kept in mind that there are challenges regarding the possibility to renew products. When the context of knowledge changes (e.g. new product requirements or technological progress) the usefulness of the captured knowledge decreases [8]. Knowledge is always a reflection of the past whereas products are developed for the future. Failing to adapt the dynamics of knowledge might end up harmful for an organization, and too much reuse of knowledge might even be a barrier for change and innovation. The amount of novelty introduced between knowledge storage and retrieval is therefore a core integration challenge [6]. Furthermore, companies that seek high novelty in NPD, where the potential for reuse is limited, might not gain significant benefits from knowledge capture and waste resources on capturing knowledge that they do not need anymore. A high amount of specialists and dependencies could also be a barrier, since every specialization field uses its own terminology. A common understanding of knowledge, including both generic and specialist knowledge, is therefore necessary for the success of a common knowledge-base. Finally, too much reuse of knowledge can result in dependence of old/traditional solutions, making engineers thinking 'inside the box' with a strong tendency to solve engineering problems the same way it has always been done.

According to Davenport and Prusak [10] the majority of KM projects have the aims (1) to make the knowledge visible and show its role in the organization, (2) to develop a knowledge-intensive culture (e.g. encourage knowledge sharing) and (3) to build a knowledge infrastructure. This paper focuses on the latter topic and will propose a structure for knowledge capturing that is related to engineering design methodologies which are known to most engineers. Knowledge is going to be linked to the product architecture, aiming to make it visible, and easily accessible, using the same structure as the product architecture. In summary, four basic processes are essential for a KM system [4]: *Knowledge creation* (requiring an organizational culture), *knowledge storage/retrieval* (requiring dynamic and updated systems), *knowledge transfer* (requiring adequate searching functions), and *knowledge application* (requiring the ability to turn knowledge into effective action).

## 3. Some Definitions of Product Development (PD), Lean PD and Systems Engineering

The goal of a PD methodology is to provide guidance to engineers for how to develop, engineer and design a high-quality technical product. The methodology supports the engineering design process, while allowing for flexibility, creativity and variety at the same time [2]. Many different systematic engineering design and development approaches exist, such as Pahl and Beitz [2], Roth [11], Hubka [12], Ehrlenspiel [13], and many more. Despite the fact that many methods are influenced by their engineering field of consideration, there is a common ground beyond all. A guideline that includes the commonalities for a systematic design approach of technical products and systems is VDI 2221 [14]. It recommends a number of working steps to design a successful product. PD begins with a clear definition of the task and continues with abstracting the problem by establishing functional structures, diverging in the number of solution possibilities as principal solutions. After a number of evaluations, the process converges and a product is designed in details and developed. Important outcomes are the specification list, function structure, principal solution, product structure and architecture, and the detailed solution.

SE is an approach that solves problems of increasing product complexity and multi-disciplinarity with the goal to meet the user needs and mitigate risks by supporting all product life cycle processes, considering problems on system level [15]. ISO/IEC 15288 [16] defines the system life cycle processes, related activities, and outcomes for the complete life cycle, including development, realization, utilization, support and retirement. SE activities can be applied in a visual manner using model-based SE (MBSE) [17]. MBSE is an attempt to standardize the SE effort by developing a technique for documenting it through models, diagrams and hierarchies that follow strict rules. Requirements, functions, system architecture, and verification and validation activities all are mapped graphically, for instance by using a general system modeling language (SysML).

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 [18]. 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 (LAMDA cycle [19]) in small steps. Although these learning iterations could be considered waste (type 1: necessary waste like organizational learning, organization, etc.) 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 for organizational learning, providing strategic value for the company [19]. In the LPD philosophy, knowledge is effectively captured and communicated using 'knowledge-briefs' [20], or so-called A3 reports [21] named by the paper size format used, aiming to visualize the problem, goal, process, and solution, and risk elements in a standardized form, depending on the application and problem formulation.

In summary, PD methods offer possibilities to systematically develop and design new products, providing engineering tools for developing high-quality products at micro-process level. SE methods enable the possibility to maintain overview, to realize complex products, and systematically mitigate risks in PD and product management (PM). Rather than providing guidance for solving engineering problems in PD, it helps manage a large variety of complex products at system level, creating a better overview of the product and its surroundings. Risks become more apparent and a broader view of all life cycle processes reduces uncertainty in decision-making. LPD introduces a way to make (engineering) processes more effective to improve the outcome for a company with customer value being the driver. It describes, in more philosophical terms [22], how processes at different levels can be performed to make a company more competitive by pulling 'value' from the end customer up the value chain.

PD, SE, and LPD have different goals, but they can be applied to the same problem at the same time, and are hence complementary to each other. PD and SE can be applied on top of a 'lean' philosophy as a fundament in the value hierarchy to increase effectiveness and reduce waste in PD (e.g., lean principles introduced by Morgan and Liker [23]) and SE (e.g., 'lean enablers for systems engineering' (LEfSE) introduced by Oppenheim [24, 25]). A combination of all approaches can become a powerful engineering tool for industry companies producing complex, high-technology products. The knowledge base proposed later in this paper uses elements of these disciplines. The review of the literature in this chapter together with the semi-structured interviews, to be introduced in the next chapter, build the base for a model-based documentation, including both theoretical and practical aspects.

## 4. Case study at industry companies in Norway

In the above sections a literature review of knowledge associated with PD, SE, and LPD has been conducted. This will now be supplemented with experiences from industry practices through a case study done with a set of companies that develop advanced, technical products in multi-disciplinary teams. In general terms, engineers have discovered that they spend much time on (re)solving engineering problems and feel that knowledge transfer and reuse are poor. The storage of knowledge in project specific structures makes it difficult to find product knowledge in existing company systems and knowledge is often kept 'tacit'. Product engineers, trying to apply lean and SE principles, suggest that the companies' PD capability could be more effective if adequate tools to capture and (re)use knowledge had existed.

Table 1. Overview of interviewed companies

| | *Products* | *Scope* | *Products per year* | *Employees* | *Interviewee roles/Positions* |
|---|---|---|---|---|---|
| A | Automotive parts, e.g. driveline systems, seat comfort systems, driver and motion control systems, fluid assemblies | Global production and development locations | 50,000 to several millions | 10,000 | • Research and Design Manager<br>• Designer<br>• Program Manager |
| B | Defense, space and aerospace products, e.g. missiles | National locations, global customers | 100 | 450 | • Lean Manager,<br>• Senior project engineer(2x)<br>• PA/QA chief engineer<br>Department Manager Elect. & Mech.<br>• Department Manager, Flight structures<br>• Safety Leader<br>• Project leader<br>• Production chief engineer<br>• Clean room leader |
| C | Subsea products for petroleum industry | Global production and development locations | 2-6 of one kind<br>(ca 100 a year) | 11,500 | • Specialist engineer, Design<br>• Lead engineer<br>• Work Package Product Manager<br>• Senior Product engineer Design<br>• Senior Quality manager |
| D | Development of advanced multi-disciplinary products | National locations, global customers | 1 to several millions<br>(project dependent) | 100 | • Deputy Mechanical Systems Development<br>• Senior engineer ,Electronics<br>• Project Manager<br>• Production & Test Manager<br>• Group leader, Systems |

To explore the root causes of these problems and to determine current practices with regard to knowledge processes, a case study among four Norwegian companies has been conducted, interviewing 21 engineers. The companies represent different industry sectors (offshore , automotive, defense and aerospace, and consultancy and system development). Table 1 shows an overview of the four companies, including products, number of employees, production numbers, and interviewee roles. Although all four companies develop advanced products, there are major differences between the companies, as illustrated in Fig. 2. The principal diagram arranges the companies according to their relative project (value related to uniqueness of outcome) and process (value related to consistency of outcome) focus. The companies represent a variety of organizational focus that cover a wide spectrum from process and mass-production-orientated firms to entrepreneurial focused firms, and firms developing ‘one-of-a-kind’ products. Company A is an automotive Tier 1 supplier, producing parts at high volumes and a PD process of repetitive nature, resembling somewhat manufacturing. Towards the right side of the diagram, the PD process orientation is decreasing, while focusing more on uniqueness (project type activities). Company B develops and produces high-technology defense, space and aerospace products (e.g. missiles). Company C is a supplier for the offshore industries with special expertise in subsea installations. The PD strategy in company A is in big contrast to that of company D, which has its focus on uniqueness and performing PD projects for customers. Company D designs advanced products of different kinds, whereas manufacturing is done by other companies. Its main competence is project and engineering management. The strategy is to avoid product ownership, and products can be designed for mass, medium or single production. All four companies operate globally; some with different locations for development and production, and some with national locations, and international customers.

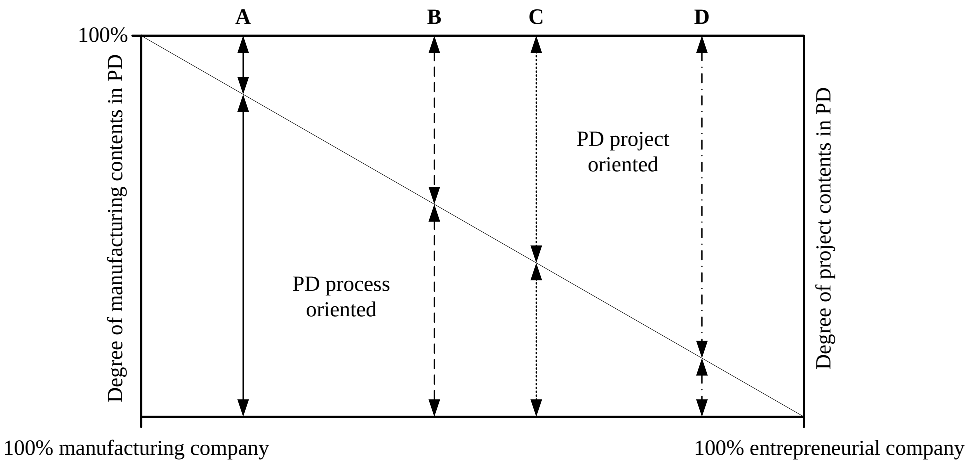


Fig. 2. Arrangement of engineering companies according to their degree of manufacturing content vs. entrepreneurial content DNA in PD

Table 1 and Fig. 2 illustrate that there are significant differences in product types, production number, and company strategies between the four companies. Hence, it is difficult to establish a common methodology to improve documentation in all four companies. Due to various fields of specialization, experience, working area, and low number of interviewees, it was essential to use semi-structured interviews [26] rather than standardized interview

schedules. This gives the opportunity to better explore the respondents' opinions and clarify interesting and relevant issues for establishing more complete information.
At each company, engineers with different functional roles have been interviewed, including PM, PD, CAD design, manufacturing, and departments, as listed in Table 1. One challenge was that the number and roles of the interviewee were somewhat different, both in terms of availability and role definitions in the different companies. Nevertheless, altogether 21 engineers with different viewpoints have been interviewed, and different needs on products and projects, PD, and product production were ultimately collected. All interviewees were asked the same set of questions (referring to the general research questions above):

- How are projects organized and executed?
- How is product related knowledge documented and stored and to what extent is product knowledge reused?
- How is communication organized and done within and between projects?
- What are your personal experiences in reusing documentation created by others?
- How well do (stipulated) documentation and communication strategies work in your company?
- What would you improve according the items identified above, and how?

## 5. Findings and propositions

The results of the semi-structured interviews and literature review will be summarized in a set of propositions. There are three key aspects related to KBD, including *PD*, *Project Communication*, and *Product Documentation*.

