THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Reuse of Engineering Knowledge

Perspectives on Experience-Based Codified Knowledge in Incremental Product Development

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Illustration of a Knowledge
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Is there anyone so wise as to learn by the experience of others?

- Voltaire

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ABSTRACT

Product development is a knowledge-intensive activity and as products become more complex and competition intensifies, the amount of knowledge increases. A prerequisite for engineers who apply current best practices and continuously improve their working methodologies is to efficiently reuse existing knowledge. However, current trends during which individuals switch positions at an increasing speed and when the information is more dynamic, fleeting and more rapidly gained than ever before, calls for enhanced preparedness to meet these challenges. Numerous initiatives have been made, yet repeated design-related product issues are a recurring phenomenon which ultimately results in organizations either succeeding or disappearing from the market place.

Guided by three research questions faced by the engineers, this thesis sets to (1) identify and analyze the characteristics of codified knowledge that support knowledge reuse; (2) Develop and enhance knowledge reuse support based on the characteristics identified in order to increase such knowledge reuse within product development organizations; and finally, the thesis aims to (3) evaluate the implementation of this support.

In order to answer the first research question, a study exploring barriers to the reuse of codified knowledge highlighted eighteen potential barriers, eight of them associated with the individual at the engineering level. The discoveries within literature formed the basis for analyses and identification of ten characteristics regarding the quality of knowledge for reuse.

As a continuation of the identified characteristics resulting from the first research question and to answer the second research question, a framework to efficiently support knowledge reuse has evolved. This framework is referred to as Engineering Checksheets and sets out to divide engineering knowledge into actionable pieces which not only give the engineers the answer to what to do, but also how and why a decision or action should be carried out, which have been identified as important components to foster knowledge reuse and to further enable continuous improvements.

To answer the third research question, Engineering Checksheets have been implemented in industry and have been actively applied during several years in a variety of settings within a couple of organizations. An evaluation of the support implemented testifies to several valuable lessons learned, including dividing knowledge into actionable pieces which makes it both easier to apply the knowledge, as well as being notified when new knowledge has been gained but not yet captured, which is also helpful to the process of continuously capturing knowledge. The findings bear witness of the fact that efficient Knowledge Management is not so much about the IT system as it is about the Knowledge Management process and individual motivation.

This thesis provides a pathway for organizations and engineers to extend their narrow focus of capturing knowledge by embracing and highlighting the perspective of knowledge reuse. By facilitating a habit and mindset of continuously capturing and reusing knowledge, product development organizations can greatly increase their effectiveness and quality of output.

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

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Daniel Stenholm
Gothenburg, Sweden, 2018

APPENDED PUBLICATIONS

The following research papers form the foundation for this thesis.

Paper A

Stenholm, D., & Bergsjö, D. (2018) Barriers to Reuse of Codified Engineering Knowledge in Product Development – A Literature Review. *Submitted, Knowledge Management Research and Practice.*

Paper B

Bergsjö, D., Catic, A., & **Stenholm, D.** (2018). A Lean Framework for Reusing Knowledge – Introducing Engineering Checksheets. *In press, International Journal of Lean Enterprise Research.*

Paper C

Stenholm, D., Catic, A., & Bergsjö, D. (2018). Knowledge Reuse in Industrial Practice: Evaluation from Implementing Engineering Checksheets in Industry. *Revised manuscript submitted, Design Science Journal.*

DISTRIBUTION OF WORK

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

Paper A — Daniel Stenholm established the study, conducted the literature review and wrote the paper with the support of Dag Bergsjö. The analysis was jointly carried out by both authors.

Paper B — Dag Bergsjö coordinated the study and wrote the paper together with Daniel Stenholm and Amer Catic. With the support of Daniel Stenholm, Amer Catic set up the introduction at Case Company One and Dag Bergsjö for Case Company Two. Observations and workshops was performed by all authors.

