THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Engineering Knowledge

Support for Effective Reuse of Experience-based Codified Knowledge in Incremental Product Development

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Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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ISSN 1652-9243
Report No. 100

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Cover:
The cover illustration graphically portrays a
experience-based process to finding a solution.

Printed by
Chalmers Reproservice
Gothenburg, Sweden 2016

Failure is simply the opportunity to begin again, this time more intelligently

\- Henry Ford

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ABSTRACT

Product development is a knowledge-intensive activity. The knowledge applied comes from a variety of sources, including those within a company as well as those outside. A lot of the organizational specific knowledge is gained from positive or negative experiences that in the best of worlds result in organizational learning where that knowledge is reused to increase product quality while minimizing time and cost to market.

In product development it is common to find a time gap between when knowledge is created and when knowledge becomes reused; consequently, this requires in some thoughtful codification strategy. Knowledge is often stored in handbooks, drawings, documents, electronic means and, in particular, in the heads of individuals. As products become more complex and competition intensifies, it is essential to make maximum use of available knowledge and deliver that knowledge in the appropriate form at the right time. To make it even more complicated, knowledge tends to travel over longer distances when organizations and teams are distributed across various places. People tend to move between positions at an increasing speed and on top of that, we also see the difficulties of knowledge transfer upon retirement. Developing a knowledge reuse support capability is a challenging task. Many initiatives have been taken to create effective knowledge management, yet design-related product problems are recurring phenomena.

Given three research questions, this thesis sets out from an engineering perspective to explore existing core barriers in product development organizations that decrease efficiency in knowledge reuse (1) and understand the flow of knowledge (2). Finally, the thesis (3) aims to propose a model for knowledge reuse that results in the effective reuse of experience-based knowledge.

The findings related to the first research question highlight two important barriers to efficient reuse of knowledge at the engineering level; the difficulty of finding pure organizational knowledge due to the combination of general knowledge and the motivation for reuse by for example the structure of do-check instead of check-do.

To answer the second research question, a framework has been developed combining theory, case company observations and interviews to explain the flow of knowledge.

The aim is to increase the awareness of knowledge itself for project outcomes that hold value for future work in an organization.

In response to the third research question, a model for knowledge reuse support has been proposed that combines the strengths of several other common practices to efficiently support knowledge reuse. The model is referred to as an Engineering Checksheet and is proposed to split up knowledge into knowledge elements which not only try to give the engineer the answer on what to do, but also how and why to do it which have been seen as important components to become successful with continuous improvements.

The proposed knowledge reuse support has so far only been subjected to initial tests at the case companies, and although it shows great promise, further tests will be required to validate its usefulness.

Keywords: knowledge reuse, experience-based knowledge, knowledge management, knowledge management life cycle, knowledge assets, engineering knowledge, engineering checksheet.

ACKNOWLEDGEMENTS

One day is not like another, you try, you fail, you learn, you try again, you succeed. It's internal and external motivation that makes me keep going no matter what, and that's why I want to express my appreciation for the support of the scientific work leading to this thesis.

Throughout this research, I have had the benefit of being surrounded by a lot of people who have supported and inspired me, which has kept my enthusiasm at the top and encouraged me to keep on learning. I would like express my gratitude to my supervisors Dag Bergsjö and Amer Catic who have greatly contributed to this paper by providing me with guidance, ideas and feedback.

I would also like to take the opportunity to express my gratitude to Daniel Corin Stig, Jonas Landahl, Monica Rossi, Christoffer Levandowski and Konstantinos Stylidis for good collaboration and interesting discussions that have led to worthwhile insights and inspiration, both related and unrelated to my research.

Moreover, I would like to thank everyone in the Department of Product and Production Development for the friendly and welcoming environment that is built up by everyone.

I also wish to thank all participants of the Vis-IT project: Toyota Material Handling Europe, Volvo, Autoliv, Dentsply and Repos Mjukvara AB. I want to give a special thanks to the latter for its support when it comes to software development and assistance without which I had been totally lost.

My gratitude goes beyond the Vis-IT project, which is part of a larger initiative of the Winquist Laboratory VINN Excellence Centre within the Area of Advance Production at Chalmers and supported by VINNOVA, the Swedish Governmental Agency for Innovation.

Finally, I am eternally grateful for having my family and friends support me in whatever comes along and my most sincere thank you goes to Linn Gustafsson for keeping me full of energy and for providing me with guidance in all situations.

Gothenburg, Sweden, 2016

Daniel Stenholm

APPENDED PUBLICATIONS

The following research papers form the foundation on which this thesis stands.

Paper A

Stenholm, D., Landahl, J., & Bergsjö, D. (2014). Knowledge Management Life Cycle: An Individual's Perspective. In *DS 77: Proceedings of the 13th International Design Conference (DESIGN 2014),* pp. 1905-1914, Cavtat - Dubrovnik, Croatia, May 19-22, 2014.

Paper B

Stenholm, D., Rossi, M., Bergsjö, D., & Terzi, S. (2015). Knowledge Management Tools and Techniques: Extent of Use in Organizations and Support for Modularization. *Proceedings of the 20th International Conference on Engineering Design (ICED 2015),* Milano, Italy, July 27-30, 2015.

Paper C

Stenholm, D., Mathiesen, H., & Bergsjö, D. (2015). Knowledge-Based Development in Automotive Industry Guided by Lean Enablers for System Engineering. *Proceedings of the 13th Annual Conference on Systems Engineering Research (CSER 2015),* Hoboken, NJ, USA, March 17-19, 2015.

DISTRIBUTION OF WORK

The work of each paper was distributed among the authors accordingly:

Paper A Daniel Stenholm coordinated the study, conducted interviews with Toyota Material Handling Europe (TMHE) and performed the literature review and analysis in collaboration with Jonas Landahl. Jonas Landahl conducted the interviews at Volvo Car Corporation (VCC) for the study. Daniel Stenholm performed two workshops at TMHE to wrap up the analysis. Daniel Stenholm and Jonas Landahl drafted the paper with the support of Dag Bergsjö.

Paper B Daniel Stenholm coordinated the paper and performed most of the literature review. Monica Rossi conducted interviews and statistical analyses. Daniel Stenholm and Monica Rossi drafted the paper with support from Dag Bersjö and Sergei Terzi.

Paper C Daniel Stenholm planned and coordinated the study. Henrik Mathiesen conducted unstructured interviews and performed long-term participant observations while supporting engineers with best practices. Daniel Stenholm and Dag Bergsjö conducted semi-structured interviews over the period and supported the implementation of these practices. Daniel Stenholm wrote most of the paper with the support of Dag Bergsjö. Henrik Mathiesen drafted the section 'About the company' and 'Transforming the product development process'.

ADDITIONAL PUBLICATIONS

Although not making a central contribution to the result, the following publications are related to the research presented in this thesis

Kaya, O., Stenholm, D. & Bergsjo, D. (2013). Towards Global Deviation Management in Product Development Using Pulse Methodology: A Case Study. *Proceedings of the 12 th Annual Conference on Systems Engineering Research (CSER 2014),* Redondo Beach, CA, USA, March 20-22, 2014.

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LIST OF ABBREVIATIONS

COK	Codified Organizational Knowledge
DRM	Design Research Methodology
ECS	Engineering Checksheet
KBD	Knowledge Based Development
KE	Knowledge Element
KM	Knowledge Management
KMS	Knowledge Management System
KO	Knowledge Owner
KRS	Knowledge Reuse Support
LL	Lessons Learned
LPD	Lean Product Development
NPP	New Product Development
OK	Organizational Knowledge
OL	Organizational Learning
OMS	Organizational Memory System
PD	Product Development
PDP	Product Development Process
PSS	Product Service System

1 INTRODUCTION

The dynamic changes in the market situation and global business environment are driving a rapid evolution of needs for learning in manufacturing organizations. Edward Hess (2014) states, “learn or die” as a short but sharp statement of the importance of learning as the underlying fundamental process for **operational excellence** – getting better, faster, and cheaper – and **innovation** to drive growth. Hence, there is a need to increase experiential knowledge application concerning processes, methods and technologies to solve problems, exploit opportunities, and be ahead of the competition (Riege, 2005).

1.1 Focus on Knowledge Reuse

Peter Drucker (1994) broadly describes the shift from industry to information to knowledge, which started around 1960 and is expected to continue until 2020. This is in line with Nonaka & Takeuchi (1995, p. 43) who argued in 1995 that “we are entering the knowledge society in which the basic resource is no longer capital, natural resources, or labor, but is and will be knowledge, and where knowledge workers will play a central role”.

The most widely used standard for Quality Management Systems, ISO 9001:2015, has added a knowledge management clause (7.1.6 Organizational Knowledge) that explicitly points out this importance. The clause states that to fulfill the ISO 9001, an organization shall determine the knowledge necessary for the operation of its processes and achieve conformity of products and services, maintain and make this knowledge available to the extent necessary and when addressing needs and trends, an organization shall consider its current knowledge. Organizational knowledge is defined as knowledge specific to an organization and generally gained by experience—knowledge that is used and shared to achieve the objectives of an organization.

In a knowledge-driven economy, as in product development organizations, the intangible assets of an organization, such as skills pertaining to employee know-how, are increasingly becoming differentiating competitive factors. The significance of this knowledge is widely acknowledged today and organizations constantly seek ways of increasing their knowledge base in order to guarantee long-term success, organizational performance and sustainability (Epple, Argote, & Murphy, 1996). Consequently, Knowledge Management (KM) was established as a discipline to empower organizations with supporting tools, principles, methods, models and theories. A common KM effort is project-to-project knowledge transfer in order to accelerate learning from experience and to bridge the gap between standard processes and task-based reality (S. Thomke & Fujimoto, 2000). This method also has the potential for improving the “front-loading” of problem-solving related to product development, including efforts to effectively transfer design rationales and experiences between development projects to avoid “reinventing the wheel”. Important to remember is that in today’s knowledge-intensive work, it is not just a matter of presenting the knowledge in a way that is easy to acquire, it is also necessary to present the knowledge at the right time, place, to the right people and with the proper level of detail (Browning, 2000).

This thesis aims to contribute to research on how companies can systematically manage their lessons learned/experience-based knowledge to become reusable knowledge assets to incremental product development by organizing their knowledge to support the efforts of the engineering profession.

1.2 Research Focus

The research is focusing on product development in large business organizations with more than one site. Organizations trying to standardize their products and continuously improve them have been seen as vital to be effective and to retain quality. Without making any statements of their individual importance (exploration & exploitation and innovation & incremental), this research mainly focuses on supporting incremental development and exploitation of knowledge, i.e. the efficiency-focused activities of leveraging existing capabilities (March, 1991). The products that are investigated in the companies are thus relatively many and have short product cycles, factors that increase the opportunity for learning, and are often designed by individuals who hold a great deal of tacit knowledge linked to the product.

This research project and thesis are part of a wider research project called Project Vis-IT, an abbreviation for Visualization and IT (in Product and Production Development). In project Vis-IT, the following industrial organizations are contributing; Volvo, Dentsply, Autoliv, Toyota, Chalmers and Repos. The Vinnova FFI program financed the program and Volvo coordinated the efforts. For this thesis, the major affiliates have been Volvo, Toyota Material Handling and an organization outside project Vis-IT, Kongsberg Automotive.

1.1.1 Industrial & Scientific Goals

The research performed has been mainly focused on product development with moderate or high technical challenges, such as the automotive industry. In this area, the product development efforts are mostly incremental, which often have lower risk than New Product Development (NPD). However, plenty of examples exist where problems recur due to poor knowledge reuse, even if the knowledge already existed inside an organization.

Knowledge transformation in this thesis is mainly focused on the process where knowledge goes from tacit to explicit, especially when knowledge sharing is supposed to be conducted between individuals who do not disseminate and acquire the knowledge at the same time. The goal is to transfer knowledge from an experienced individual to in individual with a lower level of knowledge in the same field. The outcome of this research aims to support an engineer to make better actions and decisions during the design phase with minimal workload impact.

The intended outcome will form the basis for a system of knowledge reuse support that must be practical and useful for both capturing and reusing knowledge. This result will be possible by combining research from knowledge management, product development and lean methods for creating, capturing and reusing knowledge.

1.1.2 Research questions

To put the research focus into concrete words, three research questions are posed below. The research goals are to be met by answering these questions. The context of these questions is incremental product development when the dissemination of knowledge is performed at a time different from the acquisition of knowledge.

RQ1. What barriers to the reuse of experience-based knowledge can be identified at the engineering level within companies?

> *The first research question discusses an exploratory element of research in which the problem of reusing knowledge based on earlier experiences from similar products/projects is investigated. There are good arguments as to why knowledge reuse is of high interest in product development but there is need for additional insight into what constitutes an efficient reuse capability.*

RQ2. How can the perceived knowledge flow be visualized based on the perspective of the knowledge worker in order to increase the awareness of knowledge as both a deliverable and a resource?

> *The aim of the research question is to build a framework that supports the engineering level and explains the phases that a knowledge worker goes through when reusing knowledge for designing a specific component, as well as the phases that a knowledge worker needs to go through to efficiently prepare for future reuse. This framework will be further refined to understand and compare the cases for additional companies.*

RQ3. How can experience-based engineering knowledge be organized in order to achieve systematic reuse over time by employees in product development?

> *The research questions aim to support knowledge reuse when the exchange of knowledge is not performed at the same time without being restricted in place. The aim is to create a method based on the answer to RQ2 so that the method supports the way in which the designer performs the activities today without proposing any radical changes, which hopefully increase business success.*

1.3 Delimitations of the research

Managing knowledge in product development is of course a broad area that needs to be scaled back. A common definition of the knowledge itself is whether it is codified or not. The research performed focuses on reusing codified knowledge and eliminates tools and techniques focusing on personification strategies, which is represented by the knowledge transfer in the first box of Figure 1. The fourth box describes knowledge that is automated and reused in the design phase and is also delimited. To be able to reach automated knowledge reuse, unstructured knowledge must become structured in some way and then made reusable. Consequently, this thesis is focusing on knowledge tools that are conducted by people and applied to the structure where they were created. This delimitates the example of text mining, known as intelligent text analysis, text data mining or knowledge-discovery in text (Herschel & Jones, 2005).

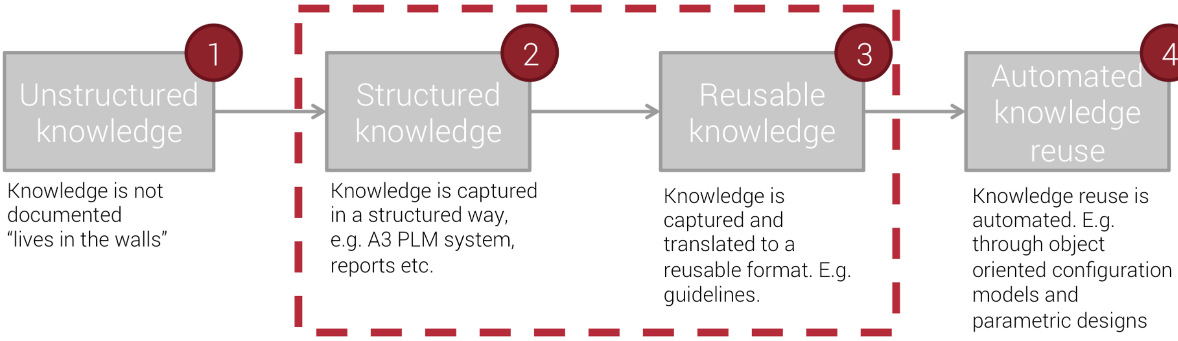

Figure 1. Describing different reuse capabilities for knowledge through the spectrum of unstructured knowledge, structured knowledge, reusable knowledge and finally automated knowledge reuse.

Text mining generally refers to the process of extracting interesting, non-trivial information and knowledge from unstructured texts. The purpose of this thesis is to increase the flow of valuable knowledge from people's minds to end up in a reusable format for future use.

In this thesis, knowledge reuse mainly focuses on the product itself, not on the surrounding development process even though it has an important role in product development. Emphasis has been placed on activities and knowledge assets that exist within firms. Thus, the possibility of accessing technological knowledge through relations with other companies has been neither acknowledged nor discussed. Even if the creation of knowledge is an important aspect of KM inside an organization, this has been delimited since the focus is on knowledge reuse.

The empirical data gathered through this research have mainly been collected from three companies, two in Sweden and one in Norway. The research focus are on companies that develop technical products which are in line with the case companies. However, to be able to make general statements, a larger study needs to be conducted.

Since this is a licentiate thesis, the research will continue further to the doctorate thesis, along with the validation of the proposed knowledge life cycle framework and knowledge reuse support developed during this research. Consequently, the verification of the results in the real environment of the product development organizations needs to be further evaluated.

1.4 Thesis structure

The subsequent chapters of the thesis are outlined as follows:

Chapter 2 is an introduction to the literature relevant to the study of this topic. The sources have been collected over the course of the project and have continuously contributed new ideas and perspectives.

Chapter 3 presents the strategy and methodology used for conducting this research, as well as important considerations for evaluating the quality of academic results.

Chapter 4 collects the results from the appended papers and summarizes them in order to provide a coherent body of findings in subsequent chapters.

Chapter 5 is where my results are discussed in relation to the research questions and criteria for research quality from Chapter 3.

Chapter 6 presents a conclusion of the findings and summarizes the contributions of this thesis.

Chapter 7 elaborates on some interesting aspects for advancing this research topic and continuing to support the research goals outlined.

2 FRAME OF REFERENCE

This chapter brings attention to the literature including concepts, phenomena and the context in which the results and reasoning of this thesis rest (Figure 2).

2.1 Product Development – Knowledge Work

Product development (PD) has been a vital part of our civilization for as long as anyone can remember. It involves the creation of products either as incremental developments including modifications of existing products or designs of entirely new products. Many times product development is described as satisfying customer needs with new or additional benefits.

PD capabilities are becoming critical for companies, as the increase in global competition and market segmentation accelerates the pace during which changes take place in many industries. The PD capability is generally defined as the integration or combination of differentiated functional knowledge (Grant, 1996a; Kogut & Zander, 1992). Successful PD is achieved by firms with better access to specialized knowledge or a broad knowledge base, and has the capability of integrating new knowledge by reconfiguring existing knowledge (Grant, 1996b).

Companies that structure their product development based on traditional models may be disadvantaged when it comes to such important dimensions as agility, flexibility and productivity. Traditional PD usually leads to a number of problems commonly seen in companies; some of them are: (i) work overload on designers and engineers who frequently perform unnecessary tasks, (ii) a PD process that is not clearly understood by designers, (iii) project cost overruns, (iv) difficulty in acquiring knowledge from previous projects and (v) an ambiguity regarding task responsibilities due to an insufficient commitment of functional departments (Liker, 2004; Oehmen et al., 2012; Oppenheim, Murman, & Secor, 2011; Rossi, Taisch, & Terzi, 2012). If knowledge is not reused properly, it has to be continuously regenerated which constitutes another form of waste (Morgan & Liker, 2006; S. Thomke & Fujimoto, 2000).

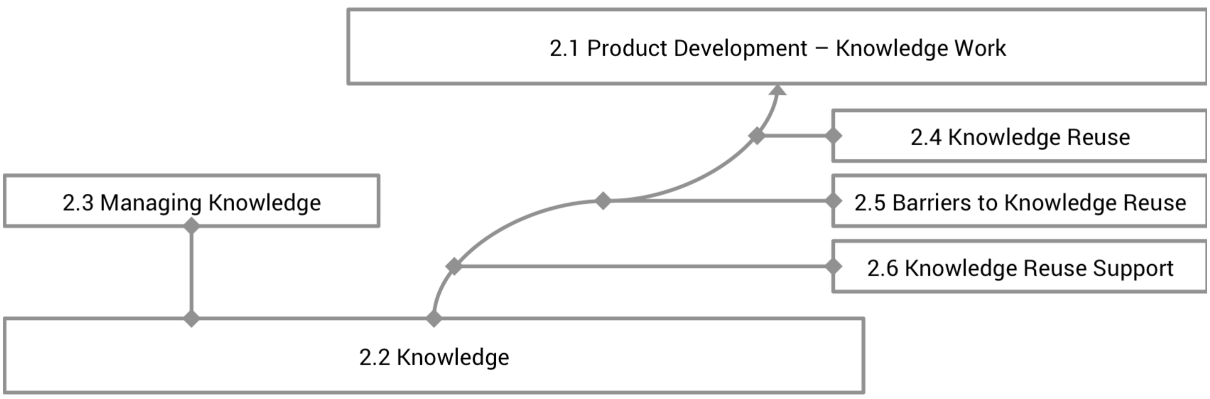

Figure 2. Overview of the topics presented in frame of reference

To overcome such deficiencies, the application of theories that strongly emphasize knowledge reuse, such as lean thinking, knowledge management and organizational learning, has been proposed by academics and practitioners (Rossi et al., 2012). It has been shown that independently of the degree of incremental or innovative development of products, they strongly remain dependent on the knowledge of older products (Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011).