### *5.1. Product Development Propositions*

- *The traceability of product development history makes it easy to understand the product:*

The interviewees pointed out that it is difficult to find out why products have been designed the way they have. For example, company B's products have a service time of up to 40 years. Decisions in development, which have been taken in the past, were taken from the past's point of view and state-of-the-art at that time. For today's engineers, this is difficult to understand. Hence, sometimes they have to solve problems, which already have been solved in the past. A knowledge-based product model would provide them with a tool to identify decisions points, documenting why the product was developed the way it is, seeing dependencies and being able to adapt those decisions to today's circumstances. Technological progress is continuous, governmental regulations change and customer needs change, too. By providing improved possibilities to adapt former product design decisions to conditions of the present, the development would be more sustainable in itself. In addition, the change of sub-systems would be easier, since dependencies are clearly defined, visible and understood.

- *Adequate product documentation in a knowledge-based product model can improve PD and make it easier to meet the project schedule:*

In a knowledge-based product model, decisions are traceable to the solutions applied in the final product or to those that were considered but did not make it all the way to implementation, meaning that the knowledge around the product grows steadily. This will have a positive impact on PD, since risks are reduced and the whole product life cycle becomes more predictable. For instance, company C uses much time (more than spent on

PD) on documenting products due to rigid customer requirements. Notwithstanding, their products are in many cases similar to a great extend, and a better reuse of documentation would considerably reduce work-load. As an alternative, resources could have been used for creating new values by improving the product or new innovations.

- *Companies with repeated, incremental PD processes can gain more from a knowledge-based product model, than do companies conducting more independent projects:*

Comparing the companies, obviously, there are differences in the way the companies could gain from KBD. Company D develops many different products on order and does not have own physical products that they manufacture or own; their 'product' is the information output from the product development process . Hence, it will be difficult to reuse specific knowledge between projects, since products are very different. They have thus to establish a reuse-strategy at a different level; for example, process and/or disciplinary/function levels). The other three companies, which mainly improve product platforms or develop new products within the same field, have ability to reuse more knowledge at product level that could be linked up to a hierarchical product model.

- *Product documentation should have a hierarchical structure, which is equivalent to the structures used in PD:*

There are four levels of information, which are necessary for product information and documentation [27]. The level of product information, the requirement structure, defines *why* the product is developed, captures the customer needs and enterprise's objectives. Second, the functional structure, describes *what* the solution is going to do, followed by the principal structure, which defines *how* functions are accomplished. Last, the physical parts build a physical structure, which represents the product with detailed descriptions, so that the product can be manufactured, distributed and made available for the user. A knowledge documentation linked to these PD levels and close to the product architecture [28] would bring the documentation closer to engineering practices.

- *Background knowledge is necessary to supply product development with necessary information:*

A common base to which a product is developed is necessary. Design iterations in development are done due to lack of knowledge [23]. More detailed information about the task, constraints, potential and known principal solution for similar type or former problems, reduces the uncertainties and confrontation to the unknown and risks [2, 11], and might increase confidence in the chosen solution. The knowledge, which is gained by iteration steps, may have value for later developments. Therefore, a fifth information level, the background information, should be introduced. It supports the other four levels. That may for instance be physical dependencies or constraints of production methods, and also literature, standards or governmental regulations.

### *5.2. Project Communication Propositions*

- *When product information is linked to the product model, it will be easier to make engineers follow a certain discipline in PD and documentation:*

Multi-disciplinary engineering projects can last over many years and involve many people (company B). To keep the documentation and communication at the same level of understanding, everyone in the projects should use the same method and discipline for documenting knowledge (company D). Due to the different background of individuals, this is not always the case as different people use different ways to document their work. Linking knowledge to the product model, the documentation structure would be dictated by the product, and not by the person who created the documentation.

- *Restrictions constrain knowledge transfer:*

Due to restrictions from stakeholders or government, it is not allowed to share all knowledge (company B). Here, some product knowledge cannot be reused in other projects. Knowledge, which has been developed here, will be challenging to make accessible for NPDs.

*5.3. Product Documentation Propositions*

- *Clear documentation of product knowledge in a hierarchical product model can replace the confusing variety of documentation between projects to a great extent:*

Today different types of documentation are used in different projects on the same product, which sometimes makes it difficult to find specific information. If all the knowledge instead would be collected at one single platform and linked to the product architecture, less variants of documentation would be necessary. In this connection it should be noted, however, that there will still be need for other types of documentation, e.g. customer specific reports.

- *The use of A3 documentation makes knowledge clear, fast and easy understandable:*

Company A uses an ‘A3-knowledge brief’, based on the lean principle ‘A3 thinking’ [21]. The documentation in A3 format is short, precise and describes just one problem and its solution on a single sheet of paper. This makes it fast and easy to read and capture. A3 sheets that are linked to each other in a hierarchical structure can make it possible to quickly understand a product, complex problems and interrelations. Nevertheless, A3 documentation cannot fully replace full reports; however, what is important in PD is to identify and understand in a rapid fashion). Thus, A3-thinking seems to be a proper approach also for documentation practices.

- *Storage of knowledge at just one central place makes it easier to find and store:*

Knowledge is usually not directed to the product, but to the project such that engineers have to know the project in which the product has been developed. Consequently, it will be difficult and time-consuming to find the desired knowledge. In addition, there are several formats of documentation, such as product models in CAx software, reports, A3s, quality assurance reports, etc., which makes it even more difficult to find specific information. Hence, engineers often prefer to solve problems at their own instead of spending time on finding solutions that have already been developed by others. A single central place, or less places, for storage and a search engine that finds documentation from different projects would improve the possibility to find knowledge in a multi-project environment. One possibility could be an internal wiki, providing that there are procedures in place for quality assurance of information that is shared with others.

*5.4. Summary*

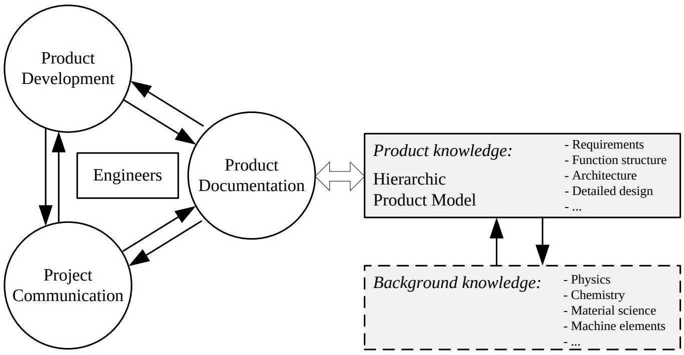


Fig. 3: Conceptual framework for technical view of knowledge-based product development

As a result of the propositions introduced above, Fig. 3 shows a conceptual framework for KBD as an engineering-friendly way for product documentation and communication. In the centre of all actions are the engineers (since this paper concentrated mainly on the technical aspects associated with the PD process), who develop solutions, communicate, document results, and reuse knowledge from former documentation. From the analysis of product development methodology, four central levels [27] (requirements, functions, principal solution, and details) of documentation are identified to be important. The documentation is A3-based, hierarchically structured, and linked to the product architecture. A3-based documentation is a structured, 'lean' method to capture knowledge and documenting learning, decisions, and planning, associated with problem-solving. In the documentation framework, all levels are hierarchical and linked to each other as well as supported by background information. The three activities product development, project communication and product documentation are not independent of each other, but need to be done concurrently to achieve a successful KBD.

## 6. Conclusions

Based on the results in this paper, which were obtained by combining a literature review with findings of semi-structured interviews, it is concluded that product information should be linked to the product architecture to make it become a proper fundament for KBD. The product architecture should be structured according to the steps of systematic engineering design processes, including the levels of requirements, functions, principal solution and detailed solution and their linkages (Fig. 4). All aspects of the life cycle need to be included in the development, by providing detailed knowledge collected from former projects, experiences, literature, and other internal and external sources. The model structure needs to be flexible to facilitate adaption to constraint dynamics imposed from the surrounding. In conclusion, the product model should describe a holistic system, integrating all life cycle phases, showing dependencies between sub-systems, hence making it possible to quickly understand a product from different perspectives.

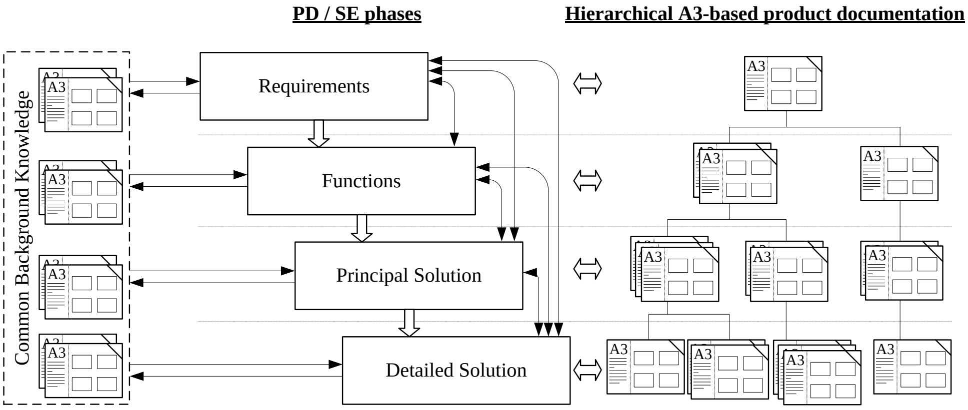


Fig. 4: A3-based, hierarchic product model

Many of these functions are provided by PLM systems, but just copying existing products into PLM systems does neither improve their structure nor support KBD. For many companies, product structures in PLM systems need to be reconfigured to clean up variants that have been developed over many years and been copied into the PLM system without systematic approach. Thus, a clear product portfolio that evolves out of a robust product and knowledge architecture needs to be established, e.g. by re-engineering/re-structuring exiting products. Leveraging visualization and A3-based documentation structured like the product architecture shown to the right side of Fig. 4, will make it easier to both identify and capture information as well as understand it. The use of visualization on physical planning and development boards adds an additional dimension of communication, which can support more abstract PLM systems and provide a base for KBD.

The propositions established herein form the basis for further research in developing methodologies for appropriate documentation that describes a product including its variants, its dependencies of the system, its design history and decisions made during the course of development, along with its technical attributes in an easy, clear, traceable, extendable, and changeable way. A further challenge will be to develop a strategy for integration of an existing product portfolio and a product architecture. When developing a product architecture, with the knowledge aspect linked to it, it should be kept in mind that the architecture will last longer than the product. Therefore, it should be flexible enough to allow the product to evolve to changes in its surrounding [28].

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# Paper II

## On the use of a product portfolio map and variant maps as a tool to enable platform-based manufacturing strategies

Sören Ulonska and Torgeir Welo
Submitted to a journal

Is not included due to copyright

# Paper III

## A3-reports as tools for supporting organisational learning and knowledge reuse: A comparative survey-based study

Sören Ulonska and Torgeir Welo
Submitted to a journal

Is not included due to copyright

# Paper IV

## Strategies for implementing a dynamic knowledge standard in product engineering using structural representations and knowledge artifacts

Sören Ulonska and Torgeir Welo
Submitted to a journal

Is not included due to copyright

# Appendix B – Supplementary papers

# Paper V

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

Sören Ulonska and Torgeir Welo
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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.

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 3.** 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 4.** Lean Elements in Traditional Product Development Methodology
(Legend: - not mentioned; (x) implicitly mentioned; x mentioned)

| **Lean Principle** | **Roden -acker** | **Tjalve** | **Pahl, Beitz** | **Roth** | **Ehrlen -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.