Paper C — Amer Catic initiated the implementation with the support of Daniel Stenholm. Daniel Stenholm conducted semi-structured interviews and observations for the evaluation whereas Amer Catic conducted long-term observations. Daniel Stenholm transcribed the interviews, performed the analysis and wrote the majority of the paper, whereas Amer Catic contributed parts of the content and supported during analysis. Dag Bergsjö supervised the work and provided ideas and feedback.

ADDITIONAL PUBLICATIONS

Although not making central contributions to the final results, the following publications are related to the research presented in this thesis.

Stenholm, D., Moore, D., & Bergsjö, D. (2018). Fail early, fail often: Exploring Stanford's ME310 Course as a Basis for Improving Innovation Outpost Efficacy. In *DS 92: Proceedings of the DESIGN 2018 15th International Design Conference*, Dubrovnik, Croatia, May 21-24, 2018.

Sandvold, L., Stenholm, D., Mathiesen, H., & Bergsjö, D. (2018). A System of Knowledge Briefs to Support Decision-Making and Knowledge Reuse in Product Development. In *Proceedings of the 16th Annual Conference on Systems Engineering Research (CSER 2018),* Charlottesville, VA, USA, May 8-9, 2018.

Moore, D., Ge, X., Stenholm, D., Sirkin, D., & Ju, W. (2018) Active Navigator: Toward Real-Time Knowledge Capture and Feedback in Design Workspaces. *International Journal of Engineering Education, 34, 723-733.*

Noruzi, F., Stenholm, D., Sjögren, P., & Bergsjö, D. (2018). A holistic model for inter-plant knowledge transfer within an international manufacturing network. *Accepted*, *Journal of Knowledge Management*.

Stenholm, D., Stylidis, K., Bergsjö, D., & Söderberg, R. (2017). Towards robust inter-organizational synergy: Perceived quality knowledge transfer in the automotive industry. In *DS 87-6 Proceedings of the 21st International Conference on Engineering Design (ICED 17)* Vol 6: Design Information and Knowledge, Vancouver, Canada, August 21-25, 2017.

Stenholm, D., Stylidis, K., Bergsjö, D., & Söderberg, R. (2016). The Challenges of Different Roles with Engineering Knowledge Reuse. In *DS 85-2: Proceedings of NordDesign 2016*, Volume 2, Trondheim, Norway, August 10-12, 2016.

Stenholm, D., Bergsjö, D., & Catic, A. (2016). Digitalization Challenges for Lean Visual Planning in Distributed Product Development Teams. In *DS 84: Proceedings of the DESIGN 2016 14th International Design Conference*, Cavtat - Dubrovnik, Croatia, May 16-19, 2016.

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

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

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

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

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

DRM	Design Research Methodology
ECS	Engineering Checksheet
KE	Knowledge Element
KM	Knowledge Management
KPI	Key Performance Indicator
KRS	Knowledge Reuse Support

1 INTRODUCTION

This chapter provides a brief introduction to the research documented in this thesis, the project goals, the research questions and a brief outline.

Dynamic changes in the market situation and global business environment are driving a rapid evolution of accelerating needs for learning in product development organizations. Edward Hess (2014) advises, “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. Accordingly, there is a need to increase experiential knowledge application concerning processes, methods and technologies to solve problems, exploiting opportunities, and remaining ahead of the competition (Riege, 2005).

1.1 Research Background

Peter Drucker (1994) broadly describes the shift from industry to information and knowledge, which started around 1960 and is expected to continue until 2020. This observation 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”. In product development, knowledge and expertise based on experience are highly valued as the process of knowledge acquisition is typically viewed as a bundle of interdependent human problem-solving activities (S. Thomke and Fujimoto, 2000). The existing knowledge helps organizations speed up the development process while decreasing product cost and fulfilling quality objectives.