2.1.1 Lean Product Development

Lean thinking has attracted a wide variety of organizations and supported them in focusing on value streams (knowledge value stream and product value stream), eliminating all non-value adding activities and consistently aligning all required activities to external and internal customers (Morgan & Liker, 2006).

Problems addressed in the LPD literature may be grouped into two classes. The first class congregates problems dealing with the effectiveness of the development process in terms of market success of newly developed products (Hines, Francis, & Found, 2006). Problems within this class include a lack of alignment between product development strategy and the wider business strategic plan, unnecessary development activity, lack of understanding of customer requirements and high new product failure rates (Bauch, 2004). The second class of problems is concerned with the efficiency of the development process itself. These problems include the lack of a formal or standardized process, ineffective control of high-volume development environments, poor internal communications, a lack of common focus, the inability to improve or learn from mistakes and ultimately poor project deadline achievement and fiscal control (Oppenheim, 2004; Reinertsen, 2009). These two categories can also be seen as doing the right things and doing things right to enhance both effectiveness (the former) and efficiency (Drucker, 1994). To address the problems listed above, a major topic in the LPD literature is the identification of best practices that may lead to their mitigation (Hoppmann et al., 2011).

Lean Product Development (LPD) consists of many interrelated enablers, which demand changes in basic values and ideas to be successfully adopted. Browning and Worth (2000) emphasize that removing waste in a PD context requires a system perspective, rather than focusing on individual activities. Thus, a certain degree of organizational unlearning must be pursued so that old beliefs regarding procedures and measurements are deconstructed to welcome change (Leon & Farris, 2011).

Hoppmann et al. (2011) present a framework of 11 LPD Components, where one of them are *Cross-project Knowledge Transfer*. In relation, Table I presents the other 10 components and how they might affect Cross-project Knowledge Transfer.

Table I. 10 Lean Product Development components and their effect on Cross-project Knowledge Transfer (Hoppmann et al., 2011).

Component	**Theoretical Qualitative Interdependency with the component *Cross-project Knowledge Transfer***
Strong Project Manager	Enforcement of use of checklists and knowledge transfer.
Specialist Career Path	Higher ability for reflection and documentation of lessons learned.
Workload Leveling	Time for reviewing past project findings before project start, time for reflection and documentation of lessons learned.
Responsibility-based Planning and Control	Higher incentive for using past knowledge due to accountability and ownership.
Simultaneous Engineering	Documentation and reuse of knowledge on requirements of and design for manufacturing
Supplier Integration	Integration of supplier requirements and ratings in documentation
Product Variety Management	Easier documentation of best practices for structures and designs due to lower part variability and clearly defined interfaces.
Product Variety Management	Generation of objective test data through early and short problem-solving cycles.
Process Standardization	Better reuse of knowledge due to similarity of subsequent projects and tools employed
Set-based Engineering	Increased rate of knowledge creation and documentation through the consideration of a wide range of possible solutions.

2.1.2 Knowledge workers

People in PD can be defined using different terms, such as product developers and product designers, as well as knowledge workers. The application process is where the PD knowledge is used and where it gives value to the other KM processes, such as refinement and dissemination. It is important to fit the knowledge to the receiver to the greatest extent possible in order to increase reusability. Hence, the knowledge needed and the way in which the reuser prefers to access it are critical requirements in understanding how the KM system should be designed to be maximally effective. To point out different user needs when it comes to reusing codified knowledge, Markus (2001) identified four types of situations where knowledge reuse takes place, and suggests that these situations dictate the particular needs of knowledge transfer (Table II).

Table II. Types of knowledge reusers and recommendations on how to support their needs. Adapted from Markus (2001) and Corin (2015a).

Type of Reuser	**Description**	**Recommendation to Improve Reuse**
Shared Work Producers	Reusers who have worked together with the source of knowledge. These reusers will typically experience less challenge reusing knowledge, partly because they understand the implicit knowledge and assumptions that may be missing in the records.	- Be clear about the context and rationale in the knowledge records. - 'Raw' records can often be sufficient. - Do not provide general access to these repositories.
Shared Work Practitioners	People who do similar work as the knowledge source but in a different setting, e.g. during a previous project at the company (sometimes referred to as project-to-project knowledge transfer). Since they share the general knowledge in their field of expertise, they normally have little difficulty assimilating the knowledge once they have located it.	- Repackage and decontextualize knowledge, but keep the context for reference. - Provide quality assurance - Provide access to both experts and expertise - Push content to recipients - Create incentives for contribution and use
Expert-Seeking Novices	A type that faces several challenges in reusing knowledge since they are looking for advice on topics in which that they are not themselves knowledgeable. They may not know that they need advice at all, where to find it or how to interpret their findings for their problem at hand.	- Repackage and decontextualize knowledge, but keep the context to support recontextualization - Make an effort to make the records understandable to novices - Provide access to both experts and expertise - Provide training to increase awareness of the existence of expertise
Secondary Knowledge Miners	Reusers looking to develop new knowledge from existing records for a purpose that differs from the purpose of the authors of the records. Their main challenges are to locate the right repositories for their purposes and defining precisely the content for which they search.	- Store context information as metadata - Provide training in how the knowledge base is structured - General training in how to analyze and validate results

Because of the focus on incremental PD in this thesis, *Share Work Producers* and *Expert-Seeking Novices* are mainly regarded. All of these situations face different challenges regarding how to know what to look for, how to find knowledge, how to assess whether it is relevant and the ability of the knowledge-seeker to acquire and apply that knowledge. For instance, a novice who seeks expert advice would need decontextualized knowledge with indications on how to recontextualize it, while those reusing the work of their own colleagues probably will use the context as a reference for the new design.

2.1.3 Summary

The literature reviewed on product development can be summarized as follows:

- In product development there exists a problem of using existing knowledge to its greatest extent. A common problem is for example acquiring knowledge from earlier projects (Oehmen et al., 2012).
- To overcome deficiencies included in PD when it comes to effectively (re)using knowledge. Researchers and practitioners have been proposing the application of theories that strongly emphasize knowledge reuse, such as lean thinking, knowledge management, organizational learning etc. (Rossi et al., 2012).
- Lean Product Development (LPD) emphasizes the need for a system perspective rather than focusing on individual activities to be able to change organizational behavior (Browning, 2000), thereby forcing some unlearning of bad habits and deconstructing in order to welcome change (Leon & Farris, 2011).
- Hoppmann et al. (2011) present and propose an organization to follow the 11 LPD components to increase *Cross-project Knowledge Transfer*.
- Trying to make sure that you know your receiver of the knowledge to be able to adapt it for increased acquiring opportunities (Markus, 2001). Recommendations to improve reuse in project-to-project transfers are for example providing access to both experts and expertise and pushing content to recipients.

2.2 Knowledge

The term knowledge is heavily discussed by others and this thesis does not aim to expand on the term but rather to give a common understanding of the applied context. In this thesis, the key characteristic of knowledge is that it is applied to the design and manufacture of products, focusing on the technical "know-how" of the organization.

Knowledge is commonly described as built on data and information, often heavily dependent on context, and created within the individual (Davenport & Prusak, 1998; Wiig, 1993). Ackoff (1989) explains that the relationship between data, information and knowledge is not interchangeable. However, each category is dependent on the other categories in the hierarchy. The hierarchy is often displayed by a pyramid starting with data from the bottom and followed by information and knowledge, and sometimes also wisdom and intelligence (Rowley, 2007).

The difference between data, information and knowledge differs between authors and there exist several definitions and interpretations. In this thesis, a rather pragmatic stance is assumed and the following means of the terms are offered. Following Wiig (1993), Davenport & Prusak (1998) and Tuomi (1999), **data** involve a set of discrete and uninterpreted facts about events and are considered to be sequences of numbers and letters; spoken words; pictures; even physical objects when presented without a context. **Information** is described as structured data with some given level of context and meaning, noting that both context and meaning require human interpretation and understanding. It is usually presented to describe a situation or condition and therefore gives added value over data.

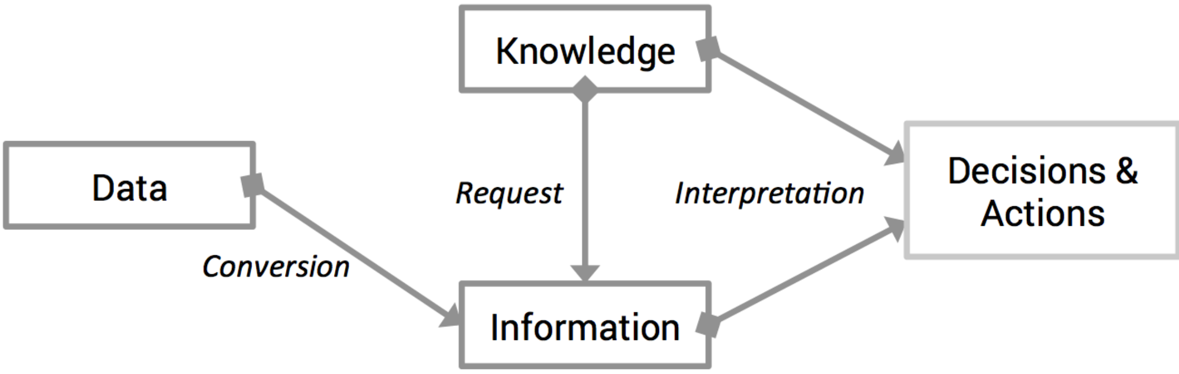

Figure 3. Relationship between data, information and knowledge adapted from Lehner & Maier (2000)

Knowledge represents understanding of situations and their context, insights into the relationships within a system, and the ability to identify leverage points and weaknesses and understanding future implications of actions and decisions taken to resolve problems. Knowledge represents a richer and more meaningful awareness and understanding that resonate with how the knowledgeable individual views the world. Figure 3 illustrates the relationship between these terms.

2.2.1 Forms and Types of Knowledge

To further understand different forms of knowledge, a common KM perspective to categorize organizational knowledge is to divide it between tacit or explicit knowledge depending on the extent to which it can be expressed, codified and stored (Nonaka 1994). To further categorize explicit knowledge, the terms codified and encapsulated are added. There is disagreement about the relative importance between these forms (Markus 2001) and different strategies support their transfer and reuse (Catic, 2011; Yeung & Holden, 2000).

Explicit knowledge is commonly defined as knowledge that is formally expressed using a system of symbols (e.g. words, formulae) and is then primarily supported by a codification strategy for knowledge dissemination.

Codified knowledge involves knowledge put down in writing without incurring undue losses of information (Evans, Dalkir, & Bidian, 2014) and allows for greater fluency, especially in its dissemination. This form of knowledge allows it to more easily, rapidly and extensively be disseminated in the organization than other forms (Grant & Baden‐Fuller, 2004; Van den Berg, 2013).

Van den Berg (2013) argues that it may be constructive to consider knowledge organized in an encapsulated configuration as a classification of knowledge distinct from codified knowledge. **Encapsulated knowledge** is an object based explicit knowledge, where the codification is a process that takes place in the design and functionality of artifacts (Gorga & Halberstam, 2007; Van den Berg, 2013; Wiig, 1993) Some common examples include technical drawings, models, software code, prototypes, tools, products, patents etc. (Kogut & Zander, 1992; Van den Berg, 2013; Wiig, 1993). Since the substantive knowledge that went into the design and development of artifacts remains partially hidden from its users, encapsulated knowledge is not fully codified (Van den Berg, 2013). According to the definition of knowledge used in this paper, encapsulated knowledge does not fully support this term as it needs further effort to be added before being able to support actions in order to resolve problems and in this context, it is often treated as information.

Tacit knowledge is uncodified knowledge (Ikujirō Nonaka & Takeuchi, 1995; Polanyi, 1966; Van den Berg, 2013). This form of knowledge is commonly referred to as being complex, unrefined and difficult to articulate (Boisot, 2013; Van den Berg, 2013; Wiig, 1993). Tacit knowledge is personal and action oriented and is created by experiences over time (Polanyi, 1966). Wiig (1993, p. 161) refers to it as non-conscious knowledge or 'so internalized that we have lost conscious access to it'. It is utilized in employee problem-solving and decision-making and is evidenced in the way in which relationships are utilized and information and other resources are used. Choo (1996, p. 335) argues that 'Organizations need to become skilled at converting personal, tacit knowledge into explicit knowledge that can push innovation and new product development'. Nickols (2000) differentiates between implicit knowledge and tacit knowledge by arguing that tacit knowledge is not possible to articulate whereas implicit is.

Further, in attempting to codify or encapsulate tacit knowledge, it is important to understand that some remnants remain in the human mind (Choo, 1996; Spender, 1996; Van den Berg, 2013). In efficient management models, both tacit and explicit knowledge is accumulated simultaneously (Ikujiro Nonaka, 1994). However, Nonaka (1994) recommends circulating individuals between project and knowledge layers so that they can make an "inventory" after completing a project and coding the knowledge created (Ikujiro Nonaka, 1994). Nonaka (1994) believes that individual knowledge can be systematized through rules, procedures and databases, which allow for the application of tacit knowledge in a collective setting.

In addition to these forms of knowledge, researchers also divide knowledge into different types used to categorize knowledge: declarative (know-what), procedural (know-how) or casual (know-why) (Alavi & Leidner, 2001; Lundvall & Johnson, 1994). Declarative knowledge describes the state of something and represents an appreciation of the kinds of phenomena worth pursuing. Declarative knowledge is often explicit knowledge and is then arguably easier to disseminate to others and to refine in documents. Procedural knowledge represents an understanding of the generative processes that constitute phenomena and often describes a process by which something is done and therefore can often be codified as process-steps and practices. Procedural knowledge also has elements of tacit knowledge that is acquired only by extensive experience and "learning by-doing". Casual knowledge represents an understanding of the principles underlying phenomena (Garud, 1997). These different types of knowledge are presented in Table III together with conditional and relational knowledge.

Table III. Knowledge Categories

Knowledge types		Knowledge forms
Declarative knowledge (Alavi & Leidner, 2001)	Knowledge About (Alavi & Leidner, 2001) Know-What (Lundvall & Johnson, 1994) Know-Who (Lundvall & Johnson, 1994)	Explicit (Nickols, 2000; Ikujirō Nonaka & Takeuchi, 1995; Polanyi, 1966)
Causal knowledge (Alavi & Leidner, 2001)	Know-Why (Alavi & Leidner, 2001; Lundvall & Johnson, 1994)	Tacit (Ikujirō Nonaka & Takeuchi, 1995; Polanyi, 1966)
Procedural knowledge (Alavi & Leidner, 2001)	Know-How (Alavi & Leidner, 2001; Lundvall & Johnson, 1994)	Tacit (Nickols, 2000) & Implicit (Nickols, 2000)
Conditional knowledge (Alavi & Leidner, 2001)	Know-When (Alavi & Leidner, 2001)	
Relational knowledge (Alavi & Leidner, 2001)	Know-With (Alavi & Leidner, 2001)	

2.2.2 Actionable knowledge

> A little knowledge that acts is worth infinitely more than much knowledge that is idle
>
> - Kahlil Gibran (1883–1931)

Knowledge is frequently considered actionable. In brief, knowledge is the human capacity, both potential and actual, to take action in varied and uncertain situations. Actionable knowledge is what we base our decisions and actions on and is further supported by the definition of knowledge value by Davenport and Prusak (1998, p. 6), “Knowledge can and should be evaluated by the decisions or actions to which it leads”.

The theoretical framework has led up to the understanding that in order to increase knowledge reuse, an important factor is to what degree such knowledge is actionable. Wheelwright and Clark (1992) explain that the knowledge that is reused needs to be rich and intense. Complex problem-solving often requires more than simply finding the correct answer. It typically entails defining relevant dimensions of a problem space, crafting a solution that is both feasible and appropriate to the social context where it will be introduced, and convincing to others of the correctness of a proposed course of action.

A recurrent comment on how to make codified knowledge reusable is to capture its rationale (S. M. Duffy et al. 1995; Busby 1999; Markus 2001). A design rationale includes the justifications for a design, alternatives considered, evaluated trade-offs and other argumentation (Lee 1997), which explains the ‘why’ of a previous design and supports the evaluation of how conditions may be different when that knowledge is reapplied to a new context. There is no simple definition of actionable knowledge but it rather works as an expression for defining rich and intense knowledge. Cross and Sproull (2004, p. 446) define actionable knowledge as "knowledge that leads to immediate progress on a current assignment or project". Actionable knowledge is further explained by Cross & Sproull (2004) as representing a pragmatic view of knowledge creation and application toward specific ends. Argyris (1996, p. 392) defines it as ” actionable knowledge informs us how to create or produce what we claim has high external validity”. In this context, external validity is what we believe is valid based on our experience.

Factors for actionable knowledge can be categorized into five different components: (1) *solutions* (both know-what and know-how that directly answer the questions of reusers), (2) *referrals* (pointers to relevant people or databases), (3) *problem reformulation* (knowledge provided to support the understanding of the problem to help the knowledge seeker redefine the problem and understand the factors that need to be addressed), (4) *validation* (refers to an expert giving feedback on the correctness of the solution provided), and (5) *legitimation* (similar to validation but convinces others that the solution is correct) (Cross & Sproull, 2004). Actionable knowledge can briefly be explained as knowledge that is relevant and easy-to-use. Relevant means that the knowledge should be of interest to intended users, in the right time and at the right place. To make knowledge easy-to-use, there are a lot of aspects to take into account. Thompson and Madigan (2013) present evidence that it is difficult for the human mind to remember information. Therefore, it is important to prioritize the information that should be presented. In making specific knowledge actionable, such knowledge must also be easy to understand in order to enable the knowledge user to acquire as much knowledge as possible. In order to make the knowledge relevant, the knowledge needs to be categorized in a way that supports the intended user in finding it.

2.2.3 Summary

The literature reviewed on PD knowledge can be summarized as follows:

- Knowledge is often heavily dependent on data and information and together with information forms the understanding to be able to take legitimate actions and make appropriate decisions (Davenport & Prusak, 1998; Lehner & Maier, 2000; Wiig, 1993).
- Codified knowledge can be more easily, rapidly and extensively disseminated throughout an organization than other forms (Grant & Baden‐Fuller, 2004; Van den Berg, 2013).
- Encapsulated knowledge often needs further effort to be added before it can support actions in order to resolve problems and in this context, it is often treated as information (Van den Berg, 2013).
- Knowledge can be categorized into different types: Declarative – telling what to do, procedural – explaining how to do it, casual - argues why you should do it, conditional – when it should be done and relational – understanding the context and other interactions (Alavi & Leidner, 2001).
- Actionable knowledge is knowledge leading to immediate progress on a current assignment or project. Factors for actionable knowledge can be divided into five components: (1) solutions, (2) referrals, (3) problem reformulation, (4) validation, and (5) legitimation (Cross & Sproull, 2004).