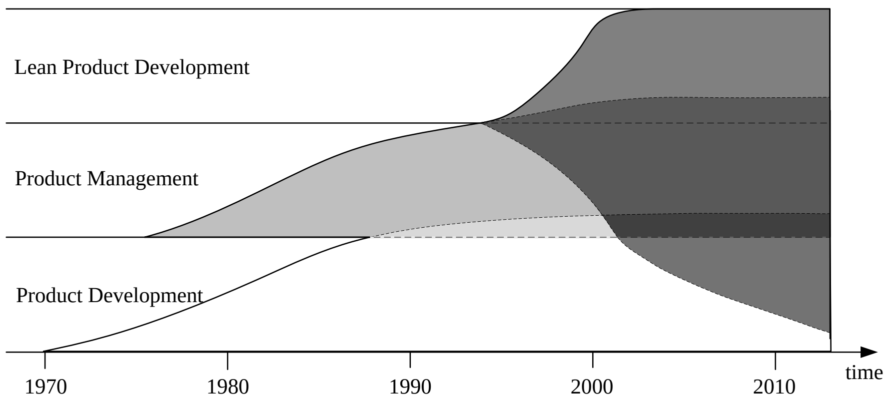


**Fig 2.** Development of traditional PD, PM and LPD literature

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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# Paper VI

## Keep Systems Engineering Simple to Get the Job Done

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Presented at 23rd Annual INCOSE International Symposium in Philadelphia 2013.

# Keep Systems Engineering Simple to Get the Job Done

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**Abstract.** This paper is a continuation of the reporting on the result of the application of systems engineering and (lean) product development techniques in a student team. The project setting is Trondheim, where the multidisciplinary student team (their two systems engineers are co-authors) designed and produced a car to compete in Shell Eco Marathon. The paper introduces approaches and discusses the effects of the student team applying SE in a simple way, using visual planning, modeling, and knowledge briefs of lean product development. The paper includes examples of work-break down structure, A3-documentation, computer-based models, and visual planning, as well as experiences with effective knowledge capture and exchange based on knowledge briefs and the systems architecture. The conclusion is that keeping SE simple and visual helps to motivate team members and makes product development and knowledge exchange between team generations more efficient.

## Introduction

Shell Eco-Marathon (SEM) is a worldwide competition that challenges student teams to design, build and test energy-efficient vehicles. The competitive element is the car’s energy consumption converted into gas mileage measured in petrol equivalents (km/l), where the winner in each class is the team that goes the furthest using the least amount of energy (Shell 2012). The competition is arranged once a year, always with slightly different requirements to make the teams improve and adjust their cars.

The Norwegian University of Science and Technology (NTNU) has participated in the urban-concept-class in SEM Europe since 2008. The student teams have experienced several high moments but also a few low ones. The 2009 team set a track record of 1246 km/l in the Urban Concepts class using a hydrogen-powered vehicle. Unfortunately, the following year (2010), the car did not make it to the starting line. Individual technical components all worked in 2010, but the system as a whole failed due to a lack of time for integration and testing. Technical problems were identified too late in development, causing design rework, corner cutting, reactive problem-solving and ultimately a less-than-optimal product that lacked the desired robustness. To avoid such situations for the future the team realized that they needed a systems engineer to ensure the car's performance on a system level and to manage the technical development so that the car was ready according the time-schedule. Benefits of using systems engineering were visibly apparent after a systems engineer was added to 2011's team and the car finished second in the same class as before (Haskins and Welland 2012).

Each year, the development team is composed of a multidisciplinary group, including students with backgrounds in mechanical engineering, electrical engineering, cybernetics, and media. The team of master students is completely replaced by new students once a year. The student project is divided into two phases covering activities for the fall semester and spring semester. Typically, the fall semester is spent doing concept exploration, evaluation and design of solutions as a part of a mandatory project course at NTNU. The following spring semester is spent producing the car, followed by verification, validation and testing as a part of their MSc thesis. The subsystems are designed and developed concurrently. For example, the process of integrating body and motor involves numerous iterations to result in an overall good quality product. Production is also done in parallel, providing subsystems finishing at approximately the same time. The final activity is attending the race and delivering master theses.


Figure 1: NTNU's Shell Eco Marathon team and car at the competition in 2012

In this way the project is nearly continuous, as the car and developed knowledge is transferred from one team generation to the next. Development cycles follow mainly the principle of continuous improvement (Morgan and Liker 2006). However, in 2012, the requirements changed so dramatically that the team moved from continuous improvement to new product development (NPD). They entered the competition with a car that was basically similar to former cars, but actually required new development and production of (nearly) all components, sub-systems, etc. This paper presents the results of the work done to field a car for the 2012 race, based on the final master's thesis written by the two systems engineers on the project; Itxaso Yuguero-Garmendia (SE1) (Yuguero-Garmendia 2012) and Oluf Roar Tonning (SE2) (Tonning 2012). Figure 1 shows the team photo taken at the race site in Rotterdam, NL.

## Background

Since 2011 the NTNU SEM project team has included a systems engineer. Challenges for the first systems engineer in 2011 were mainly the need for careful planning to reduce the risk while modifying the car, by coordinating team efforts and organizing the integration testing (Haskins and Welland 2012).

For the 2012 competition, technical reasons motivated the NTNU team to change the category of class in which to compete. The so-called Battery-Electric class is more competitive and prestigious than the hydrogen-class (fuel cell) in which the previous teams had competed. They selected Lithium-ion batteries as the energy source. When the rules from Shell also changed the race from a track to road-based competition, the SEM2012 team faced the challenge of designing and building an-all new vehicle, dubbed the DNV Fuel Fighter 2 (DNVFF2).

Building a car from scratch is a challenge that no team after the SEM2008 team had attempted. This challenge incurred much higher technical risk as compared to improving an existing vehicle. In addition, extending the size of the team to 14 people (previously 6), from different engineering disciplines for the new concept, represents a considerable managerial risk. Fortunately, two students were willing to accept the role of systems engineer to help the team meet these challenges. They split the responsibility by SE1 focusing on verification, validation, and testing, and SE2, on implementation of lean systems engineering with particular focus on simplicity in documentation and use of visualization techniques, including computer-based modeling, both to provide the team a good project and product overview and for the up-coming knowledge transition from the 2012 team to future teams. From 2010, the subsequent teams had learned that knowledge transfer is important for continuous improvement and project success.

This paper is a report on the results of the application of lean principles and SE methodologies by the SEM2012 student team with some observations on its impact on the SEM2013 team. It illustrates how keeping to the basics and making SE simple, visible and effective for a multidisciplinary team delivered a result that everyone was proud of. The paper includes examples of artifacts produced by the SEM team, such as the A3 documentation, and the WBS white board. Topics are linked to the following research questions:

- How can team members ensure easy and effective communication?
- How can knowledge be captured effectively and (re)used in the next team generation?
- How can knowledge be structured ensuring a clear and simple overview?
- Is systems engineering a discipline or an attitude?

## The race and the race team SEM2012

The race team for SEM2012 benefitted from the good results of the prior year and eventually attracted 14 engineering students, two of whom took roles as systems engineers for the project. The SE work that was done during the first semester of the SEM project consisted of defining a new System Architecture based on the one used by SEM2011, developing a Trade-off analysis to facilitate all the decisions that were made, creating a requirement checklist in order to make sure that the solutions that were designed met the specifications and detailed attention to interfaces. The architecture from the prior year was used primarily to create a rough estimate of cost and schedule, and to allocate initial responsibilities for subsystems and interfaces that were known to exist. For the most part, a straightforward SE process was used that followed the SE V-model. Excerpts from the thesis illustrate the critical steps taken in the second semester (Tonning 2012).

Stakeholder analysis. The view of the stakeholders changed over the year. Eventually, the team came to accept that the ultimate users of the DNVFF2 are the sponsors and subsequent SEM Teams. The driver of the car is also a special stakeholder, with real and immediate needs for safety. The sponsors of the DNVFF2 are looking for media attention that the project can give them. Thus, the team has made huge effort in order to fulfill the stakeholder's need for attention by participating in non-engineering PR activities. Only the Systems Engineers with their overall vision of the project understood that PR is value-adding and that it would enable future teams to attract sponsorship and much-needed funding.

**Changes to the car.** For the first time in the Shell Eco-Marathon Europe race history the competition was held on a street-track in Rotterdam. The new track and associated requirements, such as stops between laps, made a new suspension necessary and there was not space in the original car body to implement this upgrade, therefore the development of a new body was necessary. Once in Rotterdam, the new suspension gave the car the ability to be the fastest car in the second half of the track where the turns were closer to each other. The car was also able to enter the turns faster than was anticipated when the track analysis was made. In the track analysis the speed that was defined for the turns was between 20-25 km/h but the car was able to enter the turns at up to 33 km/h. This speed increase gave the team freedom to design a better race strategy onsite.

Another major change from the previous year was the propulsion system; this year for the first time in NTNU's history the SEM team entered the battery electric (BE) class. The decision to change from fuel-cell to BE was based on knowledge transfer from the previous year regarding the reliability and safety of the fuel-cell solution. After the decision was made it was uncovered that the competition in the BE class was much tougher than that for fuel-cell cars.

**Decision gates.** The SE team also implemented a visual board where the work breakdown structure (WBS) of the subsystems could be seen; this board also defined the milestones, some of which were also defined as Decision gates. The board was used to keep track of all subsystems (represented by the cars) and to address the risk related to schedule slips that could impact the number of days available to test the vehicle. Figure 2 illustrates the board 27 days before leaving for Rotterdam.

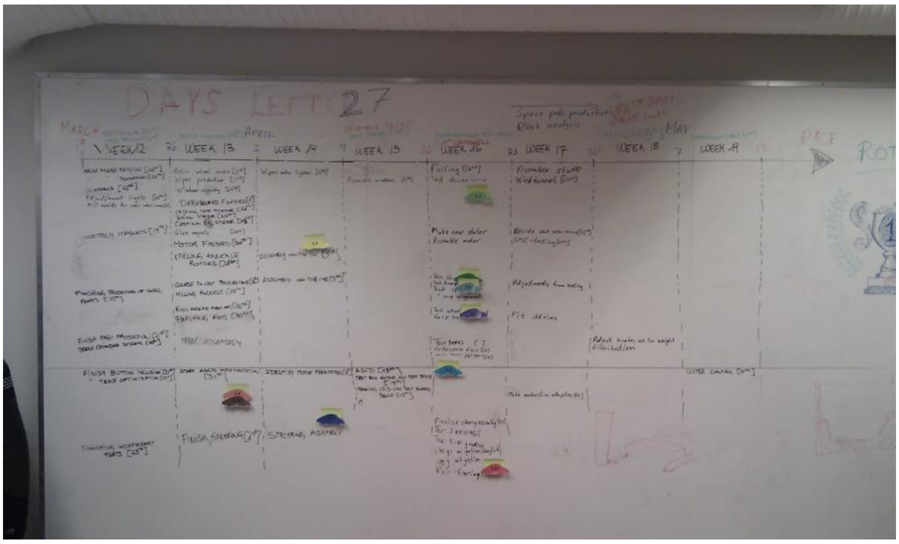


Figure 2: WBS schedule

One of the most challenging decision gates was encountered in deciding what to do with the new engine. The milestones for the engine were delayed, and the project reached a point where the decision had to be made. The engine is one of the critical subsystems as it has interfaces with the rear suspension, the control system and the engine wheel. The suspension and the rims were designed to fit in the new engine that was being built. But problems appeared when the team discovered, by testing the engine at test facilities provided by sponsor SmartMotors, that the new engine was not efficient enough. When that decision gate arrived, all the possibilities were studied but due to some production problems, the outcome was unacceptable. Luckily for the SEM team the engine of the prior year was available, which kept project on track. One of the main problems caused by reverting to the older engine was weight; the new engine was designed to be about 10 kilograms lighter. The changes that needed to be done were minor adjustments but the use of the old engine, on a car that was designed for the new engine, potentially could have jeopardized the car and the race results.