The most widely used standard for Quality Management Systems, ISO 9001:2015, has recently added a knowledge management clause (7.1.6 Organizational Knowledge) that explicitly points out its importance. In 2017, a draft of a new international standard, ISO/DIS 30410 Knowledge Management Systems – Requirements, was released with the intention in supporting organizations in developing management systems that effectively promote and enable value-creation through knowledge. To fulfill ISO 9001, the clause states; 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 assets. Following ISO 9001, this thesis defines the reuse of Organizational Knowledge as; knowledge specific to an organization and generally gained by experience—knowledge that is used and shared to achieve the objectives of an organization through actions and decisions. In Chapter *2.2 Knowledge* this is further elaborated on.

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, et al., 1996). Consequently, Knowledge Management (KM) has been established as a discipline to empower organizations with the help of supporting tools, principles, methods, models and theories. A common KM effort is cross-project knowledge transfer in order to accelerate learning from experience and to bridge the gap between standard processes and task-based reality (S. Thomke and Fujimoto, 2000). This method has also 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". It is important to remember 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, in the right place, to the right people and with the proper level of detail (Browning, 2000). In this way making knowledge reuse and management practices become critical activities to enable organizations to consistently learn from experience and employ best practices in the development of future products.

Multiple researchers regard learning from experience as building blocks for organizational learning and knowledge creation because such learning enables the capture and transformation of individual or group experience into Organizational Knowledge, which is considered crucial in a modern organization.

To summarize, dynamic changes in the market situation and global business environment are driving the rapid evolution of needs to apply best practices throughout entire product development organizations. Hence, there is a need to create better experiential knowledge capturing, disseminating and reusing practices as well as support to build on past experience, to allow companies to stay ahead of the competition.

1.2 Research Problem

Brown and Daguid (2000, p. 5) claimed that most tasks in organizations are spontaneous, practice-centered and that "there is a large gap between what a task looks like in a process manual and what it looks like in reality". In particular, knowledge gaps related to design problems in the early phases are often unclear (Rittel and Webber, 1973), as designers are usually seeking directions rather than specific solutions (Sharmin, et al., 2009). Thus, design teams use trial-and-error approaches with varying levels of prior knowledge, such as physical artifacts of previous products, drawings and reports (Wallace, et al., 2005). Although existing product design systems address many issues related to use of prior knowledge, their main focus is on detailed design and the latter phases, when designers are seeking solutions to defined problems (Chandrasegaran, et al., 2013; Sharmin, et al., 2009). Moreover, researchers have also highlighted the limited use of KM Systems and even where systems are used, the promotion of knowledge sharing and reuse is generally limited due to the adoption of ad hoc approaches (Weber, et al., 2001). Thus, there are several barriers to cross-project experiential knowledge reuse, especially knowledge about the systemic design rationale.

In many organizations the proven practice at the beginning of a new project has been to carry forward knowledge from past and parallel projects. However, many organizations are struggling with the collection and dissemination of design-related experience-based knowledge, which greatly hinders the attainment of potential benefits of learning from experience (Keegan and Turner, 2001; Milton, 2010; Rhodes and Dawson, 2013; Williams, 2008). There is a disparity between the goals and outcomes of knowledge reuse practices and a lack of transparency about what happens to captured knowledge (Rhodes and Dawson, 2013). Milton (2010) found that 60% of 74 organizations examined that attempted to implement any method for systematically learning from experience were dissatisfied because learnings were identified and captured but had often not been followed through and reused internally to deliver the intended changes in personal or organizational behavior, best practices or standards.

The existing literature is primarily referring to practices for capturing knowledge while still highlighting the lost potential of increasing the reuse of already captured knowledge.

In addition, knowledge in action (Amin and Roberts, 2008) from complex tasks is largely tacit and embedded in local norms and practice, as well as deeply "contextualized" in the experiential environment (Wood, et al., 2009). However, most codified assets trying to transfer experienced-based knowledge seem to lack both contextualized information and tacit knowledge (Goffin and Koners, 2011; Milton, 2010; Williams, 2008), which hinders the application and reuse of captured lessons to new situations (Ahn, et al., 2005). As existing information systems require codification without guidance on the content structure of these experiences, it is difficult for people to articulate their experiential knowledge without losing the original "context" of this knowledge (Weber, et al., 2001; Zack, 1999).