2.3 Managing Knowledge

2.3.1 Knowledge Management

For centuries it has been known that knowledge has a great potential in PD. But only in the past 20 years, a specific field called "Knowledge Management" (KM) has emerged. KM is based on the assumption that just as people cannot exploit the full potential of their brains, organizations generally do not have the capability to fully utilize the knowledge they possess. KM activities help organizations focus on the acquisition or creation of potentially useful knowledge to achieve maximum effective utilization to positively impact organizational performance by such factors as problem-solving, dynamic learning, strategic planning and decision-making (Herschel & Jones, 2005) in order to increase innovativeness and responsiveness (Hackbarth, 1998).

Effective knowledge management requires an infrastructure made of technology, the formalization of knowledge into rules -which should be up-to-date, the formal reuse of previous knowledge and continuous improvement methodologies for the capitalization, update and reuse of the past knowledge of a company (Baumeister, Reutelshoefer, & Puppe, 2011; Gold, Malhotra, & Segars, 2001; Kamsu Foguem, Coudert, Béler, & Geneste, 2008; Sanchez & Mahoney, 1996; Teece, 2000). The success of knowledge management initiatives and activities is highly dependent on the infrastructure, i.e. the processes, tools, structure etc., through which they are implemented (Heisig, 2009; Phaal, Farrukh, & Probert, 2004). By comparing 160 knowledge management frameworks, Heisig (2009) identified four categories of key factors for creating a successful infrastructure: human-oriented factors (culture and people), organizational aspects (structures, roles, responsibilities and processes), information technology and management processes (leadership, strategy, goals, measurement and control).

It is important to remember that knowledge is highly dynamic and continuously in motion. What was true yesterday might not be true today and knowledge needs to continuously adapt to new factors, data, inventions and problems (Wenger, McDermott, & Snyder, 2002). Wenger et al. (2002) state that what makes managing knowledge a challenge is that organizations must manage their knowledge in ways that do not merely reduce it to an object. They need to keep in mind that knowledge utilizes and evolves through the skills, understanding, and relationships of its workers, as well as through the tools, documents and processes that embody aspects of this knowledge. Collins and Smith (2006) emphasize the need for understanding the best internal and external practices to increase the level of efficiency and effectiveness of processes with respect to KM.

2.3.2 Knowledge Management Life Cycle

This section provides a compact overview of some of the most influential KM life cycle models that exist. Each life cycle introduced valuable new elements to be considered in understanding how OK is processed throughout its useful lifespan. There have been numerous KM life cycles models that describe the relationships of the key processes of KM. Early life cycle models include Wiig KM Cycle (Build, hold. Pool & Use) (Wiig, 1993), Meyer and Zack KM Cycle (Acquire, refine, store distribute & present) (Zack, 1999) and McElroy KM Cycle (Knowledge production, organizational knowledge and knowledge integration) (McElroy, 2003). KM life cycles are typically described from a broad perspective outlining the activities that are intended to have a healthy KM work inside an organization (Davenport & Prusak, 2000; Ward & Aurum, 2004).

Other KM life cycles describing the relationship range from for example Davenport and Prusak's (Davenport & Prusak, 2000) 3-stage model ("Generate, Codify/Coordinate, Transfer") to Ward and Aurum's (Ward & Aurum, 2004) 7-stage model ("Create, Acquire, Identify, Adapt, Organize, Distribute, Apply")

KM Processes	Organizational Processes	Intermediate Outcomes	
Knowledge: - Acquisition - Assessment - Application - Creation - Identification - Refinement - Dissemination	Improved: - Innovation - Individual Learning - Organizational Learning - Collaborative Decision-making	Improved: - Organizational Behaviors - Decisions - Products - Services - Processes - Relationships (with suppliers, customers and partners)	Improved Organizational Performance

Figure 4. KM in an organization, adapted from King (2009)

King (2009) argue that KM processes directly improve organizational processes, such as innovation, collaborative decision-making, and individual and collective learning. These improved organizational processes produce intermediate outcomes that, in turn, lead to improved organizational performance (Figure 4). King (2009) also argue that KM initiatives sometimes forget that organizational performance improvement is what KM is ultimately all about.

2.3.3 Organizational Learning

Organizational learning (OL) is a supplement to KM. An early picture of OL was "…encoding inferences from history into routines that guide behavior" (Levitt & March, 1988, p. 319). So, OL standardizes what has been learned for an organization.

There are different ways of conceptualizing the relationship between KM and OL. Easterby-Smith and Lyles (2003) consider OL to focus on the process, whereas KM focuses on the content in the flow of knowledge.

In line with this view, OL should be considered the goal of KM (Lehner & Maier, 2000). By motivating the creation, dissemination and application of knowledge, KM initiatives pay-offs by helping an organization embed knowledge into organizational processes so that it can continuously improve its practices and behaviors and pursue the achievement of its goals. From this perspective, KM is one of the important ways by which OL may be supported to sustainably improve its utilization of knowledge.

In describing an "organizational learning cycle", Dixon (1999b), suggested that "accumulated knowledge… is of less significance than the processes needed to continuously revise or create knowledge" (Dixon, 1999b, p. 7). These processes are closely related to the notion of "continuous improvement". Continuous improvement is the planned, organized and systematic process to continuously increase and accelerate learning. Key to the success of continuous improvement is an ongoing process of learning cycles and these have often the following common characteristics (Garvin, 1993; Lotti Oliva, 2014):

- a systematic approach to problems-solving
- a culture focused on the experimentation of new experiences and methods
- learning from history and experience
- adopting best practices by learning from others
- efficiently and effectively building a flow of knowledge based on the knowledge acquired to everyone in the organization.

The improvements are embedded in the organization through routines that may constitute written policies, prescribed machine settings, quality control limits or “best practices” for dealing with frequently recurring circumstances (William R. King, 2009).

2.3.4 Organizational Knowledge

The preserved and accumulated knowledge through time is called Organizational Knowledge (OK) and the means by which organizations can learn from their past by avoiding repetitions of past mistakes and by adopting proven successful practices (Barros, Ramos, & Perez, 2015; Johnson & Paper, 1998). OK recognizes the capacity of organizations to learn from their past experiences. It is comprised of both tacit and explicit knowledge. Routine-based conceptions of learning require that the lessons from experience are maintained and accumulated through routines despite staff turnover and the passage of time. When employees retire from an organization, it may be relatively uncomplicated to replace job-related knowledge, skills and abilities; however, replacing lost organizational knowledge gained from experience creates greater challenges (Dunham & Burt, 2011). Rules, procedures, techniques, beliefs and cultures are preserved through socialization and control. Although organizational memory is largely characterized as a resource, only allowing organizational memory to guide future practice can be counterproductive when change is necessary (Johnson & Paper, 1998; Kransdorff & Williams, 2000). In this thesis, the focus is on codified organizational knowledge (COK) (e.g. information systems & other artifacts)

Based on Nonaka and Takeuchi’s work, Spender (1996) elaborated further on OK and divided explicit and tacit knowledge into a matrix with individual and social knowledge as columns. Although all fields are part of OK, he argues that organizations need to stress the importance of balancing individual against social knowledge. Explicit social knowledge is referred to as objectified knowledge, which is embodied in patents, designs or information stored on databases. Tacit social knowledge is referred to as collective knowledge and represents all knowledge embedded in social and institutional practices, systems, workflows and culture (Riege, 2005).

2.3.5 Summary

The literature reviewed on managing knowledge can be summarized as follows:

- OL is a supplement to KM and can be explained as the goal and process while KM focuses on managing the content and flow of knowledge (Easterby-Smith & Lyles, 2003; Lehner & Maier, 2000).
- KM activities aim to support the organization to effectively utilize knowledge for organizational performance, such as problem-solving, dynamic learning, strategic planning and decision-making in order to increase innovativeness and responsiveness (Hackbarth, 1998; Herschel & Jones, 2005).
- Knowledge is dynamic and evolves/moves over time (Wenger et al., 2002).
- Four different categories of key factors for creating a successful infrastructure have been identified by Heisig (2009): human-oriented factors, organizational aspects, information technology and management processes.
- Organizational knowledge is the means by which organizations may learn from their past by avoiding the repetition of past mistakes and by adopting proven successful practices (Barros et al., 2015; Johnson & Paper, 1998).

2.4 Knowledge Reuse

Engineers intuitively reuse previous designs and knowledge when performing new design tasks, either by a complete carryover of parts or through the reuse on an abstract level, such as concepts or knowledge (Schulz et al. 2000; Smith & A. H. B. Duffy 2001).

When performing an incremental product development project, an initial process of acquiring past knowledge is common. In that case, the designer hopes to find test reports and guidelines that can easily be adopted and applied to the new design. For most organizations, a likely scenario would be for engineers to ask colleagues about directions on how to find knowledge that applies to the current case. They will then have to explore several different sources, such as documentation, people and artifacts to understand the differences between the current and past projects. Such investigations are time-consuming and require a lot of redundant activities to catch up with the knowledge that was once at the top of the minds of an entire project group. One might think that the probability of using codification as a strategy for learning among projects would decrease in correlation to the degree of innovativeness of the product developed in this context. This hypothesis was tested by Cacciatori et al. (2012) but it was not supported.

To succeed in transferring from one project to another, many practices can be applied. The chapter on Knowledge Reuse Support for Codified Knowledge further elaborates on this subject.

2.4.1 Front-loading Knowledge to Support Decisions

Decisions made in early development stages have high impact because they determine up to 80% of costs in the latter stages (Boothroyd, 1994; Duverlie & Castelain, 1999; K. T. Ulrich & Pearson, 1993). These decisions often rely on uncertain information (Augustine, Yadav, Jain, & Rathore, 2010; Kihlander & Ritzén, 2012; Pomerol, 2001) and knowledge to evaluate which decision is the “right” one (Verworn, Herstatt, & Nagahira, 2008). Engineers frequently generate the required knowledge after prototyping or just before product launches when design changes cause significant costs (S. H. Thomke, 1998; Verganti, 1999). These design reworkings negatively affect both time and cost.

To make less design changes late in the product development process (PDP), concurrent engineering and front-loading have been proposed by researchers (Morgan & Liker, 2006) and have in many companies been interpreted as a necessity of making a greater number of more explicit decisions early. In practice, this has been implemented through a requirement to involve people early on in late-stage functions. In most companies, however, this poses an issue as the amount of resources (=employees) is much lower in the latter phases which means that a manufacturing engineer would need to be the manufacturing representative in a greater number of projects than can be handled by one person. In essence, the knowledge has to be available in other form(s) to support some of the early decisions. In this way, an individual can be relieved and focus on questions which are "tricky" and need personal attention upon request. Making knowledge experts become reachable for more people are what Dixon (1999a) called a shift from an expert model to a distributed model.

Front-loading pulls unavoidable decisions earlier in order to proceed towards upcoming development activities, such as prototyping, testing, manufacturing, etc. The importance of decisions that have a heavy impact on both the efficiency and effectiveness of product performance later on can sometimes be neglected because their consequences are not immediately observable. Short deadlines can lead to a lack of consideration, which may force ignorance of the long-term risks of decisions and make it more likely to underinvest efforts at the front-end.

According to a number of studies, front-loading is one of the major factors of PD team performance (Brown & Eisenhardt, 1995). Front-loading, referred to as problem solving (S. Thomke & Fujimoto, 2000), up-front homework (Cooper & Kleinschmidt, 1994) or as detailed pre-development planning (Brown & Eisenhardt, 1995; Tatikonda & Rosenthal, 2000), is a countermeasure against expensive waste later in the PDP usually caused by inaccurate or missing knowledge.

Systematical knowledge front-loading

Front-loading knowledge reuse support (KRS) should be supportive of critical knowledge in the early stages of a project where most problem-solving activities take place. The notion of front-loading suggests that project-specific knowledge should be generated as early as possible in order to reduce late engineering modifications and to fill in relevant knowledge gaps. Thomke and Fujimoto (1998) underline two methods by which PD performance may be improved in terms of cost and time: early problem identification and rapid prototyping. They consider front-loading as an early problem-solving activity, a countermeasure against the effects of late learning costs during the testing phase. It involves exploring alternative solutions while there is maximum design space and while the risk of change is low (Morgan & Liker, 2006). Regarding the empirical effect of front-loading, it has been suggested that, by implementing rapid prototyping and project-to-project transfer at the front-end, Toyota could deliver new designs with 30% less lead time (S. Thomke & Fujimoto, 2000).

The literature on LPD and total quality management deals with efficiency issues in knowledge-intensive tasks. A study of lean principles suggests the standardization of development processes and the application of templates, such as A3 sheets for problem-solving, failure mode effect analysis (FMEA) to identify risks, checklists, visual maps and decision matrices (Morgan & Liker, 2006; Reinertsen, 2009). Hence, these studies propose using simple tools to support PD decisions to standardize common elements in the PDP. Reinertsen (2009) suggests that a systematic front-loading method would ensure that PD teams resolve problems early in the process.

2.4.2 Summary

The literature reviewed on front-loading knowledge reuse to support decisions and actions can be summarized as follows:

- Knowledge in PD is naturally reused either by people, artifacts or documents.
- The knowledge owner from the latter PD stages cannot personally support all knowledge needed in the early stages due to time (resource) constraints.
- Front-loading knowledge aims to support decisions based on defined knowledge, not assumptions or gut feelings.
- A systematical approach of front-loading knowledge between projects is suggested to ensure that PD teams resolve problems early in the process (Reinertsen, 2009).

2.5 Barriers to Knowledge Reuse

To categorize and capture organizational knowledge over time, a KRS consisting of codified knowledge is typically applied. Research shows that there exist several barriers in the interaction of activities in the knowledge life cycle that relates to asynchronous (different time) as well as synchronous (same time) knowledge transfer.

In the human interaction with the KRS several barriers are faced. When creating codified knowledge assets, there are a number of critical challenges to making them effective; the willingness of employees to contribute and their accessibility and ease of use (Watson & Hewett 2006). Employees who find such practice useful are more likely to make contributions to them and make sure that they contain updated and trustworthy information (Watson & Hewett 2006). In addition, the ability to access to the most relevant lessons learned at the most appropriate time in the most appropriate format is critical to ensure project success (Carrillo, Ruikar, & Fuller, 2013; Kotnour, 2000; Weber, Aha, & Becerra-Fernandez, 2001). Some authors argue that the lack of motivation to receive lessons learned is in fact a greater obstacle than motivating experiences project members to tell what they have learned (e.g. Dixon, 1999a).

Project members regularly have unrealistic expectations that KRS alone will do the work of sharing knowledge. In order to support knowledge reuse, it is vital that these codified knowledge assets be organized and not just remaining bins of information (S. M. Duffy et al. 1995). There might be an inappropriate technology integration, mismatching the needs of engineers and adoption, support, IT project management, upgrades and costs (BenMoussa, 2009). Any method implemented must support knowledge to be updated, accessible and available to the personnel within the organization (Davenport & Prusak, 2000).

There exist different typologies to group the barriers and the typology proposed by Brandt and Hartmann (1999) has become a classic in the analysis of obstacles to management in socio-technical systems. It consists of three factors—technology, organization and people (TOP). Riege (2005) used this topology to categorize three dozen knowledge reuse barriers related to SMEs and MNCs (Table IV).

2.5.1 Summary

The reviewed literature on barriers for knowledge reuse can be summarized as follows:

- A common way to categorize barriers is by three groups: individual, organizational and technology.
- Individual barriers mainly involve motivation (not understanding what the benefits are for the individual as well as organization), individual capability (age, gender, language, past experience, etc.) and the opportunity (e.g. accessibility, lack of time, form of presented knowledge).
- Organizational barriers mainly involve a lack of strategy, culture (e.g. only top-down flow), lack of incentives (e.g. rewards) and appropriate infrastructure.
- Technology barriers mainly involve a mismatch between the needs of engineers and an understanding and unrealistic expectations of IT.

Table IV. Knowledge reuse barriers (Riege, 2005)

Individual	
I1	General lack of time to share knowledge and time to identify colleagues in need of specific knowledge
I2	Apprehension for fear that sharing may reduce or jeopardize people's job security
I3	Low awareness and realization of the value and benefit of knowledge possessed by others
I4	Dominance in sharing explicit over tacit knowledge such as know-how and experience that requires hands-on learning, observation, dialogue and interactive problem-solving
I5	Use of strong hierarchy, position-based status, and formal power ("pull rank")
I6	Insufficient capture, evaluation, feedback, communication, and tolerance of past mistakes that would enhance individual and organizational learning effects
I7	Differences in experience levels
I8	Lack of contact time and interaction between knowledge sources and recipients
I9	Poor verbal/written communication and interpersonal skills
I10	Age differences
I11	Gender differences
I12	Lack of social network
I13	Differences in education levels
I14	Taking ownership of intellectual property due to fear of not receiving fair recognition and accreditation from managers and colleagues
I15	Lack of trust in people because they may misuse knowledge or take unfair credit for it
I16	Lack of trust in the accuracy and credibility of knowledge due to the source
I17	Differences in national culture or ethnic background; and values and beliefs associated with it (language is part of this)
Organizational	
O1	Integration of KM strategy and sharing initiatives into the company's goals and strategic approach is missing or unclear
O2	Lack of leadership and managerial direction in terms of clearly communicating the benefits and values of knowledge sharing practices
O3	Shortage of formal and informal spaces to share, reflect and generate (new) knowledge
O4	Lack of a transparent rewards and recognition systems that would motivate people to share more of their knowledge
O5	Existing corporate culture does not provide sufficient support for sharing practices
O6	Knowledge retention of highly skilled and experienced staff is not a high priority
O7	Shortage of appropriate infrastructure supporting sharing practices
O8	Deficiency of company resources that would provide adequate sharing opportunities
O9	External competitiveness within business units or functional areas and between subsidiaries can be high (e.g. not invented here syndrome)
O10	Communication and knowledge flows are restricted into certain directions (e.g. top-down)
O11	Physical work environment and layout of work areas restrict effective sharing practices
O12	Internal competitiveness within business units, functional areas, and subsidiaries can be high
O13	Hierarchical organization structure inhibits or slows down most sharing practices
O14	Size of business units often is not small enough and unmanageable to enhance contact and facilitate ease of sharing
Technology	
T1	Lack of IT systems and processes impedes the way people do things
T2	Lack of technical support (internal or external) and immediate maintenance of integrated IT systems obstruct work routines and communication flows
T3	Unrealistic expectations of employees as to what technology can do and cannot do
T4	Lack of compatibility between diverse IT systems and processes
T5	Mismatch between the needs and requirements of individuals and integrated IT systems and processes that restrict sharing practices
T6	Reluctance to use IT systems due to lack of familiarity and experience with them
T7	Lack of training regarding employee familiarization with new IT systems and processes
T8	Lack of communication and demonstration of all advantages of any new systems over existing ones

2.6 Knowledge Reuse Support for Codified Knowledge

In order to assist and realize the knowledge flow by learning from mistakes and other experiences over time, several tools and methods, here referred as knowledge reuse support (KRS), have been developed and deployed (Lehner & Maier, 2000). Examples of practices for lessons learned include Blogs and Wikis, Social Media and Web 2.0, Post Project reviews, Best Practices, E-learning and Training, A3, Engineering Checklists etc.

The objective of a KRS, including the knowledge repository, is to support organizational learning and increase organizational effectiveness by supporting the KM life cycle and in that sense assisting individuals in their decisions inside the organization (Alavi & Leidner, 2001). This can be conducted by providing knowledge assets held by knowledge repositories, which include explicit knowledge including routines and know-how, concepts, patents, technologies and designs (Ikujiro Nonaka, Von Krogh, & Voelpel, 2006). Levinthal and March (1993, p. 103) focus on how to optimize 'knowledge inventories', defined as collections of knowledge on "products, technologies, markets, and social political context" to decrease decisions under uncertainty. It follows a number of challenges in the optimization of such knowledge assets because of the uncertainty in the trade-off between knowing what, how and when you might need such assets in the future.

The knowledge taken care of by the knowledge repository is exclusively describing product and manufacturing systems and performed by the communication between man-computer, computer-computer and computer-man. The knowledge records are delimited to describe manufacturing system capabilities, guidelines of "know how" and ISO, as well as corporate standards in a product development context (Christoffer E Levandowski et al., 2013).