Ultimately, this decision was made by the cybernetic engineer, who dealt with control and mechatronic systems. He was the person whose work was delayed by the availability of the engine. The parameters of the engine needed to be defined in order to optimize the control system. As it happened, this deadline was postponed two days since the team thought that the characteristics of the new engine were better. Looking back to that moment, the SE reflected on this trade-off; if the original deadline had been maintained, the time to develop the control system would have been longer, but on the other hand if the new engine had performed as expected the decision of delaying the deadline could have been a winning decision.

**Risk mitigation.** There were different risk mitigation activities. Most of the risks were mitigated by producing spare parts or by following them up. An example of the mitigation plan can be found in Table 1: Risk Mitigation Plan. Each risk item contained a specific mitigation activity and a responsible engineer. Careful attention to these items was a critical factor for keeping on schedule.

Table 1: Risk Mitigation Plan

| Part | Risk | Mitigation plan | Responsible | Status |
|---|---|---|---|---|
| S.5.5 Tie rods | Misaligned | Realign | A.Q | |
| S.5.4 Hub | Lug threads wear out | Use 2nd set of lug threads on same component | A.Q | |
| S.5.1Linkages | Misalignment | Fine tune alignments | A.Q | |
| | Rods may bend | Use spare | A.Q | |
| S.5.4 Hub | Brake disc threads wear out | Use 2nd set of threads on same component | A.Q | |

**VVT activities.** The focus of the VVT activities was on the implementation, integration and qualification activities, defined for four different test phases; unit testing, assembly/integration, performance and race test, all of which are related to the right side of the SE V-model.

As an example of unit testing, the complete drive train was tested on a test bench with different loadings at different speeds to measure efficiency for different operating points. The test bench was also used to study battery behavior for low battery voltage and over current. The outcome of these tests was used to discover that under voltage protection was needed to prevent coming to a complete stop while racing, torque limitation to prevent under voltage, and over current to prevent stand still while racing. Measurements were used to find the most energy efficient velocity/torque profile for the given track. However, this was one of the more problematic subsystems under race conditions, a circumstance attributed to insufficient resources within the team.

The performance test is focused on testing the car under different environments and circumstances, while the race test was intended to simulate the race conditions in Rotterdam. The biggest problem for the systems engineers was the lack of time and resources to be able to perform better VVT activities. The time and resource problems are as pervasive in the SEM projects as they are in the real-world.

Once arriving at the Race Site, the Shell technical inspection is the first in a series of validation steps. The objective of this inspection is to make sure that cars fulfill the safety and size requirements and it is compulsory to pass in order to be able to compete. During the inspection all Shell rules are checked by different marshals who use checklists and make a tic when a requirement is checked. They are able to do this because Shell has refined the requirements until they are expressed as pass/no pass requirement statements. The

SEM2012 team also worked in this way with the requirements, which meant the car had no problems in passing the inspection, and this allowed the team to enter the track to test the car during all the test days and competition days. This was the first NTNU SEM car able to run on the first competition day

**Stakeholders revisited.** Systems engineering is a lifecycle approach to projects that covers all the stages from Definition to Disposal. However, each year the whole team changes and the time constraints do not allow the team to design a car that anticipates the whole life cycle. The SEM2012 changed that point of view by framing their project as a delivery to the teams of the following years as users of a prototype that has been designed and built by them. While the VVT activities of 2011-2012 are linked to definition, design, implementation, integration and qualification stages, ultimate Acceptance/Validation of the product will be done by the following SEM Teams.

Future SEM teams are seen as ultimate users as they are going to be the ones "inheriting" the vehicle. The DNVFF2 passed its qualification tests but it is the final user's duty to accept the product and they will be the responsible for conducting acceptance tests as they determine the strengths and weaknesses of the current car and make critical decisions about future modifications.

## Lean Product Development and A3 documentation

Challenges in SEM are to develop the car efficiently to be able to keep the project schedule. The source for what many consider as Lean Product Development (LPD) is the Toyota Product Development System (TPDS). 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 (Morgan and Liker 2006) with a systems perspective. The primary objectives of LPD are to minimize waste, improve quality, reduce time-to-market and cost, all driven by the desire to pull value from the customer and up the value chain. Regarding SE, Oppenheim (Oppenheim 2011) introduces six principles for lean SE, as 'lean enablers for SE' (LEfSE). Those are *customer value*, *value stream*, *continuous flow*, *pull of value by the customer*, *pursuit of perfection*, and *respect for people*.

LPD it is not just a methodology for engineers, it is a way of working, organizing, and making the product development and SE processes more effective, considering both product engineering and product management problems at engineering and management levels. It is more a philosophy of working, rather than a methodology guiding engineers from step to step and proposing concrete working steps (Welo 2011).

**Knowledge briefs and A3 Thinking.** Knowledge capture and reuse is an important part of lean philosophy. It is also a major issue for SEM because the whole team shifts once a year, which means that knowledge from one team has to be captured, stored and transferred to the next team without the benefit of interpersonal contact. Knowledge is an important resource for product development and systems engineering, because it mitigates risks, and its reuse saves time and prevents repeated problem solving and unnecessary design loops (Mascitelli 2007). One challenge is to make knowledge capture and reuse efficient. The knowledge brief (K-brief) is a collaborative problem-solving tool, providing a concrete documentation structure to implement PDCA (Plan-Do-Check-Act) management following the principle of continuous improvement (Kennedy 2010). A common type of K-brief is the so-called A3 report (Sobek and Smalley 2008) 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. The mind-set of A3 thinking includes seven important elements (Sobek and Smalley 2008):

1. Logical thinking process
2. Objectivity
3. Results and process
4. Synthesis distillation and visualization
5. Alignment
6. Coherence within consistency across
7. Systems viewpoint

Sobek and Smalley introduce different kinds of K-briefs, which capture information in a clear and visual manner. One is the 'problem-solving-A3', which documents challenges and results in product development in relation to the background and overall context. For a good K-brief, Sobek recommends following a certain layout to make it readable and understandable. Examples will be provided in the next section. Further, K-briefs should be reviewed to ensure a certain quality in knowledge-storage. The K-brief becomes a mentoring tool, since the A3 report should make the author's thoughts visible, and the documentation illuminates important targets of the whole organization or team.

When talking about knowledge documentation and reuse it should be kept in mind that there are two dimensions of knowledge: tacit and explicit (Nonaka 1994). Tacit knowledge includes an individual's belief, viewpoint, paradigm, or concrete know-how, craft, and skill. Explicit knowledge, on the other hand is, articulated and communicated between individuals. A K-brief encourages the author to express the tacit knowledge in a visual manner, and turns it into explicit knowledge. In knowledge management, four basic processes are essential (Alavi and Leidner 2001): Knowledge creation (requiring an organizational culture), knowledge storage/retrieval (requiring dynamic and updated systems), knowledge transfer (requiring adequate searching functions), and knowledge application (requiring the ability to turn knowledge into effective action). A K-brief helps a team deal with all these processes.

In summary, two major points seem to be important in A3 thinking. First, writing a K-brief is important for the writer's statement of the problem. When writing an A3 report, the author has to distil the essence of the described problem and fit it into a template. This requires an objective, logical thinking process and encourages the author to compress the problem - documenting processes from identifying the cause to presenting a better solution. Going through this documentation process, the author will have to rethink his/her work and get a deeper understanding (tacit knowledge). A second point is that the K-brief provides a standardized way of documenting knowledge making it easier and more effective for the reader to uncover important material. K-briefs speed up communication and improve transfer of explicit knowledge, letting the graphics 'talk' (Sobek and Smalley 2008).

### Application of knowledge brief documentation in SEM

When applying LPD it is important to know the stakeholder or customer, because customer value is a central element of lean philosophy. In SEM team knowledge transfer, the student teams themselves represent the stakeholders (not including sponsors and teachers). By this is meant not only the current team, but also the following team generations, who gain from the work of prior teams.

The student team works on the SEM project for one year and each student documents the results (knowledge) in the form of a master thesis where the primary goal is to please the supervisors over sharing knowledge with other team members or following team generations. Nevertheless, the team recognized that there exists the need for knowledge sharing both within the team and between team generations. SE2 interviewed the team members, using suggestions from Mascitelli (2007) for data on technical knowledge, and found out that following points represent the most important data for the team and added system level information and risks:

- Important design trade-offs and decisions
- Reusable design elements
- Raw material/component data
- Test results for common design elements
- Reliability data
- Supplier design rules/capability data
- Overview over the interfaces
- Overview over potential risks

Based on these results, SE2 developed a 3-page K-brief, consisting of a set of three A3 sheets, for the car's subsystems with the intention to create documentation that was easy and fast to read and applied lean thinking. The three A3 pages are summarized in Table 2.

Table 2: Three-page knowledge brief for subsystem report

| **A3 layout** | **Content** |
|---|---|
| Subsystem / Responsible / Date / 1<br>Photo/ Figure<br>Component table<br>Supplier data<br>Trade-off analysis and design decisions<br>Interfaces<br>n2 diagram<br>Details | • Figure of the subsystem<br>• Component table :<br>    ○ components<br>    ○ materials<br>    ○ properties<br>    ○ purchased/ own design/ own production<br>    ○ satisfaction/reliability<br>    ○ constructive weaknesses<br>    ○ needs for improvements<br>• Manufacturing methods<br>• Trade-off curves<br>• Design decisions<br>• n2 interface diagram<br>• Details about interfaces and dependencies |
| Subsystem / Responsible / Date / 2<br>Design analyzes<br>Results<br>Conclusions<br>Photos/illustrations/ charts with explanations | • Engineering Design<br>• Design Analyzes<br>• Visual design description<br>• Critical design review |
| Subsystem / Responsible / Date / 3<br>Risks table<br>Advice to prevent risks<br>Performance<br>Outlook / Future Work | • Risks<br>• Risk evaluation<br>• Advice for risk mitigation<br>• Performance report:<br>    ○ Verification<br>    ○ Validation<br>    ○ Testing<br>• Advice and suggestions for future work |

**First page.** The first page introduces the sub-system, presenting its components, dependencies and interfaces. It is divided into three sections, beginning with a photo or illustration of the system, followed by a table that gives an overview over the sub-system's components, including information such as material, important physical properties (e.g. weight), and information about whether the component is purchased or produced 'in-house' and whether it is a continuous improvement or NPD. The component table provides also a 'ratio of satisfaction' dependent on the component's reliability, constructive weaknesses and the severity of the impact of possible failure. This table gives engineers in following team generations an overview over necessities and possibilities for improvements. Further, the first A3 page includes information about manufacturing methods. The mid-section is dedicated to important design trade-offs and decisions, encouraging visualization and simplicity, using illustrations, graphs or lists for explanations. In the right column, the first page includes an n2 interface diagram, which makes it possible to gain easy insight into dependencies of the sub-systems. Lastly, there is open space to add information on type of interfaces, tolerances, data exchange, etc.