A lack of contextual information in relation to design decisions excludes important knowledge from original situations, resulting in the limited and distorted understanding of past decisions, thereby affecting the selection and reuse of relevant knowledge in new situations.

In fact, this finding could be the reason why most people depend on informal sources, i.e. personal contacts and networks, in order to obtain and access past experiences rather than the formal documentation available in their companies (McMahon, et al., 2004). Several researchers assert that IT-mediated methods are appropriate for capturing codified knowledge to act as dynamic storage and to be shared across global organizations. The literature also indicates that a standardized structure focusing on knowledge reuse can lead to increased understanding and accelerated action. However, it is my understanding, that practical tools have been developed and are being applied for the former but not in combination with the latter.

There is a lack of practical methods and tools for representing experience-based knowledge from skill-oriented activities in order to support a continuous approach to knowledge reuse leading to actions/decisions.

1.3 Industrial & Scientific Goals

This thesis aims to contribute research on how companies can systematically organize and manage their lessons learned/experience-based knowledge to become reusable assets in the organizational memory to support the efforts of the engineering profession and for the creation of prosperous product development organizations. The research has primarily been focused on product development in large, multi-site organizations as efforts to standardize their products and continuously improve them have been perceived as vital to be effective and retain quality. The products within these organizations are associated with moderate or high technical challenges, such as those in the automotive industry. In this industry, the product development efforts are mostly incremental, which often carry lower risk than purely innovation projects or those commonly referred to as New Product Development projects. However, plenty of examples exist where problems reoccur due to poor knowledge reuse, even if knowledge for avoidance already existed inside the organization.

Due to its focus on product development organizations, this thesis focuses on knowledge reuse through a codification process as knowledge is often forgotten if there is a time gap between learning and reuse of knowledge along with the increased potential for standardizing the guidelines. The goal is commonly to transfer knowledge from an experienced senior to a subordinate or individual with less knowledge in the same domain. The outcome of this research aims at contributing to research with a theoretical understanding of what aspects are supportive of an engineer contributing to make better decisions and actions during the design phase based on knowledge from codified assets with minimal workload impact.

This research was initiated as part of a wider research project, Vis-IT, an abbreviation of Visualization and IT in Product and Production Development. In the Vis-IT project, the following industrial organizations have been contributing; Volvo Trucks, Dentsply, Autoliv, Toyota Material Handling Europe, Chalmers and Repos Mjukvara AB. For this thesis, the major affiliates have been Volvo Trucks and an organization outside the Vis-IT project, FMC Technologies.

In line with the close collaboration with industry, an outcome will be the development and evaluation of a practical and useful Knowledge Reuse Support IT-system based on needs and requirements identified for both capturing and reusing knowledge. This result will be possible by combining research from product development, lean thinking and knowledge management for creating, capturing and reusing knowledge along with empirical data and results from industry collaborators.

1.4 Research Questions

To put the research into concrete focus, three research questions are posed below. The research goals are to be met by answering these questions.

RQ1. What are the characteristics of captured codified knowledge that empower knowledge reuse in product development?

There are good arguments as to why knowledge reuse is of high interest to product development but there is a need for additional insight into what constitutes an efficient reuse capability of these assets. The first research question sets out to identify and analyze knowledge characteristics with high quality for reuse by investigating the challenges of reusing existing codified assets jointly with known theoretical practices to build a framework of characteristics.

RQ2. How can engineering knowledge be structured to make it more reusable to knowledge workers?