Dalkir (2013) states that successful knowledge sharing examples are codified in the form of lessons learned and best practices. It is further claimed that specific knowledge assets need an owner to be completed. Several definitions on knowledge ownership exist. In this thesis, it is defined as the knowledge responsible for the accuracy of the knowledge content and ensuring its validity over time (Jarvenpaa & Staples, 2001).

2.6.1 Informal and Formal Knowledge Codification for Building Knowledge Assets

Knowledge can be routed from its creation to reuse through either spoken form (personification strategy) or embodied in e.g. documents or software (codification strategy). The former are supported by KRS for **connection** while the latter, which is in focus in this thesis because of its possibility of transferring knowledge through time, is supported by KRS for **collection;** Figure 5 (Hansen, Nohria, & Tierney, 1999). The KRS can also be divided into different segments whether they be formal or informal.

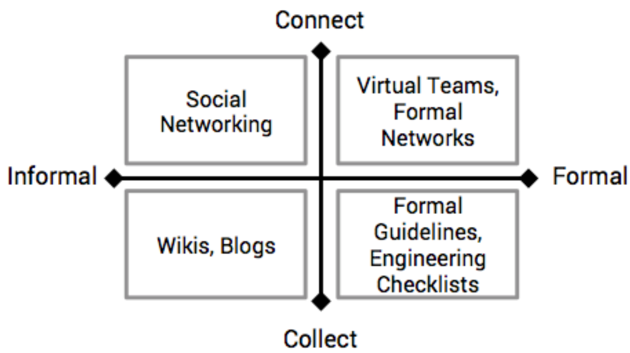

Figure 5. Knowledge reuse support can be roughly categorized across the spectrum of connect-collect and informal-formal.

The KRS is often not completely one or the other and four examples that span across the connect-collect spectrum are: (1) Communities of Practice, (2) Computer-supported Collaborative Work, (3) Information Systems, and (4) Knowledge-Based Engineering (McMahon, Lowe, & Culley, 2004). In all cases, KRS plays an important function which without it, the knowledge flow would be less effective (Riege, 2005).

The organization becomes a 'manufacturer' and 'steward' of such knowledge assets and KRS. Some of the knowledge assets need to be kept for current or future business and projects, whereas others may be discarded. Organizations may use KRS to assist the knowledge assets created by the knowledge work flowing through the KM life cycle. The knowledge work of product design is a continuous learning process; thus, the knowledge assets need to be dynamic and continuously changing to maintain their validity (L. Blessing & Wallace, 2000). A codification strategy can benefit from referring to experts or document authors to support interpretation of the codified knowledge in cases where its application is not straightforward, as well as increasing knowledge validity (Cross & Sproull, 2004).

Information technology (IT) is argued by Yeung and Holden (2000) to be important for knowledge reuse because it packages codified knowledge and makes it possible to distribute on a larger scale. IT for KM is commonly referred to as knowledge management systems (KMS). Related to KMS is Organizational Memory System (OMS) which is generally characterized by the fact that a whole bundle of tools is used, not an isolated single tool (Lehner & Maier, 2000). Corin (2015a) elaborates on five enablers that IT should embrace in order to support knowledge reuse:

(1) Discovery: Make knowledge accessible to users by enhancing search capabilities.
(2) Filtering: Extract only relevant pieces of knowledge to seekers to avoid cognitive overload, e.g. by using hyperlinks for linking details about its context.
(3) Storage: Create an organizational memory of explicit knowledge by using well-planned codification schemes.
(4) Collaboration: Mediate between knowledge seekers and knowledge holders by allowing them to find one another.
(5) Organizational scale: Enable the whole organization to access the knowledge repository to leverage its assets more broadly.

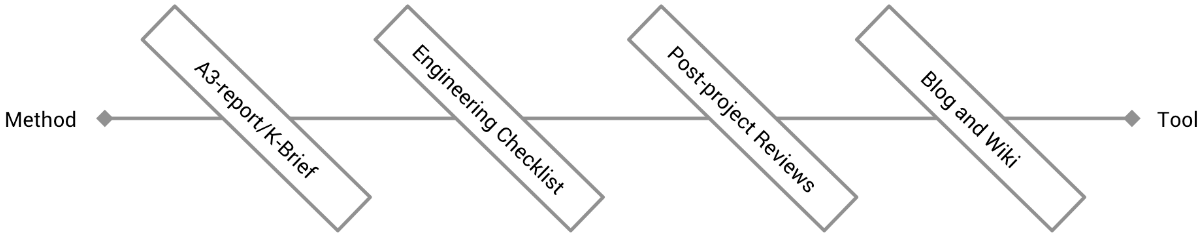

Figure 6. Knowledge reuse support roughly divided across the spectrum method-tool.

Do not forget that even if IT is interesting, the purpose and what needs to be achieved must be settled in order to define the basic thrust—striving to enhance knowledge processing (Firestone & McElroy, 2002).

Every KRS exists along a different scale between technical solution (tool) and method (Figure 6). People tend to view wikis more as a tool than a method, even if there is a method behind wiki. And the opposite pertains to A3.

A common misconception of KM tools is that the strategy "implement and they will come" will satisfy all needs and will automatically generate good knowledge work. Sadly, many KM initiatives fail due to an insufficient understanding and implementers then wonder why employees do not make use of this potentially great new tool, KRS. For KRS to be successful, it needs to take on a broader perspective in both holistic and user-centered terms. It needs to focus on the understanding of how improved knowledge work can affect and benefit specific individuals, groups, and the organization as a whole (Dalkir, 2013).

Even if this thesis is skewed towards the collection of knowledge, a balance between all circumstances is recommended. There is a risk of having to much knowledge collected in digital repositories because it easily leads to information overload and excessive costs for finding and making use of the knowledge (Garud & Kumaraswamy, 2005). Ideally, a KRS is only populated with knowledge that might be retrieved, rather than everything known to man (L. Blessing & Wallace, 2000).

2.6.2 Post-project reviews

Some practitioners suggest applying 'lessons learned meetings' towards the end of every project (Mascitelli, 2007) in order to prepare for the dissemination of knowledge into the organization. The concept is used in product development and is also referred to as post-project reviews. However, it has been found that post-project reviews carry at least four malfunctions:

- Typically carried out at the end of a project (Kotnour, 2000), when much of the project learning has already been forgotten
- Typically conducted by one individual, often the project manager (Busby, 1999; Kotnour, 2000; Williams, 2008)
- There is a lack of useful input, and such input is often stated in general terms (Bresnen, Edelman, Newell, Scarbrough, & Swan, 2003)
- The outcome is regularly a large, inaccessible record (Parry & Turner, 2006; Schindler & Eppler, 2003; Von Zedtwitz, 2002)

The concept of post-project reviews might be a useable model since it considers constructing individual knowledge into organizational knowledge. However, it must clearly be further elaborated. The four bullet points above indicate that post-project reviews include the risks of being ineffective. And since post-project reviews are widely used in product development, these projects are seldom as effective as they might be. Effectiveness in this case can be defined as a low chance of error. Fewer errors ideally indicate shorter lead times, lower development cost and better product quality.

An elaboration of post-project reviews suggests that much individual knowledge can feed a knowledge repository continuously between projects. This deduction is, however, not revolutionary. The concept of continuous improvements is known and thoroughly deliberated in research, for example in the concept of the knowledge value stream (Kennedy, 2008), the approach of Kaizen or, more specifically, post-project reviews by von Zedtwitz (2002).

2.6.3 Engineering checklist

According to Kennedy at al. (2008), the engineering checklist is the principal lean tool used by Toyota for knowledge reuse. Morgan and Liker (2006) state that such checklists serve as reminders of the things that must be done including design standards and knowledge captured through years of experience. According to Morgan and Liker (2006), engineering checklists are about "what a company has learned over time about good and bad design practices, performance requirements, critical design interfaces, critical quality characteristics, manufacturing requirements, as well as standards that communize design". Catic and Malmqvist (2013, p. 459) present the engineering checklist as a tool that presents what to do but "the knowledge on how and why can … be appropriate to exclude from the checklist and put in a reference document". Morgan and Liker (2006) further state that the most crucial part of utilizing the checklist effectively is to assign appropriate people that are responsible for continuously updating and maintaining the checklists, making sure that they reach the right recipients and fostering a "sense of ownership" without letting them ending up as meaningless activities that is performed because of requirements from management.

Kokkoniemi (2006) point out some important aspects to remember concerning Checklists. Catic & Malmqvist (2013) agree while reinforcing the importance of the last two aspects.

- The checklists must be as extensive as necessary without being excessively long.
- The checklists cannot take everything into consideration without stopping being effective.
- When the checklists are expected to become too long, it is advised to divide them into a number of separate checklists.
- The checklists are unique to every company and adapted to its specific needs.
- The checklists need be inspected after their generation.

Catic and Malmqvist (2013) state that the challenge using the method of creating engineering checklists is how to support product designers in transforming their experiences into applicable and legitimate knowledge encoded into engineering checklists that further on can be reused in a proactive way for a future project.

2.6.4 Blogs & Wiki

Knowledge repositories based on Web 2.0 solutions, such as blogs and wikis, have been proposed as means of facilitating knowledge-sharing (C. E. Levandowski et al., 2012; Standing & Kiniti, 2011). Wikis are web pages for collaborating between multiple users and differ from other websites because they allow users to collaborate by adding and editing their content while keeping track of each other's contributions (Standing & Kiniti, 2011). However, these repositories still require a culture of sharing and collaboration as well as ease of use in order to be effective (Wagner & Prasarnphanich, 2007). Some people voluntarily take on the role of "information shapers" who reorganize and edit content to improve readability and searchability for others (Yates et al. 2010). However, there is often a lack of policies on how to manage the content of corporate wikis and who should be allowed to correct the information submitted by others (Standing & Kiniti 2011).

2.6.5 A3 Reports

A known tool in the LPD process is the **A3 Report**, which originally refers to Toyota's form of communicating purposeful information and systematically solve problems, all on a single sheet of paper (Morgan & Liker, 2006). The name "A3" originates from a paper size (297 × 420 mm), which seems to be an appropriate size to limit report space available to the creator. When the A3 report has been written, it is usually stored digitally on the organizational server. A characteristic of A3s is the standardized form that makes it easier to read (Kennedy, 2008; Morgan & Liker, 2006; Shook, 2008; Sobek II & Smalley, 2011).

To increase understanding and enable thorough information in spite of its compact form, visual information is recommended to the largest possible degree (Shook, 2008). The size limit fosters well-defined descriptions of a single concentrated subject, which can be positive as well as negative in that multiple A3s may be created to describe different aspects of a subject, resulting in an increased number of reports. In the LPD literature, different types and purposes of A3 reports are suggested, although only problem-solving A3s are highlighted in this thesis (Morgan & Liker, 2006; Sobek II & Smalley, 2011).

Problem-solving A3s encourage systematic problem-solving (while questioning the problem from different functional units), including problem formulation and experimental design, which address high quality solutions to immediate local problems. Important to remember is that if a problem is small enough and local enough, it might not even need an A3. However, most problems benefit from the added rigor that writing a problem-solving A3 provides (Raudberget & Bjursell, 2014). Saad et al. (2013) argue that A3 reports work well for knowledge capture and further references but do not elaborate on how to store the A3s for effective accessibility.

2.6.6 Summary

The literature reviewed on Knowledge Reuse Support for codified knowledge can be summarized as follows:

- Challenges in optimizing KRS are for example knowing what, how and when you might need the knowledge in the future.

- Five enablers that IT should support in order to support knowledge reuse include Discovery, Filtering, Storage, Collaboration and Organizational scale (Corin Stig, 2015b).
- Post-project reviews often carry at least four malfunctions:
    - Typically carried out towards the end of a project (Kotnour, 2000) when much of the project learning has already been forgotten
    - Typically conducted by one individual, often the project manager (Busby, 1999; Kotnour, 2000; Williams, 2008)
    - There is a lack of useful input, and such input is often stated in general terms (Bresnen et al., 2003)
    - The outcome is regularly a large, inaccessible record (Parry & Turner, 2006; Schindler & Eppler, 2003; Von Zedtwitz, 2002)
- The engineering checklist aims to remind the engineer on things that must be done throughout the PDP (Morgan & Liker, 2006).
- Morgan and Liker (2006) point out a crucial part of utilizing engineering checklists effectively, which is to assign appropriate people responsible for continuously updating and maintaining the checklists while making sure that they reach the right recipients and foster a "sense of ownership".
- The engineering checklist needs to be kept short and cannot consider all knowledge (Kokkoniemi, 2006).
- Blogs & especially Wikis aim to foster collaboration on the creation of codified knowledge assets. However, they still require a culture of sharing and collaboration in order to be effective (Wagner & Prasarnphanich, 2007).
- Blogs & Wikis often lack policies on how to manage the content (Standing & Kiniti 2011).
- One strategy behind the A3 format is to limit the space in order to foster the creation of visual information and well-defined descriptions in concentrated forms (Shook, 2008).

2.7 Sustainability

Sustainability in a PD context is broad and there is no simple way of how to develop 'sustainable products'. The Circular Economy is a concept continuing to gain interest across society and is a key strategy to improve the resource efficiency of products by focusing on reuse, refurbishment, remanufacturing and recycling (Allwood, Cullen, & Milford, 2010; Chen & Graedel, 2012). An instrument by which to achieve this is Product Service Systems (PSS) combined by traditional products. Isaksson et al. (2009) conclude that manufacturers increasingly offer services that are integrated into their traditional products (Ljungberg, 2007; Tukker, 2013). They also argue for an integrated development approach for both products and services. Such an approach stresses the need for service designers to be involved in the development of the artifact, whereas traditional product developers need to be involved in the service design.

Ljungberg (2007) defines a good sustainable product as a product, which will give as little impact on the environment as possible during its life cycle while still giving as much satisfaction as possible to the user, who is not always in line to create a trade-off. To be able to perform these trade-off decisions, proper knowledge needs to be considered which presents a major challenge for industry both in the design of products, business models and reprocessing used products.

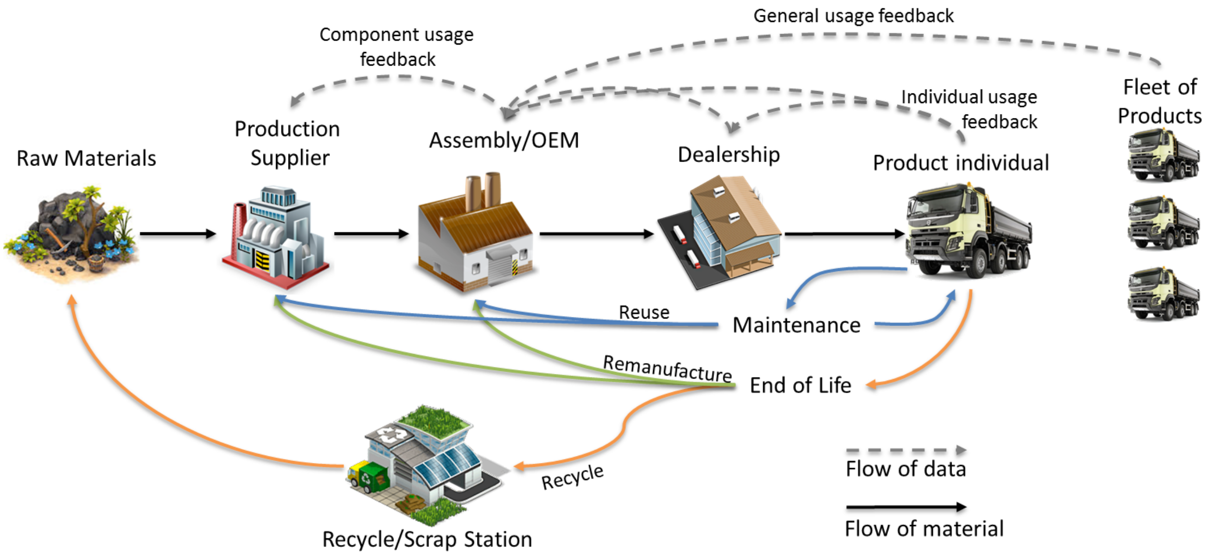

Figure 7. Component and information flow from latter to earlier phases. The figure also illustrates the data from individual products and fleet of products, which can be used in different ways in earlier phases.

During the PD phase, most product properties are defined. As elaborated earlier, designer decisions should be based on knowledge and in the lean philosophy, a major focus is on product stakeholders (customers and users), who drive the importance of product individual data from customers (Oehmen et al., 2012; K. Ulrich & Eppinger, 2011). However, the product should be designed to consider all product life-cycle phases, including manufacturing, use/service and end-of-life to facilitate sustainability involving optimization for reuse, remanufacturing and/or recycling (D. Maxwell & Van der Vorst, 2003). Remanufacturing places requirements on product design to facilitate disassembly and upgrading, whenever necessary (Sundin & Lindahl, 2008). Blevis (2007) agrees on the need for upgrading products and elaborates on the fact that people seem to have a strong preference for new things over old. Today, few products are designed with remanufacturing in mind (Hatcher, Ijomah, & Windmill, 2011).

A fully functioning KRS has the potential for moving knowledge from all product life-cycle phases to PD to allow designers to make decisions based on knowledge regarding product sustainability. Kurilova-Palisaitiene et al. (2015) investigated five (four large and one small) remanufacturing companies and the results show that even if remanufacturers create a comprehensive set of valuable data and are willing to share their information, it seldom flows back to earlier phases. They refer to this as the *information bottleneck*. In the case companies *"no attempt to pull or push remanufacturing product information to PD was observed"* and in a majority of the case companies, there exist no channels for interaction between product designers and remanufacturers, and therefore they were unaware of the data available (Kurilova-Palisaitiene et al., 2015, p. 784).

This points up a need for a functioning knowledge flow from latter phases into PD (Figure 7), and the need to present knowledge in a way that can be useful to engineers in their quest to make more sustainable products (Tukker, 2013).

3 RESEARCH APPROACH

To obtain credible research results, different disciplines have varying approaches and the research carried out should be supported by a correct research methodology. This chapter describes the methodology that has been chosen as the basis for the research performed, why it was chosen and how it has been adopted.

3.1 Design research and science

Many different definitions of design exist and engineering design is generally referred to as the field of activities that generates products using different PD methods. Here design is a broad term stretching from specific needs from customer and other stakeholders to a finished product or knowledge.

Design research has three major and overlapping phases: experimental, intellectual and empirical (L. T. Blessing & Chakrabarti, 2009). The experimental phase existed until 1950 and focused on design seniors and their work explaining and writing about design processes. These observations were specific to the domain they described and were not placed into any framework. The intellectual phase followed and remained for around 20 years. The emphasis moved to design processes and a variety of methodologies to create a design basis. The latest phase, empirical, started in the 1980s with empirical studies. The empirical phase investigated the impact of new methods and tools on the process on how designers performed their design processes. This requires a good understanding of what the process looked like beforehand.

3.2 Design research methodology

The research methodology should be chosen with respect to the research gap and research questions. It should be clear that the research methodology could help collect the data to answer and discuss the research questions. The methodology behind this research was based on Blessing and Chakrabarti's (2009) proposed Design Research Methodology (DRM) for conducting research on topics related to this field. Other related research methodologies include the qualitative study theory by Maxwell (2012), the case study theory by Yin (2013) and Gerring (2006), and the theory in relation to information and system research by Williamson (2002). The research into design science is based on the research tradition of the university department and its strong relation to mechanical development, both as a field and as company relations. Blessing and Chakrabarti argue that in order to meet both practical and academic contributions, DRM strives to fulfill two purposes, first to understand the object being studied and then propose tools, methods or guidelines that can be applied. Therefore, there is greater freedom for the researcher in the creative part of the research to find new ways to deal with the questions studied. The DRM consists of four main stages and employs an iterative methodology that means that the implementation of the stages is not necessarily executed in the chronological order (Figure 8). It is not often possible to perform all four within the boundaries of a single research project (L. T. Blessing & Chakrabarti, 2009).