**Second page.** The second A3 page is dedicated to the design process, focusing on analysis, product modeling and engineering design. The page is divided into two sections, the left-hand section containing textual information on important requirements, assumptions made, materials and software used. The right-hand side provides open space to present the design/analysis process as a graphical way, using sketches, screenshots, and photos.

**Third page.** The third page consists of two sections, presenting a table of potential risks on the left-hand side. Likelihood of risks are correlated to a simple rating (1, 3 or 5), which include both the likelihood of the risk's occurrence and the impact of its consequences. On the right-hand side, the A3 sheet provides space to describe the sub-system's performance, containing information on verification, validation, testing (procedures and history), and identified weaknesses. Finally, the engineers can give an outlook or suggestions for future work.

The body of A3 pages taken together provides a rough, but relatively complete overview over each of the car's subsystems. Information is illustrated graphically or in tables where possible, and text is reduced to the core elements, which simplifies reading the K-brief. A discussion about impact will follow in a later section.

# Model-based Systems Engineering

For the first time the SEM team included an engineer whose background included use of model-based systems engineering (MBSE) tools. Since leaving a strong legacy was important to this team, the following artifacts were modeled: requirements, functional analysis, architecture, interface and sub-system design, with traceability. The product used was Vitech Corporation's CORE8 University Edition. A few diagrams are presented here for illustration: the vehicle architecture hierarchy and the interface N-squared diagram (figures 3 and 4, respectively). These and other representations were posted on the Wall and in the workshop to help the team visualize the whole car, the interfaces and to track progress and issues.

**Requirements.** The requirements provided from Shell were used to propagate the first version of the database, but these were often expressed as run-on sentences, and needed careful review to be restated as individual statements. Eventually the team derived additional requirements to track the weight allocations to subsystems, and other design decisions and allocated each of these onto a component of the vehicle. The requirements included verification and testing criteria, and were used by the entire team.

**Functional analysis.** The team understood the mechanical functions of the car well enough that modeling this was not seen as adding value. What did need clarification was the competition itself; hence, the functional models dealt with the activities necessary to transport the car, prepare it for transport and participate in the race. The race FFBD (functional flow block diagram) is shown in Figure 5. However, notwithstanding the availability of sophisticated tools, SE2 still did most of the real thinking with brown paper, pens and post-it notes (Tonning 2012).

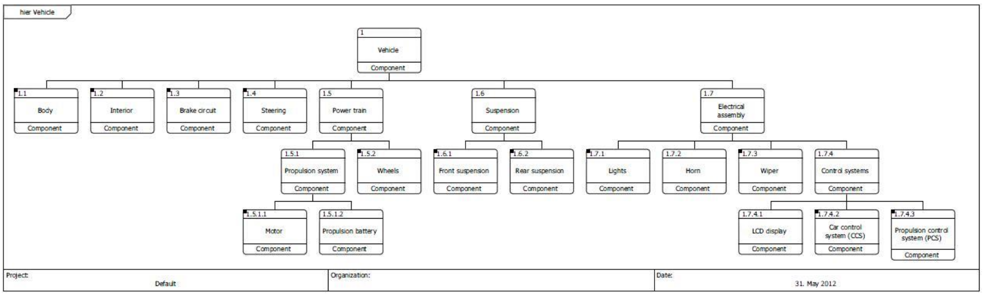


Figure 3. Vehicle architecture of DNVFF2

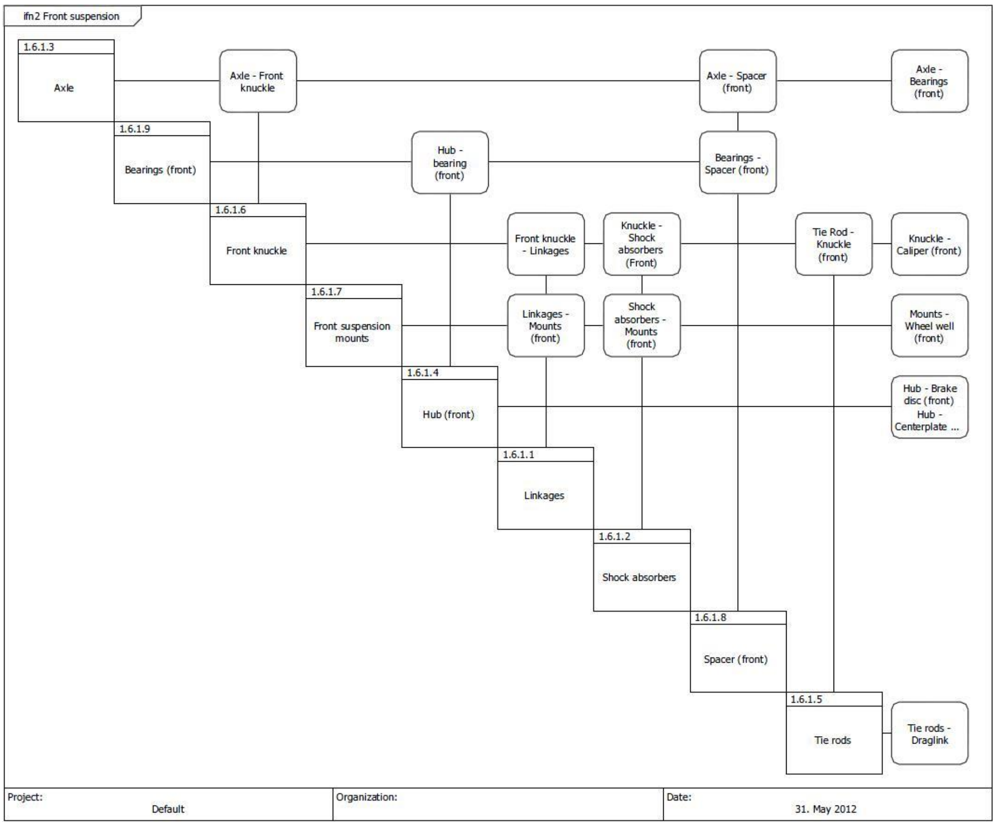


Figure 4. Interface n-squared diagram for DNVFF2 front suspension

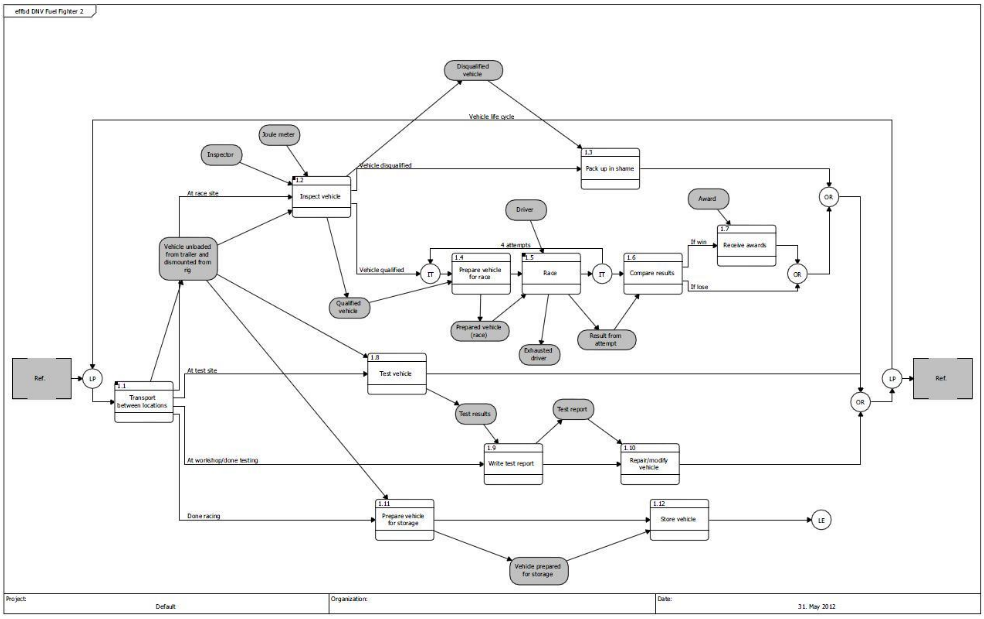


Figure 5. FFBD for SEM2012 race competition

## Discussion

This section is organized around the research questions proposed in the introduction.

**How can team members ensure easy and effective communication?** An approach that SE2 introduced in the architecture is that he included not only the parts and assemblies that have been chosen in the final solution, but also principal solutions that have not been chosen for further development, as shown in Figure 6. Color coding of the boxes in the architecture differentiate between chosen designs and alternatives. This makes communication in terms of evaluation of design alternatives much easier and transparent. By including unselected design alternatives and adding reasons, it will be easier for following team generations to understand how the product has been developed, which choices have been made, and why they have been made. Other technical solutions might become better by technological progress, but might not be suitable to choose today. By visually showing those alternatives, design evaluations become easier.

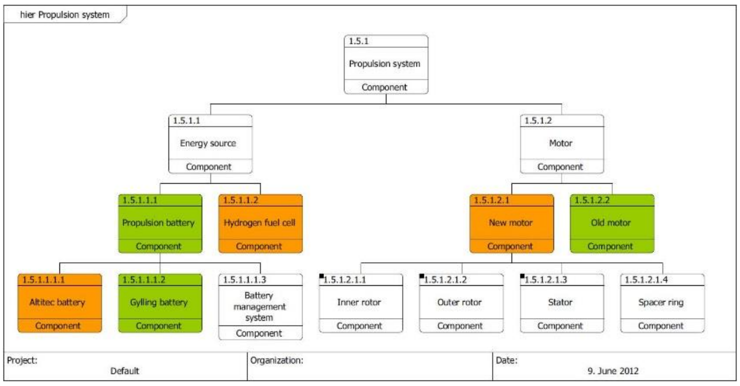

Figure 6. Propulsion system trade-off options

**How can knowledge be captured effectively and (re)used in the next team generation?** Due to frequent team changes (once a year) it is important for each SEM project to capture the team's knowledge effectively and transfer it to the next team, so that the process of continuous improvement of the SEM car is secured. Before SEM2012, knowledge was documented mainly in master theses. SE2 introduced K-briefs to the SEM2012 team. At the end of the project they remain incomplete and do not cover all development issues related to the car. Nevertheless, they represent a starting point in direction of more effective, lean documentation.

To find out how well the knowledge exchange using master theses, K-briefs, and team meetings worked between the 2012 and 2013 team, the team members of 2013 team have been asked to complete a questionnaire. Questions were related to the structure of information, clearness of development history, traceability of requirements, functions, principal solutions, and detail solutions, interfaces, clearness of dependencies, definition of the root cause, information about suppliers, countermeasures and follow-up actions, etc. The students rated their satisfaction with both master theses and K-briefs, which were their main sources for information from the former team generations.

In general, the students were satisfied with both the master theses and the K-briefs. The major disadvantage of the master theses is that it is time-consuming (up to 3 days) to read and understand the information. Information about development history is fragmentary and interfaces and dependencies on sub-system level are not well documented. It is an inefficient process because much information that is not essential for the actual task has to be read, while it is difficult to find the necessary, useful information for determining follow-up actions.