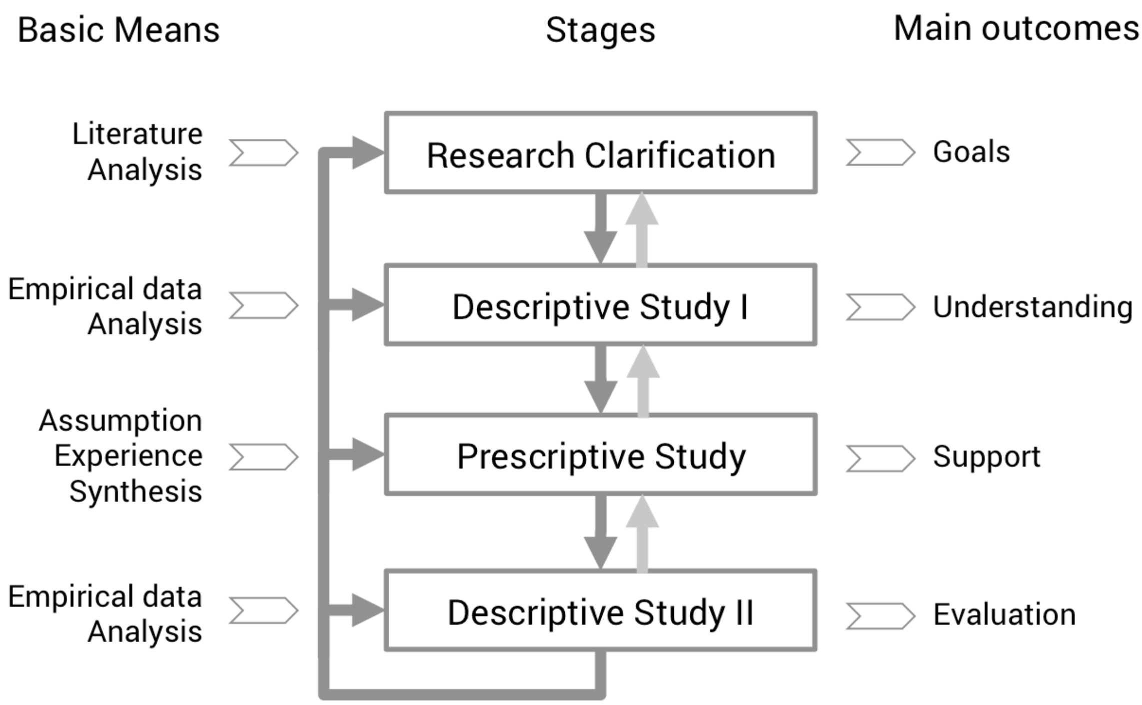

Figure 8. The DRM framework, redrawn from Blessing and Chakrabarti (2009)

The first stage is research clarification (RC) and the main goal is to define a success criterion that will evaluate research success. The main source of information and method at this stage is literature study. In the next stage, the descriptive study I (DS-I), the researcher usually tries to clarify the situation and detect possible problems and research gaps. At this point, an extensive literature review is performed together with empirical analysis, if necessary, to increase understanding. The prescriptive Study addresses the gap between the current and desired situation. The researchers decide on a focus where the understanding gathered by DS-I can provide guidance and an intended support designed in order to evaluate the concept and verify the underlying assumptions. The descriptive study II (DS-II) aims at evaluating the true effects of the support implemented.

3.3 Applied Research Methodology

All appended papers are preceded by a literature review. Paper B is furthermore a broad analysis of quantitative data collected from a survey while Papers A and C are based on interviews, observations, workshops and implementation. The interviews are supported by observations, informal meetings and surrounding discussions to gather contextual information. Papers A and C are what Blessing and Chakrabarti (2009) refer to as Type 2 Studies including RC, DS-I and initial PS whereas Paper B is Type 1 including RC and DS-I (Figure 9).

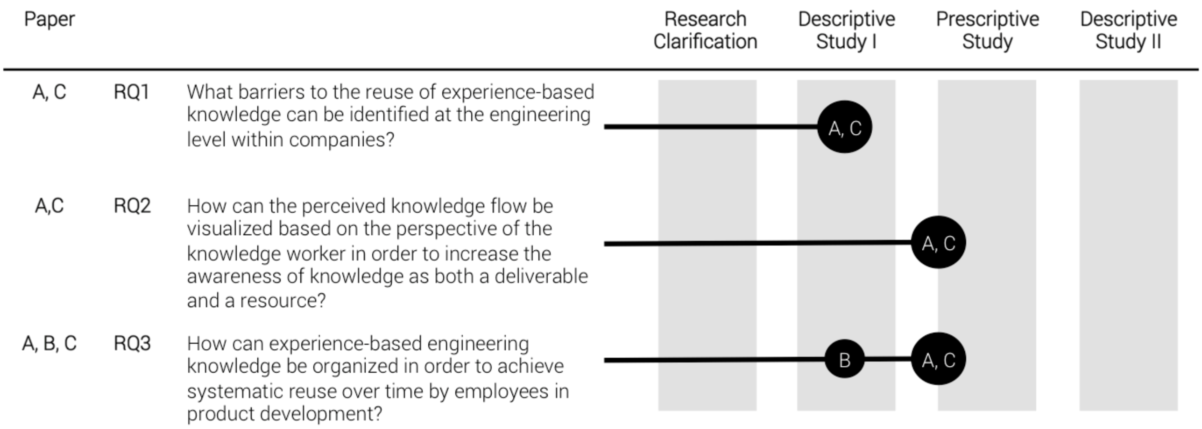

Figure 9. Distribution of Papers A-C in the context of DRM framework

I. Paper A

This research was based on a qualitative exploratory-descriptive design and entails conceptual or theoretical research. First, a literature review was performed mainly focusing on the field of KM where the KM life cycle and related barriers were investigated. Interview material collected by Dag Bergsjö and Daniel Corin Stig during 2013 worked as a basis for grasping an understanding of the knowledge work at case company A and to build up the materials for the upcoming semi-structured interviews. A simple model for the knowledge management life cycle (create, capture and (re)use) was used to map the questions for the interviews. Eight interviews were performed in company A to improve the understanding of current practices and eventual barriers related to the KM life cycle. Ten interviews with managers from different organizational departments were interviewed from case company B. Data were recorded both through brief notes and sound recordings, after approval from the respondents. Documents and written processes were collected to form the basis of the type of knowledge that was transferred in a codified form. For a couple of days (6-8 full days), observations were performed in case company A to understand the communication flow and a similar approach was used for case company B but for a longer time period (a total of 40 days). A content analysis followed during which the data were further on codified into properties connected to knowledge work and mapped into various sources, such as interviews, observations or documents. All these activities formed the basis for understanding the barriers that existed in the companies connected to knowledge reuse. Both the model and an early draft of a KRS were presented at a workshop for further validation at company A. A first version of the KRS was then developed and implemented for two different products in an ongoing project at company A. The cross-case research approach was used because it is always more representative of the population (Gerring, 2006).

II. Paper B

The main objective of this paper was to illuminate and evaluate which KRS was available and used by organizations. In order to achieve this objective, literature was studied to frame KM. Further, an exploratory survey was designed and run through face-to-face interviews. The data have been collected between March 2012 and

February 2013 in Italy, within the GeCo Observatory[1] research initiative. The survey also served as a preliminarily investigation into the existence of significant relationships between the use of a list of KRS, and the adoption of modularization and standardization methods.

In total 15 KRSs were considered and statistically analyzed. To test if there were a statistical relationship between the KRS and the adoption of modularization and standardization, the Kruskal Wallis test was used. This test was particularly appropriate when there was an independent variable with two or more levels and an ordinary dependent variable. Moreover, it can be considered the non-parametric version of ANOVA since it admits other normally distributed populations, as in this case (Bruin, 2006). The aim of the analysis was to test the null hypothesis of equality in the use of Modularization/Standardization methods across populations. To reject the null hypothesis basically means that there is a significant relationship between the use of modularization and standardization and the use of the KRS considered. In other words, it investigated if the higher the use of all (or some) of the KRS investigated, the higher the use of modularization and standardization. Only the statistical relationship was tested at this phase, whereas further research would be required to explain causality.

III. Paper C

A case study was assigned to follow up on the transformation to knowledge-based development for the case company. The process was ongoing and had been active for several years back in time. One of the authors of Paper B, Henrik Mathiesen, had the opportunity to be an observer during more than a year and a half. Daniel Stenholm and Dag Bergsjö performed three semi-structured interviews conducted in order to grasp an understanding of the flow, barriers and potential improvement in the knowledge work of the companies. The interviews were followed up with seven semi-structured interviews, each roughly one hour long, to build a knowledge asset for one of the products developed for many years. The knowledge asset was implemented in the KRS that was a continuation of the KRS implemented at the case company in Paper A. The knowledge document was presented in two workshops, which gave the researchers the opportunity to improve the content in-between these workshops.

3.3.1 Results

The KM life cycle was developed to fit the needs of the case companies and to create a common ground for communication, as well as increasing the understanding of the researchers. As explained earlier, the KM life cycle was seen from a designer perspective and was developed based on both theory and designer explanations on how their knowledge work processes take place. On the basis of the initial research, the first version of the model was generated. Subsequently, this first model version was submitted for analysis, appraisal and validation for all studies presented, resulting in a final version.

The same procedure was applicable to the development of the KRS, ECS, that was presented as a draft version in study A (Paper A) and then developed during its implementation in the case companies from Paper A and Paper C.

[1] *Italian research initiative launched by the Business School of Politecnico di Milano, which investigates the topic of innovation, product development and design (http://www.osservatori.net/progettazione_plm).*

4 SUMMARY OF APPENDED PAPERS

The three appended papers cover different aspects on how to support knowledge reuse in PD. Mainly three different case companies were studied and two of them worked as pilot cases for implementation of a KRS based on the method developed for the purpose of increasing knowledge reuse. In both cases, a basic understanding of work methods was investigated to set the basis for further research.

Paper A focused on understanding the knowledge flow in two case companies concerning PD, in addition to the barriers that exist today when performing different process steps in their knowledge work.

Paper B is a broader study exploring several tools and techniques for knowledge reuse described in theory and examine the extent to which companies use them today. The paper also aims to give a broader understanding of KRS used to support the knowledge work when a company has a strategy for the modularization of its PD.

Paper C explores four LPD practices that can be used to support knowledge reuse. The focus is to support all process steps found in Paper A and with relatively simple and visual means overcome some of the barriers identified.

4.1 Paper A

The purpose of Paper A was to explore how each individual product designer perceives the knowledge flowing in the organization and what type of barriers exist to obstruct that flow. PD projects are expected to deliver results according to project goals. However, long-term success (over product generations) risk to diminish when little time is given to knowledge capture and reuse (Kennedy, 2008). Effects of inefficient KM become apparent when valuable knowledge is lost over time, for example in one of the case companies where valuable knowledge about designing gear boxes first was lost due to an expert leaving the company and a second time when the need for more space resulted in physical knowledge records in folders being thrown away.

The result from the study was a KM life cycle explaining the knowledge flow from the designer point of view and to improve KM by overcoming some core barriers. Instant knowledge work was presented as mind-set.

The KM life cycle is described from an individual perspective in order to understand the knowledge work, which is why project managers may find the model appealing. The research is prescriptive since the approach is founded on the systematic mapping of industrial KM issues and where incentives to find practical solutions are presented.

In the field of KM, a distinguished challenge is found when valuable knowledge remains solely in the minds of project members (whether in compiled facts or “know-how”). The overwhelming strategy and balance between short-term and long-term effectiveness and success are seen to be critical. The respondents state that they are not measured on the rate of knowledge shared but only on time, cost and quality. Even if the creation of “knowledge documents” linked to experience were stressed, it was more of an *ad hoc* approach not directly tied to the project process. During the study, an initiative started which included creating A3s for critical problems that led to the redesign of a product after its launch in recent years. The task was handed out to each responsible manager who was given some hours each week to create the documents. When managers were asked why they have not created as many A3s as planned, the common explanation was time, not only to create the document, but also to get in contact with all parties involved who in their turn were not up-to-date with the information. The managers did not either see the benefits because the problem had already been solved and were not convinced of the benefits of the documents. That time pressure had a negative effect on engagement in knowledge sharing was further supported by Connelly et al. (2013).

Some respondents said that in other organizations in which they have worked, there had been a feeling of hoarding knowledge to secure their place in the organization. But in the case company, this was not the case. Instead, there was a mentality to help each other and take time to explain.

The KM life cycle that evolved from the case study is based on theory and empirical data, has its base in OK and follows the individual knowledge application involving four processes ("acquisition", "creation", "refinement", "transfer/sharing") and three decision points ("knowledge reused", "knowledge created", "knowledge captured"). In every decision point, the individual is encouraged to take action on what the past process has given and how to move on to the next step. The model describes how the individual travels in the model domain - searching for knowledge in the repository, understanding knowledge records, detecting a knowledge gap, closing the gap by creating new knowledge, codifying the knowledge into a record and, finally, making new knowledge available by feeding it back into the repository.

The core barriers identified at the case companies are such factors as a lack of time to perform KM activities, low accessibility and availability of knowledge, non-updated knowledge assets, motivation to utilize knowledge, knowing what, when and how to store knowledge, the fact that individuals tend to forget and non-user friendly software. The two case companies wish to act long-term in the way they present themselves and their initiatives and in their work of creating OK. However, the study shows that the processes are *ad hoc* and assume low priority.

There is also a mind-set change included in the model in order to distinguish the individual contribution to the company's aggregate knowledge capabilities. The first half describes the processes from an individual benefit perspective (eg. "what knowledge do I need?" and "what is the benefit of my work?"). However, the second half of the model describes the processes from a future user/organizational perspective (e.g. "what knowledge do future users need?" and "what is the benefit of the work for future users?").

In the final phase of the study, Instant Knowledge Work was presented as a way of working with the knowledge asset at the case companies, which involves the opportunity to directly work on a legitimate document with instructions and being able to update it continuously during the process. This way of working was influenced by Web 2.0 and Wiki. Aspects that came up and need to be taken care of were: (1) the necessity to keep valid and reliable even if every user can make changes, (2) the risk of being too heavy – not crisp and clear and, (3) supporting and user friendly editing options.

4.2 Paper B

The purpose of Paper B was to illuminate and evaluate the extent to which KRS is used in companies today. Totally 15 KRS were studied that aimed to support learning between projects, as well as capturing and reusing knowledge. The knowledge concerned in the KRS is design knowledge that is often stored in people's mind. In collaboration with Politecnico di Milano, quantitative data from 103 companies with at least one site in Italy were studied. The research also investigated the relationship between KRS and the degree of modularization. The companies studied in Sweden and Norway for Papers A and C have a modular approach to standardize their products to increase effectiveness and quality in their products, which lay the foundation for choosing the variable. In Figure 10, the KRS is presented.

It emerge from the study that from the between the different KRS presented earlier, the checklists and written design rules are potentially supporting modularization and standardization by showing that they coexist. Compared to lessons learned documents (referred as post-project reviews earlier), wiki and blogs do not coexist with high degree of standardization and modularization.

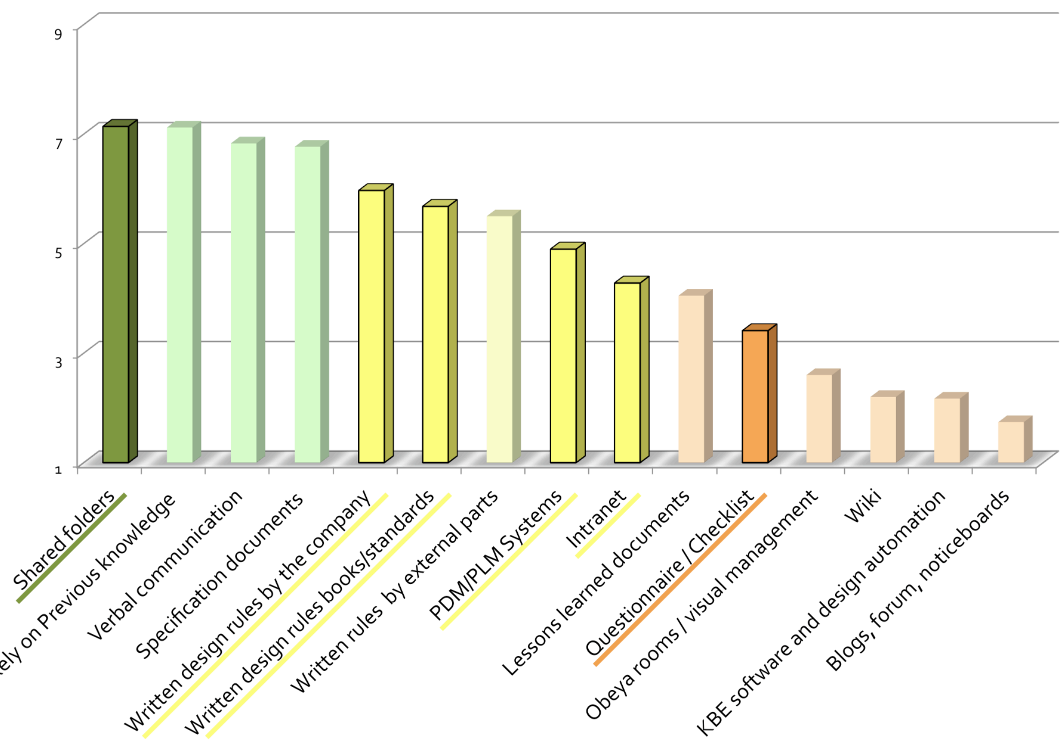

Figure 10 Summary of generic KRS available. The extent of use is shown on the y-axis with 0 as no-use and 9 as completely used, the colors of the bars also indicate the degree of use, low, medium or high. The bars with bright color indicate significant relationship to modularization.

4.3 Paper C

The purpose of Paper C was to explore the use of LPD practices focusing on knowledge in a development company and focusing on the integration between the knowledge value stream and product development (Figure 11). The case company referred to their transformation as going from traditional PD to Knowledge Based Development (KBD), which presents ways of restructuring and improving their organization to centrally focus on knowledge and learning as critical to PD. The case company in this paper was Kongsberg Automotive (KA) and its goal for the transformation was to decrease repetitive problems and time to markets, as well as increasing quality by reusing knowledge to a greater extent than previously. KA mainly adopted three different practices and towards the end of the study, they tested a pilot on the fourth practice. The practices were LAMDA as a culture, A3 for problem-solving, trade-off curves for visualizing feasible design areas and the KRS developed during the study in Paper A to support knowledge reuse and decision-making. The idea was to generate useful knowledge about both current products/projects but also incorporating a process of continuous learning in the company.

KA adopted the practices and during the time a change in mindset was shown, people become aware of the knowledge on another level than before. Instead of only focusing on building better products, learning was added as a part of their PDP outcome and knowledge was asked for as a separate deliverable from the managers. The KRS developed by the research group within the Vis-IT project for Paper A was further tested and an early pilot was implemented in a small group. The pilot indicated good potential but needed further testing on a larger scale to be able to give any major conclusions.

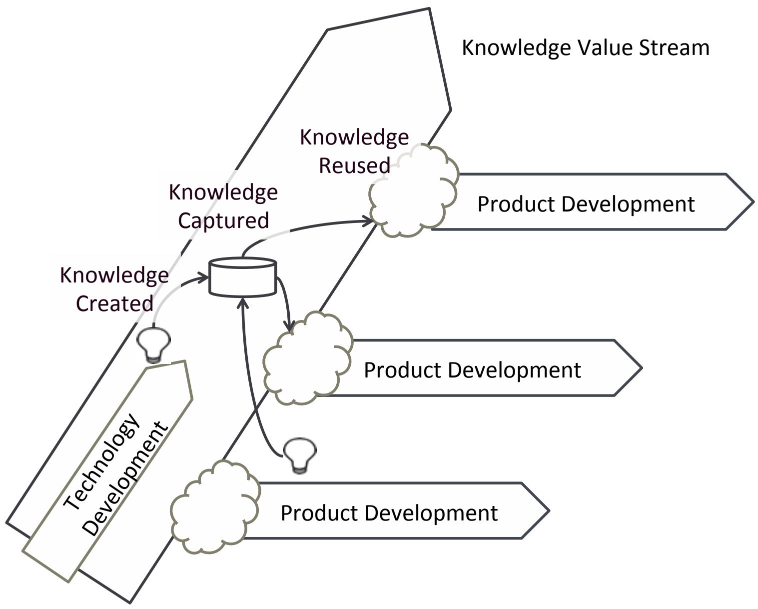

Figure 11 Knowledge Value Stream adapted from Kennedy (2008)

4.4 Analysis

Considering the exploratory research questions in this thesis and the overlap between papers, the key contributions will be presented in this section. To prepare for the next chapter where the results will be presented in relation to theory and further synthesis be conducted, Table V summarizes the key contributions from each paper in relation to the three research questions.

Table V. Summary of the key contributions to answering the research questions from the papers appended.

Item #	Result	Paper
RQ1: What barriers to reuse of experience-based knowledge can be identified at the engineering level within companies?		
R1.1	Strategy - only measuring the project success based on time, cost and quality decreases the focus on creating knowledge assets for future use.	A, C
R1.2	People forget - trying to create codified knowledge assets after the knowledge has been created requires more effort and the result is often less than anticipated.	A
R1.3	*Ad hoc* approach to working with knowledge reuse.	A
R1.4	Waste in knowledge work is hard to see, and therefore can be hard to improve.	A, C
RQ2: How can the perceived knowledge flow be visualized based on the perspective of the knowledge worker in order to increase awareness of knowledge as both a deliverable and a resource?		
R2.1	In the case companies, the engineers often felt that the need for decisions or actions drove the need to first acquire knowledge.	A, C
R2.2	The case company showed a difference in the long-term goals communicated (increase knowledge refinement and reuse) regarding KM and what was measured as success criteria in the projects (time, cost and quality).	A, C
R2.3	The managers stressed the importance of creating knowledge documents, but did not stress the need for reusing them to the same degree. For example, creating LL documents.	A, C
R2.4	The case companies stated that the process of refinement was built on an *ad hoc* approach in many cases and forced by the managers.	A
R2.5	The case company had a tendency to focus on capturing knowledge even if they understood that the value was gained when reusing knowledge.	C

R2.6	The study showed that the mean value for the companies was between 81-100 % of how much they relied on previous PD knowledge.	B
R2.7	The case companies showed that the individual mind-set was different. Regarding the focus on individual benefits (e.g. "what knowledge do I need?" and "what is the benefit of my work?") compared to future user perspectives (e.g. "what knowledge do future users need?" and "what is the benefit of the work of future users?"). The former is of much higher focus.	A

RQ3: How can experience-based engineering knowledge be organized in order to achieve systematic reuse over time by employees in product development?

R3.1	Low possibility of interacting with the codified knowledge limits the possibility to edit and comment on the content, which might affect the validity in an ever-changing environment.	A
R3.2	Long descriptions reduce the prospects that readers perceive all essential aspects.	A
R3.3	Support knowledge reuse even if people are leaving their position for different reasons.	A
R3.4	"Something is often better than nothing". One respondent pointed out the need for at least defining a place where knowledge should be codified to make it possible to begin sharing.	A
R3.5	A lack of routines for when to use/search for different knowledge documents interrupts the flow. The heavy amount of documents makes it difficult to acquire it all.	A
R3.6	The case companies experienced their document database to be out-dated and wished a more user-friendly system.	A
R3.7	The case companies wished to see an overview of their design processes to get insights into how they were doing according to plan.	A
R3.8	The case companies experienced a need to be told when knowledge did not exist.	A
R3.9	The case companies proposed that outdated knowledge should be moved to a separate database. For example, knowledge about older products, which are no longer produced.	A
R3.10	The case companies experienced a need for having a standardized document with self-explaining structure that supported them in the process of codifying knowledge.	A
R3.11	The case companies identified the need to simplify the process of absorbing necessary knowledge into an effective and standardized approach for new recruits.	A
R3.12	The case companies saw a direct need for securing their knowledge for future needs.	A

R3.13	A case company wanted to link knowledge documents to other documents, as well as experts and web pages.	A
R3.14	The case companies experienced a need of connecting the knowledge documents to the development process.	A
R3.15	The case companies saw the need for supporting visualization of the knowledge to increase understanding and to speed up the acquisition phase.	A
R3.16	The case companies expressed concerns about a knowledge asset that could be editable by each user: (1) necessary to keep valid and reliable even if every user can make changes, (2) the risk of being to heavy – not crisp and clear and, (3) supporting user-friendly editing options.	A
R3.17	The case company saw a need for continuously working with LL due to the simple fact that people forget.	C
R3.18	A case company experienced that A3 is good for discussions, sharing and workshops, not for knowledge reuse.	C
R3.19	Company interviews supported the need to create a process to regularly review, evaluate, and standardize LL and prepare them for implementation.	C
R3.20	Organizational commitment is necessary when adapting the process to a new way of working which is a change both physically and in the mindset of all parties.	C
R3.21	A3, guidelines and standard documents do not support knowledge reuse in a satisfactory way. Low adaptation to the users and their work methods.	C
R3.22	The study shows that LL documents and Checklists are more regularly used over wikis and blogs. But specification documents and written design rules are even more heavily used.	B
R3.23	The study shows that companies that prioritize the adoption of rules for respecting legal constraints and quality performance tend to update their formalized knowledge and retrieve and reuse previous knowledge.	B
R3.24	A case company expressed the viewpoint that the way in which to reach knowledge documents is to most often ask colleagues.	A, C
R3.25	The checklists of today check us when we reach a gate, instead of supporting us during the stage where we actually need it.	A

5 SYNTHESIS

This section aims to synthesize the results and answer the research questions.

5.1 Barriers to experience-based knowledge reuse

RQ1: What barriers to the reuse of experience-based knowledge can be identified at the engineering level within companies?

The interviews and observation studies performed for Papers A and C provided insights into which barriers to knowledge reuse that could be found within the case companies. Besides the empirical data collected, there is much to learn about barriers to knowledge reuse over time. The empirical findings from this research align well with existing literature on barriers to knowledge reuse, such as the willingness of employees to contribute (Watson & Hewett 2006), the ability to access the knowledge within an appropriate time frame (Weber et al., 2001), seeing the practice as useful (Watson & Hewett 2006) and time for exploration (Riege, 2005).

A precondition for effective knowledge reuse is that a reusable knowledge asset has been created in the first place. The interviews from the case companies indicate that efforts have been undertaken in creating knowledge assets, but that the focus has not been on *reusable* knowledge assets. Creating knowledge assets in the hope of someone finding them valuable has been seen as inefficient. Finding the right receiver and context is troublesome, something that was also found in the literature (Riege, 2005). The further away a potential reuser resides, the less intrinsic the motivation by the author who may not even value the codified knowledge asset for his own future use (Markus, 2001).

The degree of barriers can be measured by how easy the codified knowledge asset is and to what extent it is valuable to users. The same measurement can be used to rate the knowledge asset itself. The case companies describe their checklists to be of low value even if literature stresses their benefits. The study in Paper A elaborates on the difference between a checklist that is expressed in a check-do or do-check way, where the latter is currently used. The result showed that the checklists used, for example at a gate, were only used as a control tool from management and of low or no value for the engineers even if that was the expressed purpose by management.

A common barrier found in literature is the lack of trust in people because they may misuse knowledge for personal winning. But this barrier was not confirmed in any of the case companies and might depend on a cultural difference between countries as well as a cultural change over time.

5.2 Knowledge Management Life Cycle

RQ2: How can the perceived knowledge flow be visualized based on the perspective of the knowledge worker in order to increase the awareness of knowledge as both a deliverable and a resource*?*

The proposed KM life cycle and its processes are based on theory and empirical data from the case studies in Papers A and C. Although the processes are presented as independent and sequential, it has been seen that the process is not always one-directed, so going back and forth in the life cycle is common as are processes performed in parallel. Sometimes a process can be neglected and it is possible to skip it and go on to the next. The life cycle is a general model so the studies show that it is dependent on the situation and the emphasis and/or level of detail with which each process is performed. The cycle addresses a broad range of learning from all types of sources: personal experience, formal education and training, peers, and intelligence from all sources.

The flow of knowledge goes through different processes that together build up the KM life cycle (Figure 12). The base is in OK and followed by the KM loop represented by the processes *acquire, assess, apply, create, identify, refine and disseminate* described from the engineering level. It presents how an engineer travels in the process domain – searching for knowledge assets based on the knowledge gap detected, obtaining and grasping potentially valuable knowledge, assessing and evaluating the utility and value of the knowledge, applying it by adapting the knowledge to fit the context, closing the possibly remaining gap by creating new knowledge through extending or replacing existing knowledge, identifying potentially valuable knowledge for future use, accumulating the essential knowledge in the refinement process and, finally, making the knowledge available by establishing methods to transfer and share knowledge for increased accessibility and availability.

The study in Papers A and C shows that before the engineer starts to travel inside the KM life cycle, some sort of knowledge request needs to be triggered and can depend on numerous reasons, some of which include decision-making, knowledge gap analysis, problem-solving or innovation. If the knowledge is known before, either by the organization or outside, the process starts with acquiring. Otherwise it starts with creation. Most often some knowledge is known from before but needs to be expanded to solve the request.

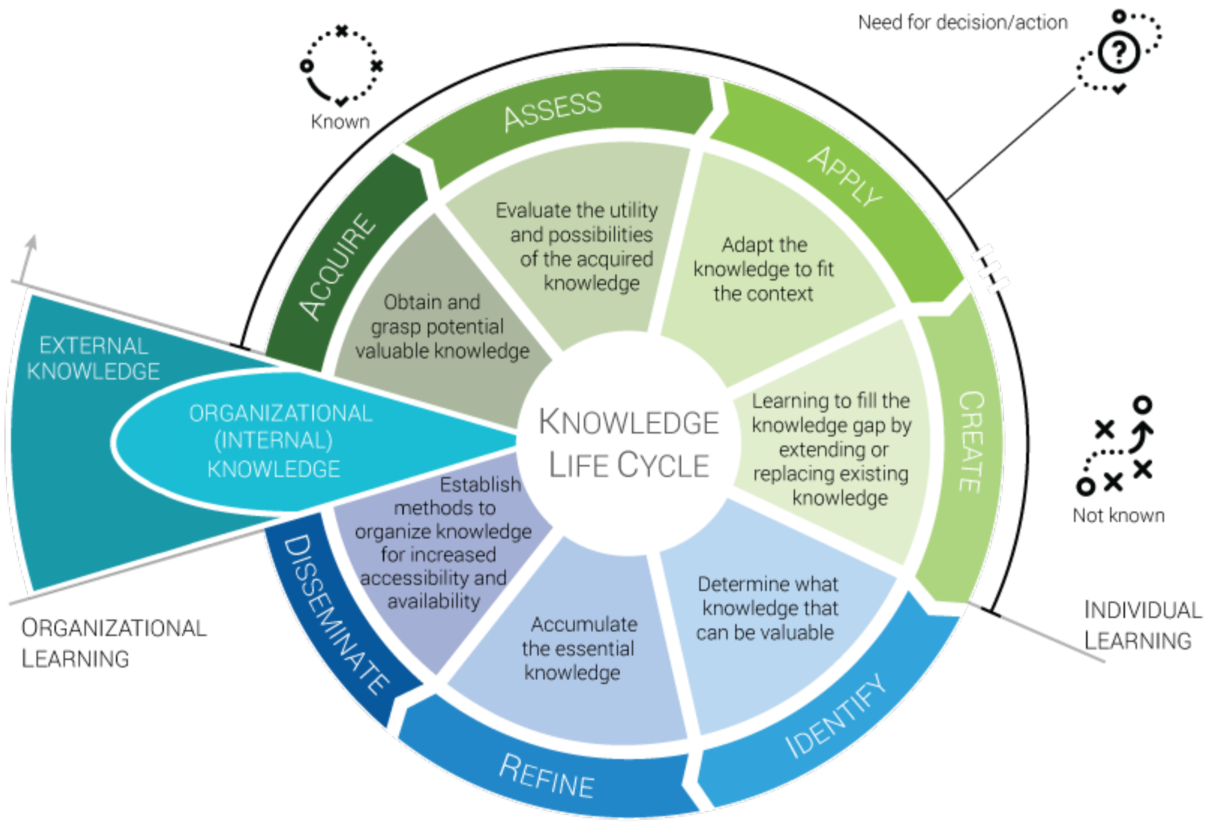

Figure 12. Proposed Knowledge Life Cycle including seven activities. The first four are integrated into individual learning, whereas the final three need to be added to add potential for organizational learning.

To explain the KM life cycle, each process is presented below.

5.2.1 Acquire

Knowledge acquisition means adding, for the individual but not necessarily for the organization or external parties, new knowledge and involves searching (Menon & Pfeffer, 2003), sourcing (William R. King & Lekse, 2006), recognition, and the assimilation of potentially valuable knowledge assets until they are understood. External acquisition such as grafting (Huber, 1991) (adding desired knowledge from outside in the form of an individual) and searching from external sources are also part of the knowledge acquisition process. Important to remember is that it is not uncommon for organizations to seek knowledge outside their boundaries, when the knowledge may already exist inside. Included in this process is also the decision to certify the validity and reliability of the knowledge assets. Some common organizational initiatives that assist these steps can be expert interviewing, information and workflow analysis and apprenticeships programs.

In all case companies, the most common way of accessing experience-based engineering knowledge was through personal contacts, which is also found to be a common preference in the literature (Cross & Sproull, 2004). Most employees had been with the company for several years so they have built up their internal social network, whereas it was not that easy for new employees. In the case of company C, they started to understand the problem of personification when a key person for one of their oldest products was about to retire and they understood that most of the engineering knowledge had not been codified.

The study in Papers A and C shows that the intrinsic motivation for the four first processes are higher than the rest, which are connected to that they solve their own problems and see the direct benefits, whereas the rest of the processes are primarily beneficial to someone else, if they are beneficial at all.

5.2.2 Assess

The assessing process involves both analyzing and assessing the knowledge assets based on specific organizational rules, cultures and evaluation criteria. The analysis involves reviewing and extracting what appears to be valuable in the asset and abstracting it further to find potentially underlying knowledge. The assessment in this process is meant to identify and extract patterns and relations, and then evaluate the value of the asset as a feasible solution to the current problem or decision. Methods and tools used for this process can be TRL (Mankins, 1995) and TERA (Stig, Isaksson, Högman, & Bergsjö, 2015).

People in the case companies expressed their concerns about the validity of the knowledge acquired from documents and expressed that a common way was to call the author to make sure that his knowledge was up-to-date. One person from the study for Paper A expressed concerns about what type of questions to ask if the knowledge captured from one project was applicable to the next project.

5.2.3 Apply

This is the process where the knowledge assets really show their value and are put to use. It is worth remembering is that unless this phase is accomplished successfully, the potential value of all of the other KM efforts is discarded. Duffy et al. (1995) defines 'design by reuse' as the process of designing something by applying previous knowledge, found either in the minds of experts or stored in objects such as documents, software and prototypes. The knowledge assets can be applied throughout an organization to solve problems, improve efficiency, promote innovative thinking and make decisions. Codified forms of knowledge can be found on different complexity levels and may not, by themselves, translate into understanding but need some work to be put into fulfilling their value. Understanding what is needed in order to adapt a knowledge asset in an efficient and correct way to a new problem may require deep expertise, which then needs to be made available to development projects (Smith & A. H. B. Duffy 2001). In a functional organization or where there are active communities of practice, this expertise is likely more available, and knowledge assets that explain the design rationale and history of previous designs help this recontextualization process (Smith & A. H. B. Duffy 2001; Busby 1999). Knowledge assets from various sources often need to be understood and applied in order to efficiently being able to discover remaining knowledge gap. When this process is finished, the knowledge gap between what we currently know inside our organization and what we need to know must be defined in order to move on the process of "creation".

5.2.4 Create

Knowledge creation involves learning to extend or replace existing knowledge and is triggered when there is a need for new knowledge and when the apply process did not fulfill the need. The knowledge that has been applied can be the foundation for creating new and refining existing knowledge through work. This can be with help from other individuals, both inside and outside the organization (socialization), adding knowledge from different explicit knowledge sources to create new knowledge (combination) or for example learning by doing which is using knowledge from different explicit sources to gain new tacit knowledge (internalization) (Ikujiro Nonaka, 1994). Common activities can be prototyping and testing.

5.2.5 Identify

New knowledge is gained, and this is the vital decision point where one needs to identify and consider if the knowledge would be valuable for future users or not, and if so, continue into the refinement phase. There is little use in refining the knowledge with which every engineer is familiar. Most interest is on the knowledge that differentiates experts from novices: the specific knowledge and experience gained during the PD (L. Blessing & Wallace, 2000). It is also of interest to consider if it would be extensible knowledge, which is when the knowledge has value outside of the specific product for which it was developed (Radeka, 2015).

Duffy et al. (Duffy et al., 1995) defines the identification process as the first two of three parts of 'design for reuse', identify and extract possibly reusable knowledge assets. Tacit, or implicit, knowledge must be explicated through methods such as network analyses or brainstorming sessions before moving on to the refinement process where it becomes codified and organized into an appropriate format. Based on this process, if the knowledge assets are found to be valuable, they would proceed to the refinement process. During the identification process, it is critical that emphasis is put on quality and relevance of the knowledge extracted. Common methods, which are closely connected to the identification process as well as the refinement process, take place after action reviews, reflection time, and lessons learned. There are certain cases where new knowledge does not lead to actions in the refinement process such as:

- When the learning simply supports previous learning, or existing guidelines.
- When the occurrence was 'one-off' and is unlikely to happen again.
- When the lesson might not be a lesson, but rather an observation or comment.

The respondents confirm that this process is challenging and takes extra time compared to just capturing all data and information created during a project.

5.2.6 Refine

The refinement process is where the knowledge that has been identified and deemed valuable becomes codified and/or encapsulated into assets (e.g., documents in electronic and print format and/or live demonstrations and observations of artifacts). Explicit knowledge needs to be formatted and evaluated according to a set of criteria and then becomes ready to be disseminated within the organization. The refinement process needs to include two opposing actions; an existing knowledge record can be either updated or replaced, or a completely new knowledge record can be composed with new knowledge (L. Blessing & Wallace, 2000). Capturing knowledge generated in the creation phase after the event requires considerable additional effort and results in a retrospective account. Depending on the frequency of capturing, this may result in a loss of important knowledge. Examples of methods that can support the refinement process are the creation of best practices, lessons learned etc. There are probably three possible types of actions performed during the refinement phase:

- Documenting procedure or process.
- Updating documented procedure or process.
- Updating training course, other training or e-learning material.

Respondents from all case companies state that this process gains the largest attention by management.

5.2.7 Disseminate

This is the process during which the knowledge asset becomes stored as an active component in the organizational knowledge such as knowledge repository. Beyond their intrinsic value, knowledge assets must be stored in a structured way that allows them to be efficiently acquired. Related common activities include metatagging, annotating, classifying, archiving, linking, optimizing for search and retrieval, in addition to creating templates. Dissemination includes both transfer and sharing; transfer means preparing for the availability and accessibility to a specified receiver and sharing is for an arbitrary receiver. This process involves both internal and external dissemination and is important, as employees are seldom aware of its existence, particularly when new knowledge is created and refined. Having an explicit, dynamic, and flexible network of expertise (e.g., community of practice) fosters collaboration and can greatly support the dissemination of knowledge assets.

This process is often referred to as an interaction between engineer and the KRS during the interviews and relating back to the barriers, this is often viewed as barriers to the IT tools. Furthermore, the activity of deciding what type of words/sentences to use when classifying the codified knowledge asset is considered to be a difficult task.

The dissemination of more tacit forms of knowledge may be supported through mentoring, procedures, culture, coaching, competence and process mapping, as well as through storytelling, narratives, and anecdotes.

5.3 Engineering Checksheets

RQ3: How can experience-based engineering knowledge be organized in order to achieve systematic reuse over time by employees in product development?