Even though the 3-page K-brief is not yet implemented completely, the most important advantages of the 3-page subsystem K-briefs are that they provide structured information, show interfaces and dependencies clearly, define specific alternatives, and have a clearly visible goal in documentation. The students like the idea of A3 documentation and see it as a useful tool for knowledge capture and transfer. Nevertheless there still are some weak points such as missing information about suppliers, requirements, and evaluation of design alternatives. If the number of knowledge briefs was increased and information was complete, knowledge transfer would be simpler and faster. A complete knowledge-base consisting of K-briefs and A3s could eventually supersede time-consuming studying of master theses. One challenge in this context (since SEM team is a team of graduating students) is that they have to write a master thesis for graduation, while they do not get any credits for writing K-briefs. Accordingly, the motivation to write K-briefs is low and became the system engineer's job in the SEM2012 team. Quality and number of K-briefs could probably be improved by establishing a suitable culture for capturing knowledge in the team. For establishing a knowledge culture it will be necessary to keep 'additional' work simple to not demotivate the team members. Apparently, team members like to read K-briefs, but do not like to spend time on writing them.

In addition to reading reports, the 2013 student team met with the 2012 team for direct experience exchange. All team members stated that this was very helpful and made it easier to understand the written documentation. The SEM2012 team has much tacit knowledge, which is not documented, thus a meeting between the team members helped reduce the gap between tacit and explicit knowledge. Communication by email became easier after this meeting, because the communication barrier become smaller. Some team members even found that meeting the old team is the most powerful knowledge resource of all. Having one of the former team members in the new team for some days is an effective way of knowledge and experience exchange.

The systems engineers observed the importance of legacy. The DNVFF2 had inside the team a team member from the previous year and access to the prior cybernetic engineer during the fall semester. The knowledge transfer that those two engineers gave to the team was absolutely crucial and it helped the team to gain knowledge faster and thereby understand the characteristics of the old car and where improvements were possible.

In conclusion given the current state with the primary documentation in master theses and incomplete documentation on K-briefs, the following two issues are important. Documentation as in a master thesis is complete, but it takes a long time to find the relevant information. The K-briefs on the other hand are easy to understand and fast to read, but information is still incomplete. Team members agreed that product documentation in a K-brief is an effective tool, and will provide a better knowledge base, when K-briefs are complete. Expanding the number of K-briefs, such that they describe the entire vehicle's information, will provide a powerful tool for knowledge transfer and (re)use. In addition to the K-briefs that describe the subsystems, other K-briefs might be considered. For instance, members of the SEM2013 team already wish to have 'improvement A3s' that describe current problems, give advice about concrete follow-up actions and further development.

**How can knowledge be structured ensuring a clear and simple overview?** SE2 found out that the K-brief is an easy way of presenting information, but it will not serve its purpose without putting them into the right context. The K-briefs need to follow a template to save time for the users (both writers and readers) and to encourage filling them out, the organization needs to adopt a culture for making and using the K-briefs, and the users need to know where and how to access and store them.

This implies that structure is necessary on different levels. First, the K-brief itself needs to be structured on a micro-level, meaning a good structure of the information within the K-brief. The K-brief introduced in Table 2 shows a template for a subsystem K-brief, having a structure appropriate to the purpose. In further development other types of K-briefs will need to be introduced. It is important that the K-briefs use templates to enable the team members to write them quickly and without forgetting important information. Lean literature recommends standardization to make the processes, in this case the knowledge capture, more efficient.

The second level of knowledge structure on the subsystem or system level is needed to store and share the K-briefs, so that it will be easy to find them when needed. Team members today complain over a diffuse file structure with inconsistent file names. SEM2013 team members complain that it is difficult to find desired information. An approach to solve this problem is to combine K-briefs with MBSE, where the K-briefs capture knowledge and computer-based models exist to structure it in a visual, clear way. The product architecture, illustrating functions and physical components and their interfaces can be used as a base for visual, simple knowledge structure, by linking the knowledge to the items in the architecture. SE2 started to build such a system, but unfortunately this requires some skills to read by other team members. SE2 implemented this knowledge architecture, filled it with information and maintained it. This made the system consistent, but has the disadvantage, that knowledge capture always has to follow a detour through the systems engineer, which creates a bottleneck and means more work for the systems engineer and possible loss of information. Further the knowledge architecture is not intuitive to understand by the new team members, so that it needs to become simpler. Team members of the SEM2013 team state that a 'knowledge wall' might solve this problem of understanding and make knowledge more visible.

Further, SE2 recommends that capturing knowledge should be done at specific points, preferably at important deliverables (twice in a month), and enforced by a strong leader. This ensures that knowledge is not forgotten due to delays.

In summary, the combination of K-briefs and modeling promises to be an effective and fast method for structuring knowledge and maintaining a clear overview.

**Is systems engineering a discipline or an attitude?** This interesting question was posed by SE1 in her closing reflections. By her own admission, she began with no knowledge or predispositions regarding systems engineering. Furthermore, she shared more in common with other mechanical engineers on the project than with systems engineers. She described this as a tendency to perfection and optimization of parts with less appreciation for the performance of the whole system and that applied engineers may not always seek the most elegant or simple solution to a problem. Only when she shifted her own attitudes toward holistic thinking and appreciated the value of Occam's razor, could she really step into her new role**.** Her background helped her understand that some team members felt that engineering is related to the design and manufacturing of a part or something tangible, something physical, and that for some of them it was hard to value SE work at first.

This was the first time for a NTNU SEM project to have a systems engineer from the start of the project. Each Monday a SE meeting was held. During those meetings the SE presented their contributions inside the team and new ideas were discussed and developed. It proved to be effective as it was used to foresee problems or to solve the ones that had already happened.

The Project Manager shared how crucial and helpful it has been for him to be able to rely on systems engineers. He appreciated the close interactions and cooperation that took place for the entire project, and appreciated that SE work is not just related to technical aspects of the project. SE are the ones that have a complete view of the project and of the different efforts that are done within the team, from mechanical or technical aspects to PR and management.

The systems engineers of the SEM team have discovered that the best way to derive information and involvement from the other team members is to talk to them directly and show interest about the work that they are doing. In addition, to be even more successful, it is important to be flexible. The SE team has been flexible to adapt their way of working to the team's needs by tailoring already known Systems Engineering practice to the project. They observed that people really appreciate SE contributions when problems arise. Then the stress and workload are highest, and the duty of the SE is to try to make the effort as efficient as possible, using boards, visual signs etc. This year, when problems appeared the systems engineers have become an important part of the solution, channeling efforts and coordinating actions.

## Future Work

The new team for the next competition in 2013 just started its work. They will work with continuous improvement of DNVFF2, which means that they need to acquire knowledge from the former team generation. The new team appreciates the use of K-briefs, even though current versions are incomplete and sometimes hard to find. They also figured out that reports and long texts are not convenient, whereas visual information is much easier and faster to understand. Early problems that occurred in knowledge acquisition is that team members notice capacity problems, which constrain the reuse of former knowledge.

In further development the use of K- briefs as communication and documentation base should be extended, aiming to build a knowledge-foundation based on K-briefs. A linkage of those K-briefs to the product architecture might be a simple way to make documentation easy to find. Today, the car's product architecture consists mainly of a physical structure of the car's subsystems and parts. An extension of the architecture to levels of requirements, technical functions, principal solutions, using methods of MBSE, might make it easier for the team members to understand and develop their product. One possibility could be to implement a knowledge wall, which shows the system architecture, and knowledge physically linked or attached to it by A3s, Post-It-notes or similar.

In conclusion the use of K-brief documentation and MBSE promise to be helpful approaches that the team can implement further in the future to increase its effectiveness in knowledge use and transfer. Keeping the processes simple seems to be a good approach in this context. These findings are consistent with similar research results reported at the 2012 CSER (Flores *et al.* 2012; Muller 2012; Murphy and Collopy 2012). A challenge that needs to be solved in the future is to keep the SE and A3 documentation effort as low as possible for the engineering team members, while establishing a culture that includes routines for knowledge transfer at the same time. The students' focus should not be detracted from engineering tasks or have a high impact on the student's capacity. Following the SE and documentation tasks need to be kept as simple as possible to encourage the students to use them. SE2 proposes a knowledge manager for the team for quality control and maintenance of the documentation. Nevertheless, to make the team and team generations transition more efficient, a culture or attitude of SE and LPD has to be established to structure the work and to ensure continuous improvement.

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## Biography

### Sören Ulonska

Sören Ulonska is a PhD student at NTNU in knowledge-based development project, combining methodologies of (lean) product development and systems engineering to improve (re)use of knowledge between and within new product development projects. His educational background includes a Master in mechanical engineering, product development, and engineering design from RWTH Aachen University in Germany.

### Cecilia Haskins

Cecilia Haskins entered academia after more than thirty years in industry. Her educational background includes a BSc in Chemistry from Chestnut Hill College, and an MBA from Wharton, University of Pennsylvania. She has been recognized as a Certified Systems Engineering Professional since 2004. After earning her PhD in systems engineering from NTNU, she lectures and mentors student projects, and conducts research on innovative applications of systems engineering.

# Paper VII

## On Knowledge-Based Development: How Documentation Practice Represents a Strategy for Closing Tolerance Engineering Loops

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# On Knowledge-based Development: How Documentation Practice represents a strategy for closing Tolerance Engineering Loops

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**Abstract**

Knowledge from multiple sources is required for defining tolerances in new product development (NPD). Successful outcomes in product development (PD) depend on the collective ability to integrate this knowledge into the product. Assessing variability and tolerance capabilities are essential parts of PD-knowledge as they represent limits of specifications with wide-ranging impact. Reducing the engineers time spend on (re)defining tolerances and searching for the right information can prevent substandard NPD performance in terms of quality, lead time, cost and product innovation. Hence, two topics of significant importance for achieving leanness (i.e., effectiveness *and* efficiency) in PD are towering tolerance knowledge and associated documentation practices. This paper presents the results of a survey among engineering professionals of two industrial companies made to study documentation and tolerance practices in different industrial environments. The results reveal similarities between the challenges that the companies face, including implementation of effective documentation (e.g. Knowledge-Briefs, A3 reports), visualization of physical relationship between product performance attributes and design parameters (e.g. trade-off curves) and the transfer of knowledge between projects for organizational learning. This paper makes a contribution to the body of knowledge related to (lean) NPD by documenting current industrial challenges and practices in achieving viable internal tolerance engineering routines and processes, along with the needs for documentation tools.



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*Keywords:* Knowledge-based development, knowledge reuse, tolerance engineering, A3-documentation, survey

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## 1. Introduction

Tolerances are often referred to as the omnipresent backbone of engineering [1]. Successful tolerancing practice in product engineering enables efficient manufacturing and high-quality products in the market place [2]. This requires processes for defining, checking, documenting, storing, and retrieving tolerance information along with knowledge of (inter)relationships between parameters [3], as well as experience and know-how of products and production capabilities. When performed correctly, towering tolerancing knowledge improves effectiveness and reduces uncertainties in NPD [4]. Additionally, tolerancing processes within internal business-quality system are sometimes taken for granted, considered to be tedious or lacking explicit focus [6]. The reason may be that companies are suffering unknowingly at a system level from their shortcomings at a detail level in the tolerance engineering (TE) practice [5]. Furthermore, the lack of adequate processes for communicating and documenting (re)useable tolerance knowledge may cause repeated problem solving, vagueness of own capabilities, etc. The overall outcome is typically substandard NPD performance, where resources are used on reactive problem-solving and firefighting instead of creating customer value [7]. An additional factor for lack of value is design engineers spending significant time searching for and organizing information [8]. TE activities may fall under the category of NPD practices commonly referred to as 'knowledge-based development' (KBD), aiming to (re)use and improve existing product and manufacturing knowledge. Knowledge needs to be created, captured, standardized, stored and reused in an effective manner [9]; e.g., by linking it to the product architecture [10]. Hence, practices and tools for good communication, collaboration and documentation are essential. For lean NPD execution, a framework for KBD can serve as a tool for linking several sources of generalized product information directly to a new product design and relate it to associated tolerances.

The aim of this research is to investigate how existing knowledge on tolerance capabilities is captured and reused within product development (PD), and how it can support the definition of more viable tolerance limits in NPD. This paper presents the results of a survey conducted among engineers in two Norwegian case companies. The following research questions are posted: RQ1: How do KBD professionals perform (lean) documentation practice? RQ2: How interlinked is documentation and Tolerance Engineering practice among KBD professionals?

## 2. Documentation and tolerances within KBD

The primary objective of Lean Product Development (LPD) is to create value to the customer [11, 12] by minimizing waste, improving quality (innovation), reducing time-to-market and product(ion) cost. Two important components of the lean philosophy are organizational learning and continuous improvement [13]. One central tool in this regard is the PDCA (Plan-Do-Check-Act) cycle [7], in which improvements and iterations are done continuously in small steps, aiming to reach the ultimate goal of a perfection through a learning-spiral with each cycle closer to the target than the previous one. Knowledge is one of the few permanent sources for competitiveness as reuse saves time and prevents repeated problem-solving and unnecessary design loops and may mitigate risks [14], providing a company with more resources, to spend more time on innovation and adding value rather than conducting 'rework'. LPD represents an extended framework of KBD, which means that the two concepts are more-than-compatible in many respects [15].

### *2.1 Lean documentation tools*

One challenge in LPD is to make knowledge capture and reuse more efficient. The knowledge brief (K-brief) may be used as a collaborative problem-solving tool, providing a concrete documentation structure to implement PDCA following the lean principle of continuous improvement [7]. Overall, the K-brief is a type of mentoring tool, whose purpose is to make the author's thoughts visible while the documentation follows important targets of the whole organization or team. A common type of K-brief is the so-called A3 report [16] named by the paper size used. When used as a problem-solving tool, it serves to visualize problems at hand, goal, process, solution and risk elements in a standardized form, depending on the application and problem formulation. The mindset of A3 thinking includes some important elements such as logical thinking, objectivity and systems viewpoint [16].

*2.2 Knowledge processes and management*

Knowledge documentation and reuse are frequently related to the two dimensions of knowledge: tacit and explicit [17]. Tacit knowledge includes an individual's belief, viewpoint, specific know-how, craft, and skill. Explicit knowledge, on the other hand, is articulated and communicated between individuals. Using a K-brief for documentation challenges the author to express seemingly tacit knowledge in a visual manner, and turns it into explicit knowledge which serves as a tool for organizational learning. In knowledge management, four basic processes are essential [9], see Table 1. A K-brief deals with all these processes.

Table 1. Knowledge process types and their typical requirements

| Knowledge process. | Typically requires |
|---|---|
| Creation | Organizational culture |
| Storage / retrieval | Dynamic and updated systems |
| Transfer | Adequate searching functions |
| Application | Ability to turn knowledge into effective action |

Two major issues are reported in connection with research on learning cycles [7] with K-briefs [16]. First, writing a K-brief is important for the writer's understanding of the problem. Going through this documentation process, the author will have to rethink his/her work, fit it into the framework of A3 thinking, and get a deeper understanding (tacit knowledge). The second point is that a standardized way of documenting knowledge makes it easier and more effective for the reader to uncover important material. K-briefs speed up communication and improve transfer of explicit knowledge, letting the graphics 'talk' [16].

*2.3 Tolerance Engineering*

Tolerances represent limits of product or process specifications that typically are defined at an early stage of PD [2]. This stage represents the "developers' dilemma" as decisions with significant impact on costs are taken, typically with lacking insight in all limiting conditions [18]. Thereby, tolerances sometimes end up being defined on previous design legacy by draftsmen or basic level designers [19]. Despite good design practice in industrial companies, inappropriate tolerance definitions still occur in many of the same companies. Zhang (1997) states "*many parts and products are certainly over-toleranced or haphazardly toleranced, with predictable consequences"*. As a consequence, negative effects of inappropriate tolerances can become visible at a later stage of product-development increasing cost and degrading product quality [20]. At the later stages, changing tolerance definitions requires very high efforts [21], which makes front-loading of the NPD process a desirable strategy [4]. Good TE relies on the ability to address relevant information that is trustworthy and pass it to knowledge creation [22]. TE becomes less likely to be a legacy-based activity when trustworthy knowledge is captured and made accessible.

## 3. **Methodology**

In this study empirical data on knowledge-based TE practice and related tools and documentation processes have been gathered through a web-based survey. The survey was designed according to guidelines recommended by [23]. It was carried out among two well-established Norwegian companies, both of which are developing high-quality, high-technology products.

Company A (CoA) is located in Norway and has both national and international customers, while Company B has different global locations for both development and production. The strategy of CoA is to develop unique PD projects for customers. CoA designs different kinds of advanced products, whereas production is done by other companies. The main competence is project and engineering management. The strategy is to avoid product ownership, and to design products for mass, medium or single unit production.

Company B (CoB) develops and produces low volume engineer-to-order products. Products have the same overall functionality, but need to be adapted to meet different customer needs. Although the companies operate with different industry sectors, they have different PD strategies and product portfolios, they have the similar challenges as described above. Both have a strong focus on increasing effectiveness of PD processes and implementing the 'lean' concept. CoA made some good experiences in implementing K-briefs in the form of A3-documentation, while CoB is mainly focusing on standardization.

The survey approach was chosen in order to gather broad and rich data [24] on the documentation- and TE practice. The driver for this work has been the desire to improve the companies' competitiveness by focusing explicitly on TE practices, and supporting KBD tools for documentation. The respondents were chosen from different functional responsibilities; like design engineers, process engineers, project leaders, QA engineers and others to cover a wide range of persons that somehow are dealing with PD processes.

Introductory survey questions mapped the company affiliation, level of education, seniority at the company, and leadership responsibility. The participants were presented with a series of statements related to the current practices on topics related to documentation and tolerances. The answers were given on a 6-level Likert-scale ranging from 1 (don`t agree) to 6 (fully agree). This "forced option" [25] prevents the selection of the "neutral" middle alternative. From altogether nearly 80 unique questions statistical data were extracted both based on individual questions, and groups of questions. The survey closed with options for participants to give individual comments to the survey topics.

Altogether, 70 out of 97 invited engineers responded anonymously the survey, resulting in a response rate of 72%. Data was exported to SPSS and analyzed with statistical tools. Subsequent to data gathering and analysis, results were presented and discussed within the companies with the purpose of raising the awareness to organizational challenges related to documentation and tolerancing practice.

**4. Analysis of survey results**

Statements targeted documentation practices were split into participants that have experience in using A3 documentation (A3) and those who had no experience. Especially CoA had made progress in implementing A3s as documentation tool in the last five years in addition to other documentation. In CoB very few participants were used to A3s. Overall the group of survey respondents had a nearly balanced amount of participants working with A3 (51,4%) and without (48,6%). The survey was designed to provide pairs of similar statements in order to detect the differences between the two groups related to learning outcomes in the documentation process. An extract of those differences are displayed in Table 2. Statements with a response n<10 were not evaluated due to low statistical power. Key questions are presented in Tables 2-4 with data for sub-groups (left/right) or centered for all respondents.

*4.1 Documentation practice*

The statement that A3 is an objective, logical, problem oriented tool, that requires training and experience for application [16] could be confirmed by answers to questions that were aimed in this area. A comment from a participant also underlines this: *"A3 is a great presentation and discussion tool. It is very challenging to make an A3 that is easily understandable for colleagues outside the project and they often need guidance to understand it"*. Nevertheless, it appears that leaders have a stronger trust in A3 documentation practice than non-leaders. Leaders have significant stronger belief that A3s support objectivity (Q10, p=0,020), logical problem solving (Q11, p=0,001), and continuity (Q12; p=0,015) in PD. In contrast to high acceptance among leaders, there is apparently high variation of the A3 acceptance in CoA. When comparing A3 users and non-A3 users, it is noticeable that A3 users bring documentation for discussions with others, but usually not in form of an A3 (Q1, p=0,00).

For some A3 questions, the standard deviation (St.D) is very high, which reduced the significance of the accordant findings. Nevertheless, they were considered as important since it indicates high discrepancy in the respondents' trust, acceptance, and experience with A3s. A3 is accepted among some, while others use A3s, for documentation but do not use them actively and retain other documentation instead.

Visualizations [26] are an important part of A3 documentation and, among these, "trade-off curves" [27]. Participants are not used to making trade-off curves and creating them is not a well-established practice. All groups evaluate their abilities to create them as low, but A3-users show a tendency to be better in creating them than non-A3 users (Q2, p=0,20), additionally leaders rate themselves significantly (Q13; p=0,047) higher than non-leaders. Hence, persons who are used to A3 thinking and visualization appear to have less difficulty in making trade-off curves.

*4.2 Learning with/without A3-documentation*

When asking if "the process of creating documentation is more valuable than the report itself" (Q3, p=0,083), A3 users support this statement stronger than non-A3 users. A comment may support this: *"The process of making an A3 is important – not the documentation"*. When asking if documentation helps to develop one's own knowledge, the A3 users (Q4, p=0,488) show a very high variance in their opinions. Furthermore, A3 also seems to better transfer tacit knowledge into explicit knowledge. Comparing A3 and non-A3 users of CoA on the accordant statement (Q5, p=0,192), shows a positive tendency for A3 users and a negative for non-A3 users. Here, it should be kept in mind that the standard deviation is high in both cases; hence, it seems that this ability is strongly dependent on the individual. Overall, the individual learning potential seems to be better when creating an A3 report rather than other documentation.

Table 2. Statistical values; differences between A3-users and non-A3 users

| Q | Question topic | A3 users [M/St.D] | Non-A3 [M/St.D] |
|---|---|---|---|
| 1 | It is natural to bring (A3) doc. For discussion | 3,46/1,63 | 5,00/0,94 |
| 2 | I am used to create trade-off curves | 2,39/1,39 | 1,93/1,33 |
| 3 | Doc-process has higher value than doc. Itself | 4,19/1,45 | 3,53/1,33 |
| 4 | Doc. Helps to develop my own knowledge | 4,76/1,05 | 3,97/1,05 |
| 5 | Possibility to express tacit knowledge | 4,00/1,53 | 3,52/1,25 |
| 6 | Possibility of reuse in other setting | 3,81/1,517 | 3,11/1,32 |
| 7 | We get a system view when combining our A3s | 2,46/1,46 | - |
| 8 | We know where doc. Is stored | 3,01/1,32 | |

*4.3 Organization of documentation*

Some participants comment that they would like to have added functional design to documentation and that often a systems view is missing. If CoA would put all A3s about one product together they would not get a systems view with dependencies (Q7). One participant recommends that *"A group of A3s should have one master document that presents and overview over the root causes and system references"*.

Another important point is to find the right information. *"Making the best documents does not help if there is no way to find and share them"* is another comment of a participant. Some respondents stated that they do not always know where the information they need is stored (Q8). Several respondents wish to have adequate searching functions and data bases.