The KRS for organizing and working with knowledge assets developed based on performed research, combining past research in the field and new case studies, is named engineering checksheets (ECS). ECS takes the positive aspects of the common KRS for succeeding with managing lessons learned based on experience e.g. Engineering Checklists, Post-project reviews, A3-reports, blogs and wikis. It also includes aspects of the theory behind, e.g. actionable knowledge. Especially Catic and

Malmqvist's (2013) model for Engineering Checklists forms a basis due to its similarities and aims to serve the same purpose.

The ECS does not try to capture all existing knowledge and tell the engineer exactly what to do; instead, the aim of the KRS is to hold the hand of the engineer while designing and supporting the maneuvering during an oftentimes fuzzy process. It helps to reveal some known obstacles along the way and is a way of creating a more "naked" design process to prepare the designer for the problems that might occur instead of designing blindly without being prepared for the problems that the process might produce. Some people in the case companies feared that using a checklist might kill the creativity and innovation energy, but an important aspect of the ECS is that it attempts to capture and present the pitfalls that needs to be avoided and best practices—not exactly how the designer needs to execute activities. In other words, the ECS helps to identify decisions as early as possible in the process to get them out of the way, all the while securing the decision to be based on existing knowledge. Even if some decisions needs to be pushed forwards in the process, understanding what needs to be known before making the decision is valuable.

In today's world, information is seldom far away when we need it. For example, if an engineer wants to know more about a turbo engine, the best way is probably to search for it on internet and take some time to read and watch instructional videos. Twenty years ago, this information was a lot harder to acquire. This is why the OK (company specific) is the most important knowledge to capture—the knowledge that has been built up through mistakes and experience, often during a long time and not just a few clicks away. ECS aims to pinpoint the knowledge upon which the expert bases his decision, even if it is based on a gut feeling. The studies in Papers A and C have shown that there is often something behind the gut feeling that can be described and codified.

5.3.1 How ECS is structured

ECS is collecting best practices based on experience and mistakes made in the past and aims to support the designer both to indicate important decisions that needs to be made and also pointing out the direction to avoid problems that have happened before. The focus of ECS is to support all the KM life cycle processes except creating and since many comparative methods on the use side (acquire, assess and apply) of knowledge assets fail, ECS puts an additional focus on supporting these processes. All efforts of refining and disseminating knowledge are of course wasteful if they are not used in the future. ECS is based on knowledge "nuggets", pieces of knowledge that are important and later referred to as knowledge elements (KE). This is similar to the engineering checklist where each KE starts to explain what to do (know-what) (Catic & Malmqvist, 2013). Studies show that many documents that exist today to support developers are built up with long texts and often contain important knowledge but this knowledge is frequently lost in all the fuzz of the rest. By slicing up the knowledge (into KE), it is a lot easier for the designer to compile and acquire everything and making sure that he really takes that knowledge into concern when designing. In a checklist, each check tends to reflect backwards, what has been done, compared to the ECS where the KE is described in terms of upcoming decisions/actions (compare "have you/did you" with "be sure/keep in mind/be aware that").

Table VI. Description of the structure of a knowledge element.

	Know-What	Know-Why	Know-How
One knowledge element include	Action/decision that needs to be made	Why does this specific action need to be undertaken? Why is it important?	How will this actions/decision be made?

Based on the theory of knowledge categorization, the design rationale and knowledge about how and why are needed (beyond know-what) to obtain reusability, which is not always the case with engineering checklists (Catic & Malmqvist, 2013). Moreover, the ECS needs to be reusable, meaning that it needs to be a part of the design process, while at the same time providing the opportunity to understand, learn and also improve the KEs. An engineering checklist that only tells someone what to do is easy to use, but is not reusable in giving a deeper understanding and facilitating the possibility of continuous improvements (Morgan & Liker, 2006).

The ECS has a structure that inhibits KEs to be divided into three layers based on knowledge types (know-what, know-why and know-how) to foster knowledge reuse and continuous improvement (Table VI) (Alavi & Leidner, 2001; Lundvall & Johnson, 1994). Other relevant types of knowledge (know-when and know-who) are provided by the PDP.

To assist the designer in the decision/action that needs to be made, each KE can include such items as text, symbols, images, illustrations, trade-off curves and references to other documents, artifacts and people. Each KE strives to be as understandable and visual as possible. Furthermore, the KE needs to follow the rule "less is more" and quality rather than quantity as it may be confusing and hard to understand if it is overly extensive. It will require some effort for the refinement process to succeed. The aim is for ECS to work as a reuse asset to assess the organizational specific knowledge for the specific case and guide the designer where to go for additional knowledge, if necessary.

The case studies in Paper A show that product designers want openness, support and the possibility of getting free hands when it comes to the order in which things are done and they tend to feel locked up when following a strict process, which in many cases is the way they feel about checklists. They feel that their innovation capacity is then held back. The ECS can thus be organized into different categories where related KEs fit in, e.g. needs & requirements, concept, detail design and verification & validation. ECS captures best practices without being ordered into a strict format to follow a specified process. An important aspect connected with capturing best practices is continuous improvement of which standardization is one part. By collecting best practices into KEs, a basis for standardization is created that aims to decrease the risk of running into the same problem again.

5.3.2 How to create an ECS

How to create an ECS is based on the practices of Kokkoniemi (2006) and Catic and Malmqvist (2013) for creating checklists and has been developed and evaluated in practice within the companies when generating ECSs (see

Figure 13). In the first phase, somebody becomes aware of the need for an ECS when for example problems recur on cables mounted to the speaker of a car. The second phase contains the recognition of individuals who hold knowledge that may be of value, such as expert interviews and collection of company specific data. Interviews have shown the best results in connection to efficiency – three meetings, each between one to maximum two hours with an expert.

The analysis and generation phase is when the ECS is starting to be shaped. Three interviews result in a process that bounces back twice before continuing to the fourth phase (workshop). The main objective of the three first phases is to increase awareness of how to recognize experiences that can be transferred to the ECS and to obtain a solid foundation with relevant and actionable elements of the ECS.

The workshop is performed when the ECS has a fair amount of elements (somewhere around 20) and it is then opportune to show it to various engineers or people affected by products design in order to ask their opinion and gather more knowledge. The workshop aims to sharpen the already existing KEs but also to stimulate and find hidden experiences within the participants. When moving on to the adoption phase, the ECS is more or less finished. The adoption phase consists of deployment of the ECS to ensure its relevance and validity. It is usually reasonable to carry out the adoption with a critical mindset to make sure that the knowledge inside is correct. After the adoption phase, the ECS is ready to be used as part of the design process and according to the company cases, it often consists of 25-40 KEs. However, this does not mean that the process is complete, probably the opposite since the process of refining the ECS will be a continuous process until its retirement or its content is transformed into another form, e.g. automation.

In total, the completion of an ECS can take up to approximately 50 hours. But it is important to remember that ECS is a dynamic tool and supposed to be changing whenever new knowledge has been gained.

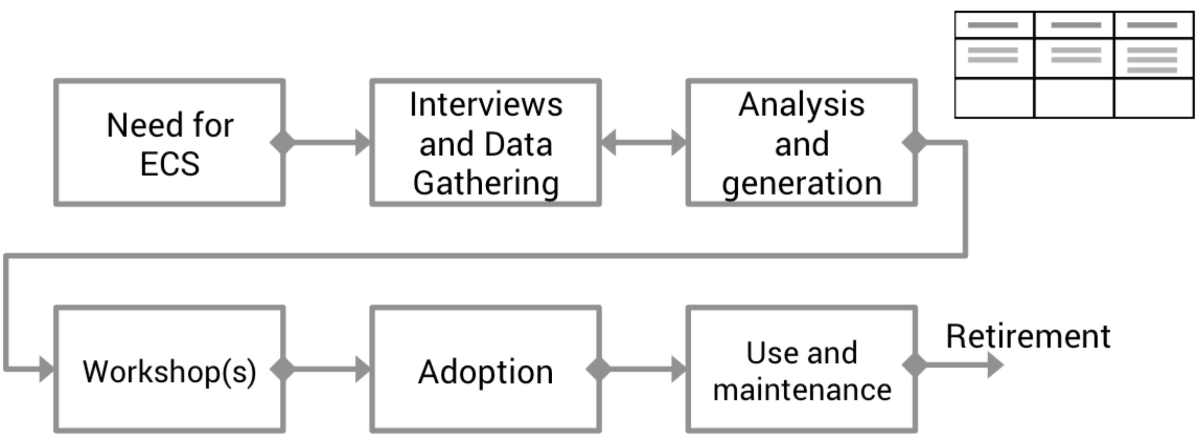

Figure 13. Method describing how to create an ECS

The practice of creating an ECS has been developed and evaluated during several cycles which only says that this is the best practice available today. So far the process has been accepted and supported by the respondents who often reflect over the conclusion that the ECS holds a lot more actionable knowledge than they could have imagined from the beginning.

5.3.3 How to use and maintain ECS

Ideally, the ECS should be so good, easy to use and supportive that the designer wants to use it, which means that the need of controlling the use will in the long run hopefully not be necessary.

To succeed with the maintenance and validity of the case studies, each ECS needs a person, for example a knowledge owner (KO), responsible for the content to ensure it is correct and updated. This is not always easy to establish because in concurrent engineering, there are often several people involved in a design part during the PDP.

Regardless of how the ECS is exactly implemented according to the design process, it is necessary that it be executed and simultaneously updated. The update can either come directly from the KO or as a proposal from the executor of the ECS for better support of the refinement process (maintaining ECS based on new knowledge). By instantly updating the ECS, solutions to recent issues are fresh in the minds of the product designers and knowledge is captured and made reusable. Therefore, it might be beneficial to detect learning cycles and identify possible ECS elements as outcomes.

The value of ECS mainly comes from the use of knowledge when making engineers aware of decisions early on in the PDP and being able to support the process with appropriate rather than incomplete knowledge. Decisions based on incomplete knowledge are often revisited when detailed product/process design and verification testing uncover problems with the decisions (Augustine et al., 2010). Theoretically, in order to front-load decisions, knowledge from various functions can be presented without decreasing the need for different people to be involved early on. In traditional stage-gate processes when several decisions need to be made between phases, the ECS helps to divide these into smaller decisions to support them with related knowledge.

The ECS has been tried out in incremental product development where the product and needs are known and the design space is relatively limited compared to more open solutions as is the case with fully innovative solutions. However, there can still be innovative and creative solutions when it comes to incremental product development but starting bandwidth and past knowledge are often more defined.

6 VALIDATION

This section aims to discuss the results presented in the Synthesis chapter. Additionally, the quality of the results in relation to the research approach will be discussed.

6.1 Discussing the results

The verification of research results can be performed by *Verification by acceptance* and *Logical verification (Buur, 1990)*. Verification by acceptance focuses on having new scientific contributions accepted by experts within the field. Research can be considered logically verified when it is complete, internally consistent and externally consistent.

The results presented in this thesis were shared and analyzed with a broad range of experts to achieve external acceptance. More explicitly, all papers have been undergoing peer reviews as part of the publication process. All papers have been presented at conferences as podium presentations where experts within the field and other disciplines had opportunities to express their opinions about the findings.

Additionally, as a part of the external verification process, the preliminary findings have been presented at a seminar for the industrial partners of the Wingquist Laboratory. The results have also been presented to the various industrial partners inside the Vis-IT project for evaluation. The methodological procedure of generating a model based on literature review and then having it verified by experts has also been used by, for example, *King et al* (2008) and *Orzano et al* (2008).

External consistency is reached when the results agree with established theory. The synthesis is based on known frameworks for both the KM life cycle as well as the ECS but has been adjusted to fit the context and overcome identified barriers. The author sees both them contributing to the evolution of existing models with particular application to the engineering level. Internal consistency is reached when no conflicts are found between individual elements in a theory.

6.2 Research quality

Managing threats that follow qualitative research, which the studies performed mainly are, is an issue that needs to be considered after the research has begun (J. A. Maxwell, 2012). A qualitative approach and case study have been used for the descriptive elements of this research to ensure validity. Yin (2013) proposes four steps; internal validity, external validity, construct validity and reliability.

Additionally, Maxwell (2012) suggests triangulation as a way of managing validity threats, including both how the results should be presented and to whom.

- The qualitative research was conducted in three different companies, developing products in the same field, yet different products,

- the respondents were from different departments and have occupied different roles in the company, being interviewed through workshops, face-to-face individual meetings and by different researchers,
- apart from interviews, observations and document analyses were performed,
- the results were presented in writing at peer-reviewing conferences, experts and presentations at the Wingquist laboratory,
- the proposed KRS, ECS, have been implemented for four different products in two different companies.

7 CONCLUSIONS

Knowledge reuse is an approach for companies to systematically maintaining product quality and standardize while enabling continuous improvement. This method has previously mainly been studied from a business strategy and management perspective. This research attempted to contribute to theory by studying the implications of knowledge reuse at the engineering level, with particular focus on existing challenges for the effective reuse of experience-based knowledge reuse. The research also aimed to contribute to practices leading to the development of a KM life cycle to shed light on the processes that need to be performed in order to create effective knowledge reuse. The research also proposed a KRS, ECS, for organizing knowledge to help engineers succeed in managing the steps of the KM life cycle.

Principally three different companies were studied in connection with this research. All three companies performed product development at the sites studied and are working in the automotive industry. The overall approach of the research was guided by Design Research Methodology and included both descriptive and prescriptive elements. In the descriptive phases, literature reviews, observations and interviews with engineers and managers served as the primary methods for data collection. The development of the KM life cycle framework and ECS for the prescriptive parts of the research were based on both findings from the empirical studies and existing literature, mostly from the academic field of knowledge management.

The first of three research questions posed in this thesis concern barriers on the engineering level to efficient knowledge reuse. A mismatch has been observed between the knowledge sources available to designers and the knowledge sources accessed by designers. Possible reasons for this mismatch are a lack of accessibility, availability and trustworthiness. All the case companies state and confirm that knowledge is often stored in another form than current practice suggests. A common barrier seems to be lack of time, but at the same time, engineers talk about the need for always prioritizing between tasks. Thus, this can be related to what is measured in the success of a product, which is often related to time, cost and quality, which do not include valuable knowledge that are created for future use. Managers seem to focus mainly on the fact that if knowledge were codified, it would automatically be reused, something that is not always supported by the studies.

The second research question aims to understand the processes that follow a request for decision or action at the engineering level. The KM life cycle built on theory and case company studies has proven to be a valuable tool in understanding and mapping the processes, which a product developer goes through when working with knowledge. The cycle also points out what processes that need to be in place to obtain effective knowledge work. It clearly shows that the intrinsic motivations for working with knowledge assets go down (between create and identify) when most product developers encounter major barriers to finding motivation.

The final research question focuses on how knowledge can be organized to increase knowledge reuse. The current KRS does not appear to deal with the high focus on knowledge reuse, because it only addresses part of the knowledge life cycle. The proposed KRS, ECS, was not developed to explicitly address the knowledge life-cycle.

However, the concept is suitable for forming the basis for knowledge life-cycle support because it is a way of indicating context, which is the basis of understanding.

The ECS model for succeeding with knowledge management when it comes to knowledge based on experiences and mistakes (often stored in people's minds), and connected to specific products has shown positive outcomes and great potential. It has been observed that waste is more difficult to discover in product development than in, for example, manufacturing. ECS aims to visualize the knowledge into KE to make it easier for the engineer to make sure that specific knowledge has been considered. Each KE is also divided into separate layers and answers as to what, how and why in each decision or action point that gives the engineer a deeper understanding and opportunity for improvement. Due to the small sample size of our study, it obviously limits our ability to draw broad conclusions. Therefore, the findings should be considered exploratory and preliminary, but nevertheless serve as an indicator of a model for supporting the organization with the knowledge management life cycle.

8 FUTURE WORK

The work outlined in this thesis is mainly of the Descriptive I and Prescriptive types and has led to new research questions and further implementation and testing correlating to Descriptive II. Future research will more deeply investigate the concepts explored in this thesis, verifying them in industrial contexts and extending them to new endeavors. The following questions provide a selection of starting points for upcoming research in the field of knowledge reuse in product development.

- How can the level of knowledge management implemented be measured?
    - How the effectiveness of goals, strategies and knowledge activities is difficult to measure and differs between companies (Argote & Ingram, 2000).
- How can the level of knowledge reuse influence organizational effectiveness?
- How can ECS support knowledge exchange between different specialist areas that influence each other?
- How can ECS support knowledge originating from remanufacturing data to be presented to the engineers in PD?

9 REFERENCES

Ackoff, R. L. (1989). From data to wisdom. *Journal of Applied Systems Analysis, 16*, 3-9.

Alavi, M., & Leidner, D. E. (2001). Review: Knowledge management and knowledge management systems: Conceptual foundations and research issues. *MIS quarterly*, 107-136.

Allwood, J. M., Cullen, J. M., & Milford, R. L. (2010). Options for achieving a 50% cut in industrial carbon emissions by 2050. *Environmental science & technology, 44*(6), 1888-1894.

Argote, L., & Ingram, P. (2000). Knowledge transfer: A basis for competitive advantage in firms. *Organizational behavior and human decision processes, 82*(1), 150-169.

Argyris, C. (1996). Actionable Knowledge: Design Causality in the Service of Consequential Theory. *The Journal of Applied Behavioral Science, 32*(4), 390-406. doi:10.1177/0021886396324004

Augustine, M., Yadav, O. P., Jain, R., & Rathore, A. P. S. (2010). Concept convergence process: A framework for improving product concepts. *Computers & Industrial Engineering, 59*(3), 367-377. doi:10.1016/j.cie.2010.05.009

Barros, V. F. d. A., Ramos, I., & Perez, G. (2015). Information systems and organizational memory: a literature review. *JISTEM-Journal of Information Systems and Technology Management, 12*(1), 45-63.

Bauch, C. (2004). *Lean Product Development: making waste transparent.*

Baumeister, J., Reutelshoefer, J., & Puppe, F. (2011). Engineering intelligent systems on the knowledge formalization continuum. *International Journal of Applied Mathematics and Computer Science, 21*(1), 27-39.

BenMoussa, C. (2009). Barriers to Knowledge Management: A Theoretical Framework and a Review of Industrial Cases. *World Academy of Science, Engineering and Technology, 30*, 901-912.

Blessing, L., & Wallace, K. (2000). Supporting the knowledge life-cycle *Knowledge Intensive Computer Aided Design* (pp. 21-38): Springer.

Blessing, L. T., & Chakrabarti, A. (2009). *DRM: A Design Reseach Methodology*: Springer.

Blevis, E. (2007). *Sustainable interaction design: invention & disposal, renewal & reuse.* Paper presented at the Proceedings of the SIGCHI conference on Human factors in computing systems.

Boisot, M. (2013). The Creation and Sharing of Knowledge. *Knowledge, Organization, and Management: Building on the Work of Max Boisot*, 109.

Boothroyd, G. (1994). Product design for manufacture and assembly. *Computer-Aided Design, 26*(7), 505-520.

Brandt, D., & Hartmann, E. (1999). Editorial: Research topics and strategies in sociotechnical systems. *Human Factors and Ergonomics in Manufacturing & Service Industries, 9*(3), 241-243.

Bresnen, M., Edelman, L., Newell, S., Scarbrough, H., & Swan, J. (2003). Social practices and the management of knowledge in project environments. *International Journal of Project Management, 21*(3), 157-166.

Brown, S. L., & Eisenhardt, K. M. (1995). Product development: Past research, present findings, and future directions. *Academy of management review, 20*(2), 343-378.

Browning, T. R. (2000). *Value-based product development: refocusing lean.* Paper presented at the Engineering Management Society, 2000. Proceedings of the 2000 IEEE.

Bruin, J. (2006). newtest: command to compute new test. UCLA: Academic Technology Services, Statistical Consulting Group.
Busby, J. S. (1999). An assessment of post-project reviews. *International Journal of Project Management, 30*(3), 23-29.
Buur, J. (1990). A theoretical approach to mechatronics design.
Cacciatori, E., Tamoschus, D., & Grabher, G. (2012). Knowledge transfer across projects: Codification in creative, high-tech and engineering industries. *Management Learning, 43*(3), 309-331.
Carrillo, P., Ruikar, K., & Fuller, P. (2013). When will we learn? Improving lessons learned practice in construction. *International Journal of Project Management, 31*(4), 567-578. doi:10.1016/j.ijproman.2012.10.005
Catic, A. (2011). *Knowledge-based Engineering in Product Development Processes-Process, IT and Knowledge Management perspectives*: Chalmers University of Technology.
Catic, A., & Malmqvist, J. (2013). Effective method for creating engineering checklists. *Journal of Engineering Design, 24*(6), 453-475. doi:10.1080/09544828.2013.766824
Chen, W.-Q., & Graedel, T. (2012). Anthropogenic cycles of the elements: A critical review. *Environmental science & technology, 46*(16), 8574-8586.
Choo, C. W. (1996). The knowing organization: How organizations use information to construct meaning, create knowledge and make decisions. *International Journal of Information Management, 16*(5), 329-340.
Clark, K. B., & Wheelwright, S. C. (1992). Revolutionizing product development: quantum leaps in speed, efficiency, and quality. *New York: NY*.
Collins, C. J., & Smith, K. G. (2006). Knowledge exchange and combination: The role of human resource practices in the performance of high-technology firms. *Academy of management Journal, 49*(3), 544-560.
Connelly, C. E., Ford, D. P., Turel, O., Gallupe, B., & Zweig, D. (2013). 'I'm busy (and competitive)!' Antecedents of knowledge sharing under pressure. *Knowledge Management Research & Practice, 12*(1), 74-85. doi:10.1057/kmrp.2012.61
Cooper, R. G., & Kleinschmidt, E. J. (1994). Determinants of timeliness in product development. *Journal of Product Innovation Management, 11*(5), 381-396.
Corin Stig, D. (2015a). *Technology Platforms: Organizing and Assessing Technological Knowledge to Support its Reuse in New Applications*: Chalmers University of Technology.
Corin Stig, D. (2015b). *Technology Platforms: Organizing and Assessing Technological Knowledge to Support its Reuse in New Applications.* Chalmers University of Technology.
Cross, R., & Sproull, L. (2004). More Than an Answer: Information Relationships for Actionable Knowledge. *Organization Science, 15*(4), 446-462. doi:10.1287/orsc.1040.0075
Dalkir, K. (2013). *Knowledge management in theory and practice*: Routledge.
Davenport, T. H., & Prusak, L. (1998). *Working knowledge: How organizations manage what they know*: Harvard Business Press.
Davenport, T. H., & Prusak, L. (2000). *Working knowledge: How organizations manage what they know*: Harvard Business Press.
Dixon, N. M. (1999a). The changing face of knowledge. *The Learning Organization, 6*(5), 212-216.
Dixon, N. M. (1999b). *The organizational learning cycle: How we can learn collectively*: Gower Publishing, Ltd.
Drucker, P. F. (1994). *Post-capitalist society*: Routledge.
Duffy, S. M., Duffy, A., & MacCallum, K. (1995). A design reuse model.

Dunham, A. H., & Burt, C. D. B. (2011). Organizational memory and empowerment. *Journal of Knowledge Management, 15*(5), 851-868. doi:10.1108/13673271111174366

Duverlie, P., & Castelain, J. (1999). Cost estimation during design step: parametric method versus case based reasoning method. *The International Journal of Advanced Manufacturing Technology, 15*(12), 895-906.

Easterby-Smith, M., & Lyles, M. (2003). The blackboard handbook of organizational learning and knowledge management. *Oxford: Blackwell Published.*

Epple, D., Argote, L., & Murphy, K. (1996). An empirical investigation of the microstructure of knowledge acquisition and transfer through learning by doing. *Operations Research, 44*(1), 77-86.

Evans, M., Dalkir, K., & Bidian, C. (2014). A Holistic View of the Knowledge Life Cycle: The Knowledge Management Cycle (KMC) Model. *Electronic Journal of Knowledge Management, 12*(2), 148-160.

Firestone, J. M., & McElroy, M. W. (2002). Generations of knowledge management. *Executive Information Systems, Inc.*

Garud, R. (1997). On the distinction between know-how, know-why, and know-what. *Advances in strategic management, 14*, 81-101.

Garud, R., & Kumaraswamy, A. (2005). Vicious and virtuous circles in the management of knowledge: The case of Infosys Technologies. *MIS quarterly*, 9-33.

Garvin, D. (1993). Building a learning organization. *Harvard business review, 71*(4), 78.

Gerring, J. (2006). *Case study research: principles and practices*: Cambridge University Press.

Gold, A. H., Malhotra, A., & Segars, A. H. (2001). Knowledge management: an organizational capabilities perspective. *J. of Management Information Systems, 18*(1), 185-214.

Gorga, É., & Halberstam, M. (2007). Knowledge inputs, legal institutions and firm structure: towards a knowledge-based theory of the firm. *Nw. UL Rev., 101*, 1123.

Grant, R. M. (1996a). Prospering in dynamically-competitive environments: Organizational capability as knowledge integration. *Organization Science, 7*(4), 375-387.

Grant, R. M. (1996b). Toward a knowledge ‐ based theory of the firm. *Strategic management journal, 17*(S2), 109-122.

Grant, R. M., & Baden ‐ Fuller, C. (2004). A knowledge accessing theory of strategic alliances. *Journal of Management Studies, 41*(1), 61-84.

Hackbarth, G. (1998). The impact of organizational memory on IT systems. *AMCIS 1998 Proceedings*, 197.

Hansen, M. T., Nohria, N., & Tierney, T. (1999). What's your strategy for managing knowledge. *Harvard business review, 77*(2), 106-116.

Hatcher, G., Ijomah, W., & Windmill, J. (2011). Design for remanufacture: a literature review and future research needs. *Journal of Cleaner Production, 19*(17), 2004-2014.

Heisig, P. (2009). Harmonisation of knowledge management – comparing 160 KM frameworks around the globe. *Journal of Knowledge Management, 13*(4), 4-31. doi:10.1108/13673270910971798

Herschel, R. T., & Jones, N. E. (2005). Knowledge management and business intelligence: the importance of integration. *Journal of Knowledge Management, 9*(4), 45-55. doi:10.1108/13673270510610323

Hess, E. D. (2014). *Learn or die : using science to build a leading-edge learning organization*. New York Chichester, West Sussex: Columbia University Press.

Hines, P., Francis, M., & Found, P. (2006). Towards lean product lifecycle management. *Journal of Manufacturing Technology Management, 17*(7), 866-887. doi:10.1108/17410380610688214

Hoppmann, J., Rebentisch, E., Dombrowski, U., & Zahn, T. (2011). A framework for organizing lean product development. *Engineering Management Journal, 23*(1), 3-15.
Huber, G. P. (1991). Organizational learning: The contributing processes and the literatures. *Organization Science, 2*(1), 88-115.
Isaksson, O., Larsson, T. C., & Rönnbäck, A. Ö. (2009). Development of product-service systems: challenges and opportunities for the manufacturing firm. *Journal of Engineering Design, 20*(4), 329-348. doi:10.1080/09544820903152663
Jarvenpaa, S. L., & Staples, D. S. (2001). Exploring perceptions of organizational ownership of information and expertise. *Journal of Management Information Systems, 18*(1), 151-184.
Johnson, J. J., & Paper, D. J. (1998). An exploration of empowerment and organizational memory. *Journal of Managerial Issues*, 503-519.
Kamsu Foguem, B., Coudert, T., Béler, C., & Geneste, L. (2008). Knowledge formalization in experience feedback processes: An ontology-based approach. *Computers In Industry, 59*(7), 694-710.
Kennedy, M. (2008). *Ready, set, dominate: implement Toyota's set-based learning for developing products and nobody can catch you*. Richmond, VA: Oaklea Press.
Kihlander, I., & Ritzén, S. (2012). Compatibility before completeness—Identifying intrinsic conflicts in concept decision making for technical systems. *Technovation, 32*(2), 79-89. doi:10.1016/j.technovation.2011.10.005
King, W. R. (2009). Knowledge Management and Organizational Learning. *4*, 3-13. doi:10.1007/978-1-4419-0011-1_1
King, W. R., & Lekse, W. J. (2006). Deriving managerial benefit from knowledge search: A paradigm shift? *Information & Management, 43*(7), 874-883. doi:10.1016/j.im.2006.08.005
King, W. R., & Marks, P. V. (2008). Motivating knowledge sharing through a knowledge management system. *Omega, 36*(1), 131-146.
Kogut, B., & Zander, U. (1992). Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science, 3*(3), 383-397.
Kokkoniemi, J. (2006). *Experiences from generating checklists.* Paper presented at the Proceedings of the IASTED International Conference on Knowledge Sharing and Collaborative Engineering (KSCE2006), St. Thomas, Virgin Islands, USA.
Kotnour, T. (2000). Organizational learning practices in the project management environment. *International Journal of Quality & Reliability Management, 17*(4/5), 393-406.
Kransdorff, A., & Williams, R. (2000). Managing organizational memory (OM): The new competitive imperative. *Organization Development Journal, 18*(1), 107.
Kurilova-Palisaitiene, J., Lindkvist, L., & Sundin, E. (2015). Towards Facilitating Circular Product Life-Cycle Information Flow via Remanufacturing. *Procedia CIRP, 29*, 780-785.
Lehner, F., & Maier, R. K. (2000). How can organizational memory theories contribute to organizational memory systems? *Information Systems Frontiers, 2*(3-4), 277-298.
Leon, H. C. M., & Farris, J. A. (2011). Lean product development research: Current state and future directions. *Engineering Management Journal, 23*(1), 29-51.
Levandowski, C. E., Corin-Stig, D., Bergsjo, D., Forslund, A., Hogman, U., Soderberg, R., & Johannesson, H. (2012). An integrated approach to technology platform and product platform development. *Concurrent Engineering, 21*(1), 65-83. doi:10.1177/1063293x12467808
Levandowski, C. E., Corin-Stig, D., Bergsjö, D., Forslund, A., Högman, U., Söderberg, R., & Johannesson, H. (2013). An integrated approach to technology platform and product platform development. *Concurrent Engineering, 21*(1), 65-83.

Levinthal, D. A., & March, J. G. (1993). The myopia of learning. *Strategic management journal, 14*(S2), 95-112.
Levitt, B., & March, J. G. (1988). Organizational learning. *Annual review of sociology*, 319-340.
Liker, J. K. (2004). *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. New York: McGraw-Hill Professional.
Ljungberg, L. Y. (2007). Materials selection and design for development of sustainable products. *Materials & Design, 28*(2), 466-479. doi:10.1016/j.matdes.2005.09.006
Lotti Oliva, F. (2014). Knowledge management barriers, practices and maturity model. *Journal of Knowledge Management, 18*(6), 1053-1074.
Lundvall, B.-Å., & Johnson, B. (1994). The learning economy. *Journal of industry studies, 1*(2), 23-42.
Mankins, J. C. (1995). Technology readiness levels.
March, J. G. (1991). Exploration and exploitation in organizational learning. *Organization Science, 2*(1), 71-87.
Markus, M. L. (2001). Toward a theory of knowledge reuse: Types of knowledge reuse situations and factors in reuse success. *Journal of Management Information Systems, 18*(1), 57-94.
Mascitelli, R. (2007). *The lean product development guidebook: everything your design team needs to improve efficiency and slash time-to-market*. Northridge, CA: Technology Perspectives.
Maxwell, D., & Van der Vorst, R. (2003). Developing sustainable products and services. *Journal of Cleaner Production, 11*(8), 883-895.
Maxwell, J. A. (2012). *Qualitative research design: An interactive approach: An interactive approach*: Sage.
McElroy, M. W. (2003). *The new knowledge management: Complexity, learning, and sustainable innovation*: Routledge.
McMahon, C., Lowe, A., & Culley, S. (2004). Knowledge management in engineering design: personalization and codification. *Journal of Engineering Design, 15*(4), 307-325. doi:10.1080/09544820410001697154
Menon, T., & Pfeffer, J. (2003). Valuing internal vs. external knowledge: Explaining the preference for outsiders. *Management Science, 49*(4), 497-513.
Morgan, J. M., & Liker, J. K. (2006). *The Toyota product development system*. Seattle, WA: Productivity Press.
Nickols, F. (2000). The knowledge in knowledge management. *The Knowledge Management Yearbook, 2000–2001*.
Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Organization Science, 5*(1), 14-37.
Nonaka, I., & Takeuchi, H. (1995). *The knowledge-creating company: How Japanese companies create the dynamics of innovation*: Oxford university press.
Nonaka, I., Von Krogh, G., & Voelpel, S. (2006). Organizational Knowledge Creation Theory: Evolutionary Paths and Future Advances. *Organization Studies, 27*(8), 1179-1208. doi:10.1177/0170840606066312
Oehmen, J., Oppenheim, B. W., Secor, D., Norman, E., Rebentisch, E., Sopko, J. A., . . . McNeal, S. (2012). *The Guide to Lean Enablers for Managing Engineering Programs*. Cambridge, MA: Joint MIT-PMI-INCOSE Community of Practice on Lean in Program Management.
Oppenheim, B. W. (2004). Lean product development flow. *Systems Engineering, 7*(4).
Oppenheim, B. W., Murman, E. M., & Secor, D. A. (2011). Lean enablers for systems engineering. *Systems Engineering, 14*(1), 29-55.

Orzano, A. J., McInerney, C. R., Scharf, D., Tallia, A. F., & Crabtree, B. F. (2008). A knowledge management model: Implications for enhancing quality in health care. *Journal of the American Society for Information Science and Technology, 59*(3), 489-505.

Parry, G., & Turner, C. (2006). Application of lean visual process management tools. *Production Planning & Control, 17*(1), 77-86.

Phaal, R., Farrukh, C. J., & Probert, D. R. (2004). A framework for supporting the management of technological knowledge. *International Journal of Technology Management, 27*(1), 1-15.

Polanyi, M. (1966). *The tacit dimension*: Doubleday/Anchor.

Pomerol, J.-C. (2001). Scenario development and practical decision making under uncertainty. *Decision Support Systems, 31*(2), 197-204.

Radeka, K. (2015). *The Shortest Distance Between You and Your New Product: How Innovators Use Rapid Learning Cycles to Get Their Best Ideas to Market Faster*. Camas, Washington, USA: Chesapeake Research Press.

Raudberget, D., & Bjursell, C. (2014). A3 reports for knowledge codification, transfer and creation in research and development organisations. *International Journal of Product Development, 19*(5), 413-431.

Reinertsen, D. G. (2009). *The principles of product development flow: second generation lean product development* (Vol. 62): Celeritas Redondo Beach,, Canada.

Riege, A. (2005). Three-dozen knowledge-sharing barriers managers must consider. *Journal of Knowledge Management, 9*(3), 18-35.

Rossi, M., Taisch, M., & Terzi, S. (2012). *Lean product development: a five-steps methodology for continuous improvement.* Paper presented at the Engineering, Technology and Innovation (ICE), 2012 18th International ICE Conference on.

Rowley, J. E. (2007). The wisdom hierarchy: representations of the DIKW hierarchy. *Journal of Information Science*.

Saad, N. M., Al-Ashaab, A., Shehab, E., & Maksimovic, M. (2013). A3 thinking approach to support problem solving in lean product and process development *Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment* (pp. 871-882): Springer.

Sanchez, R., & Mahoney, J. T. (1996). Modularity, flexibility, and knowledge management in product and organization design. *Strategic management journal, 17*(S2), 63-76.

Schindler, M., & Eppler, M. J. (2003). Harvesting project knowledge: a review of project learning methods and success factors. *International Journal of Project Management, 21*(3), 219-228.

Shook, J. (2008). *Managing to learn: using the A3 management process to solve problems, gain agreement, mentor and lead*. Cambridge, MA: Lean Enterprise Institute.

Sobek II, D. K., & Smalley, A. (2011). *Understanding A3 thinking: a critical component of Toyota's PDCA management system*. Boca Raton: CRC Press.

Spender, J. C. (1996). Making knowledge the basis of a dynamic theory of the firm. *Strategic management journal, 17*, 45-62.

Standing, C., & Kiniti, S. (2011). How can organizations use wikis for innovation? *Technovation, 31*(7), 287-295. doi:10.1016/j.technovation.2011.02.005

Stig, D. C., Isaksson, O., Högman, U., & Bergsjö, D. (2015). TERA–An Assessment of Technology Reuse Feasibility. *Procedia Computer Science, 44*, 507-516.

Sundin, E., & Lindahl, M. (2008). Rethinking product design for remanufacturing to facilitate integrated product service offerings.

Tatikonda, M. V., & Rosenthal, S. R. (2000). Technology novelty, project complexity, and product development project execution success: a deeper look at task uncertainty in product innovation. *Engineering Management, IEEE Transactions on, 47*(1), 74-87.
Teece, D. J. (2000). Strategies for managing knowledge assets: the role of firm structure and industrial context. *Long Range Planning, 33*(1), 35-54.
Thomke, S., & Fujimoto, T. (2000). The Effect of "Front‐Loading" Problem‐Solving on Product Development Performance. *Journal of Product Innovation Management, 17*(2), 128-142.
Thomke, S. H. (1998). Managing experimentation in the design of new products. *Management Science, 44*(6), 743-762.
Thompson, R. F., & Madigan, S. A. (2013). *Memory: The Key to Consciousness: The Key to Consciousness*: Princeton University Press.
Tukker, A. (2013). Product services for a resource-efficient and circular economy–a review. *Journal of Cleaner Production*.
Tuomi, I. (1999). *Data is more than knowledge: Implications of the reversed knowledge hierarchy for knowledge management and organizational memory.* Paper presented at the Systems Sciences, 1999. HICSS-32. Proceedings of the 32nd Annual Hawaii International Conference on.
Ulrich, K., & Eppinger, S. (2011). *Product Design and Development*. New York, NY: McGraw-Hill Education.
Ulrich, K. T., & Pearson, S. A. (1993). Does product design really determine 80% of manufacturing cost?
Van den Berg, H. A. (2013). Three shapes of organisational knowledge. *Journal of Knowledge Management, 17*(2), 159-174.
Verganti, R. (1999). Planned flexibility: linking anticipation and reaction in product development projects. *Journal of Product Innovation Management, 16*(4), 363-376.
Verworn, B., Herstatt, C., & Nagahira, A. (2008). The fuzzy front end of Japanese new product development projects: impact on success and differences between incremental and radical projects. *R&D Management, 38*(1), 1-19.
Von Zedtwitz, M. (2002). Organizational learning through post–project reviews in R&D. *R&D Management, 32*(3), 255-268.
Wagner, C., & Prasarnphanich, P. (2007). *Innovating collaborative content creation: the role of altruism and wiki technology.* Paper presented at the System Sciences, 2007. HICSS 2007. 40th Annual Hawaii International Conference on.
Ward, J., & Aurum, A. (2004). *Knowledge management in software engineering-describing the process.* Paper presented at the Software Engineering Conference, 2004. Proceedings. 2004 Australian.
Weber, R., Aha, D. W., & Becerra-Fernandez, I. (2001). Intelligent lessons learned systems. *Expert systems with applications, 20*(1), 17-34.
Wenger, E., McDermott, R. A., & Snyder, W. (2002). *Cultivating communities of practice: A guide to managing knowledge*: Harvard Business Press.
Wiig, K. M. (1993). Knowledge Management Foundations: thinking about-how people and organizations create, represent, and use knowledge. *Arlington, Texas: Schema*.
Williams, T. (2008). How do organizations learn lessons from projects—And do they? *Engineering Management, IEEE Transactions on, 55*(2), 248-266.
Williamson, K. (2002). *Research methods for students, academics and professionals: Information management and systems*: Elsevier.
Yeung, C., & Holden, T. (2000). *Knowledge Re-Use as Engineering Re-Use: Extracting Values from Knowledge Management.* Paper presented at the PAKM.
Yin, R. K. (2013). *Case study research: Design and methods*: Sage publications.

Zack, M. H. (1999). Managing codified knowledge. *MIT Sloan Management Review, 40*(4), 45.