Table 3. Statistical values; differences between leaders and non-leader

| Q | Question topic | Leader [M/St.D] | Non-Leader [M/St.D] |
|---|---|---|---|
| 10 | A3 is an objective doc. Approach | 5,00/1,27 | 3,81/1,33 |
| 11 | A3 supports logical problem solving | 5,70/0,68 | 4,45/1,00 |
| 12 | A3 supports continuity in PD flow | 5,10/0,98 | 3,74/1,52 |
| 13 | I am used to create trade-off curves | 3,18/1,72 | 1,95/0,95 |
| 14 | We frequently talk about tolerances | 5,50/0,67 | 4,77/1,43 |
| 15 | We frequently talk about variation | 4,58/0,90 | 3,53/1,59 |
| 16 | I use much work time on tolerances | 3,83/1,95 | 4,27/1,49 |

Both A3 and non-A3 users were asked if their (A3) documentation can be applied or reused across different problem settings, (Q6, p=0,06). It points out that A3 documentation is easier to reuse than other documentation. Nevertheless, standard deviation is high for both parties.

### *4.4 Tolerance engineering practice*

Both companies rank the statement *"working with tolerances is a challenging activity for our organization"* relatively high (Q20), yet CoB holds both a significant higher (p=0,019) awareness and a stronger consensus with significantly lower St.D. than CoA. One reason for this can be traced back to CoA`s significant challenges with reoccurring problems (Q26; p=0,01). There is a difference in the attention and workload on TE activities between *leaders* and *non-leaders*. Leaders claim significantly to talk more about both tolerances (Q14, p=0,019) and variation (Q15, p=0,007) than the employees without leadership responsibility. On the contrary employees claimed to *"use much work time on technical tolerances*" (Q16) higher than leaders, yet not significant.

Table 4. Statistical values; differences between companies:

| Q | Question topic | CoA [M/St.D] | CoB [M/St.D] |
|---|---|---|---|
| 20 | Tolerance work is challenging for the org. | 4,28/1,43 | 5,08/0,78 |
| 21 | We have a culture for knowledge sharing | 4,19/1,38 | |
| 22 | Culture for sharing tolerance knowledge | 3,60/1,53 | |
| 23 | We consult "lessons learned" when needed | 2,95/1,14 | |
| 24 | We have a system that stores "lessons learned" | 3,16/2,00 | |
| 25 | We know reasons for tolerance definitions | 3,36/1,32 | |
| 26 | Known failures reoccur | 3,49/1,43 | 4,48/1,5 |

Overall, both companies rate their general culture for *"knowledge sharing"* relatively high (Q21). Still *"knowledge sharing on tolerances"* (Q22) seems to be more challenging with a more diverse practice (high St.D.). The articulated challenges on knowledge sharing on a detailed level (e.g. tolerances) can be seen in the relation to the overall low score on the statement *"we consult lessons learned or A3`s when faced with novel requirements"* (Q23) and a relatively low awareness on the existence of *"a system for storing lessons learned"* (Q24). The importance and benefit of capturing lessons learned through a good documentation practice was clearly articulated by a respondent stating *"Good documentation is actually a learning/training material. Very often some functionalities repeat from project to project. It is critical to track "challenges" experienced in other projects. If that is done, very often it is enough to check why things were done in such a way, and implement them again"*. As design often contains repeated elements, the quality of re-occurring TE considerations can be improved with accessible and trustworthy documentation. Several recommendations on how to improve the current TE practice were stated in the open questions. Based on the statement *"we sometimes choose design solutions requiring too tight tolerances",* possible countermeasures can be found in the statements *"we should consider manufacturing aspects to a larger extent when designing"* and the challenge of making the tolerance determination a collaborative activity by including other disciplines into the tolerancing decisions. One respondent claimed that tolerance considerations are *"an activity left to the designer/draftsman to a large extent"*. Differences in TE considerations between various engineering domains were indicated by one of the electronics engineer claiming *"As an electronics engineer I am more often given tolerances than I actively can specify. In my opinion, variations in electronics assemblies are rarely a pain"*.

### *4.5 Documentation supporting tolerance engineering*

The comment *"I see that tolerance definitions always include a design rationale that should be* *documented"* supports the relatively low ranked (Q25) survey statement on the ability to find out *why* a certain tolerance is defined the way it is. Capturing the underlying assumptions behind a tolerance on a detail level, hence seems to be an area where good documentation practice can improve the quality of TE. Another area where good documentation practice can support TE is in internal and external communication. One comment on *"what tolerances you can expect from a manufacturing type/supplier"* proved the importance to access and reuse manufacturing knowledge such as capability data or others. This topic was generally ranked relatively low. Another respondent suggested *"to use a master document/sketch that gives the overview and "reason" behind the referencing and tolerancing"*. Tolerance considerations involve several activities and functional areas and consequently challenges in those issues. Hence, one respondent stated that the challenge is to *"increase the general competence level on tolerances and tolerancing, not primarily within the company, but rather towards suppliers and customers"*.

## 5. Discussion

CoA rates organizational as well as individual learning higher than CoB. The companies are of different nature with a different culture, so it can be difficult to compare them directly. However several KBD activities seem to be useful to both.

### *5.1. How do KBD professional perform (lean) documentation practice?*

One fundamental precondition for a good KBD environment is a culture for knowledge sharing in the organization. Respondents of CoA rate their knowledge sharing culture higher than participants of CoB. Both companies state that they have very high trust in their colleagues, and use them as primary knowledge resource in case of a problem. CoA rates trust in written information and quality significantly ($p=0{,}031$) higher than CoB. Trust in people is also an important fundament for good LPD practices [13]. The trust in and contact with a leader is also considerably ($p=0{,}002$) higher in CoA, as well as collaboration between departments ($p=0{,}037$) and across different projects ($p=0{,}044$). This indicates that the acceptance of asking (right or wrong) questions is higher. Recent research [28] acknowledges the challenge of establishing and truly understanding design thinking among managers. Also in this area, CoA reports a significantly higher score on the statement *"it's natural for me to discuss technical details with my leader"*. The so far discussed aspects can be summarized under the topic "people", which is one of three important topics in successful LPD [13]; providing one important pillar for organizational and individual learning.

As a second pillar, "A3 activities" seem to have contributed positively to high score. Due to high variation in answers in this area, care should be taken in interpreting the results. The survey revealed that A3 shows better potential for knowledge reuse, subject for discussion, and individual learning, and avoiding to do the same mistake twice. It can also more effectively convert tacit knowledge into explicit knowledge. This is an essential need for a learning organization [29]. The implementation of A3 documentation requires training and experience, and especially the creation of trade-off curves show a lack of experience. The high discrepancy among A3 respondents in some areas indicated that A3 is well accepted among some respondents while it is not supported by others. Hence, individual opinions on A3 use are sometimes different. Consequently, there is a lack of common understanding of learning and documentation.

Even though some positive effects could be shown, there is much room for improvements in both companies. Especially on comprehensive understanding of systems and dependencies, a single A3 seems not appropriate. One possibility could be to link A3s that describe detailed problems on different levels of abstraction to the product architecture [10]. This can ensure structure and define clear dependencies between the knowledge elements [30].

### *5.2. How interlinked is documentation and tolerance engineering practice among KBD professionals?*

Results reveal insufficient documentation practice as a potential for better organizational learning on tolerance engineering. A potential for improving the TE activities is seen in the interface between *talking about* and *working with* tolerances. Non-leaders work more and closer on the tolerancing topics, but leaders talk more about them in their work. One challenge is to exchange the knowledge about tolerances on a detailed level with the management insight on a system level. A3s can be a possibility to document tolerance dependencies as they support the description of one certain problem.

Challenges of interpreting the underlying assumptions (e.g. design rationale) are reported in literature [31], and are to some extent confirmed by this survey. It provides an ideal entry point for documenting the design rationale behind given tolerances. Since NPD design often evolves from an existing design basis, it is important to master the challenging task of identifying reusable knowledge [32]. Due to the fact that determination of tolerances is an integrated activity in PD, design engineers tend to not recognize it as a critical situation [33], and consequently it is not always documented. On the contrary, when the importance and consequences of these critical activities are understood, engineers might invest more time for creating and using the necessary documentation. According to [34] it requires the right organizational culture to support the knowledge creation process and some mandatory knowledge related process as defined in table 1. It seems that CoA has progressed further in these documentation activities, although not necessarily towards tolerancing topics. The importance is obvious for tolerances as they can easily be incorrectly reused in a similar design, which is based on underlying assumptions (interfaces, references etc.). In order to prevent unknowingly [6] suffering from substandard TE practice, it is recommended to improve the documentation practice at detailed level. Over time this change is expected to reduce the level of reoccurring failures reported in CoB.

## 6. Conclusions and Outlook

In this survey both companies appear to be good at learning. When comparing CoA and CoB, the possibilities of organizational and individual learning increase in a work environment that provides a better knowledge sharing culture, based on, among others, high-quality documentation, trust in people and documentation, and low hierarchy between employees. A3s provide several advantages such as increased individual learning, better reusability, or support of logical problem solving. A3 is an approach that is stronger supported by leaders than non-leaders, and the discrepancy among A3 opinions ranges from low trust in the A3 concept to strong support. Current A3s do not cover the system context well enough though.

TE is recognized as a challenging, yet important activity in both companies. Although learning by PD is a focus in both companies, the value of TE knowledge has not been a part of this. Hence, there are challenges in interpreting underlying assumptions for insufficiently documented TE. One of them is to exchange TE knowledge on a detail level with the management insight on a system level. Here, an A3 that provides a system view together with A3s that explain detailed TE knowledge may be an improvement possibility.

However, this research includes just a two companies; further research may include a broader sample selection to make findings more significant. Follow-up activities can be targeted towards better understanding how documentation can be performed effectively and precisely (e.g. A3) for TE and how detail and system knowledge can be related to create an engineering-friendly overview and to ensure that the desired information is easily found.

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# Paper VIII

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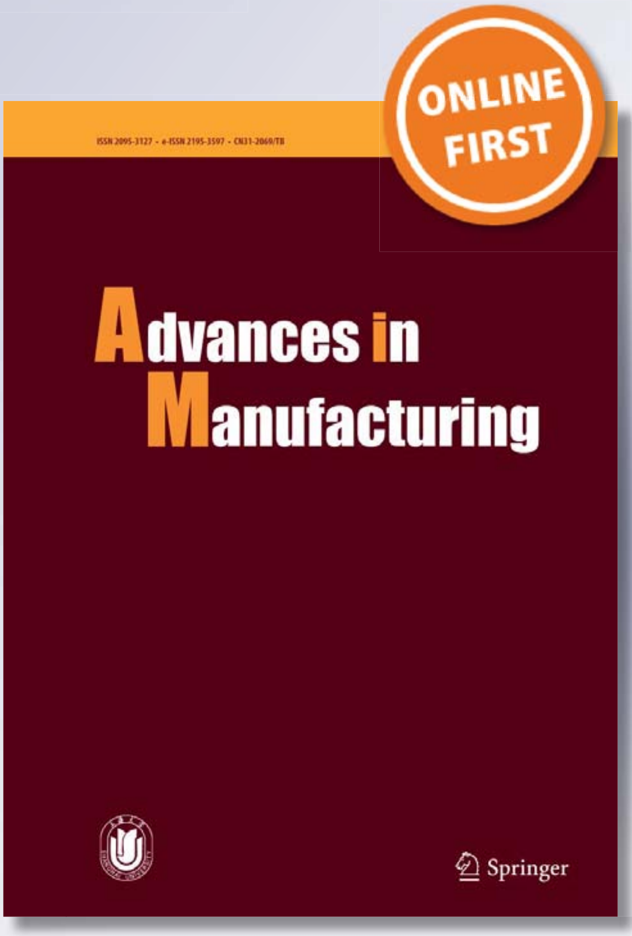

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