> *The second research question focus on developing an approach to capture and structure Organizational Knowledge in a way to support knowledge reuse from an engineering perspective. The development will be based on the outcome of RQ1 in order to foster knowledge reuse in the daily work of a knowledge worker.*

RQ3. What can be learn from implementing a support developed based on a knowledge reuse perspective?

> *The third research questions aim to provide implications regarding the future of knowledge reuse by evaluating the implementation of a support system for knowledge reuse developed from RQ2.*

1.5 Delimitations of the Research

Supporting the management and reuse of knowledge in product development is a wide topic and some delimitations have been made.

Without making any statements of the importance between exploitation and incremental development vs. exploration and innovation, this research mainly focuses on the first concepts, i.e. the efficiency-focused activities of leveraging existing capabilities (March, 1991). See Figure 1 for further visualization of this relationship. The products that are investigated are thus developed across generations based on a high amount of reference knowledge and are often designed by individuals who hold a great deal of tacit knowledge related to the specific product, factors that increase the opportunity for knowledge transfer.

A common categorization 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 2. 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. 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. Consequently, this delimits the example of text mining, known as intelligent text analysis, text data mining or knowledge-discovery in text (Herschel and Jones, 2005). Text mining generally refers to the process of extracting interesting, non-trivial information and knowledge from unstructured texts.

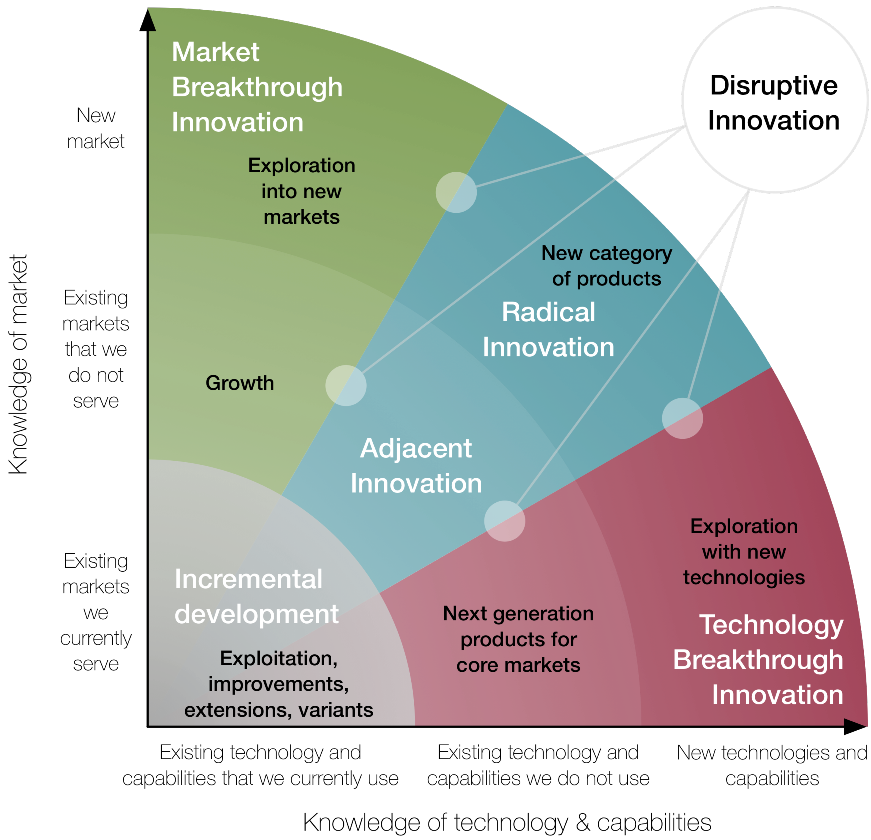

Figure 1. Map presenting common terminologies used regarding innovation. Companies may have different goals for any innovation process, from incremental development to radical or breakthrough innovation (Stenholm, et al., 2018).

In this thesis, reuse mainly focuses on knowledge related to the design of the product, not on the development process itself even though it plays 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.

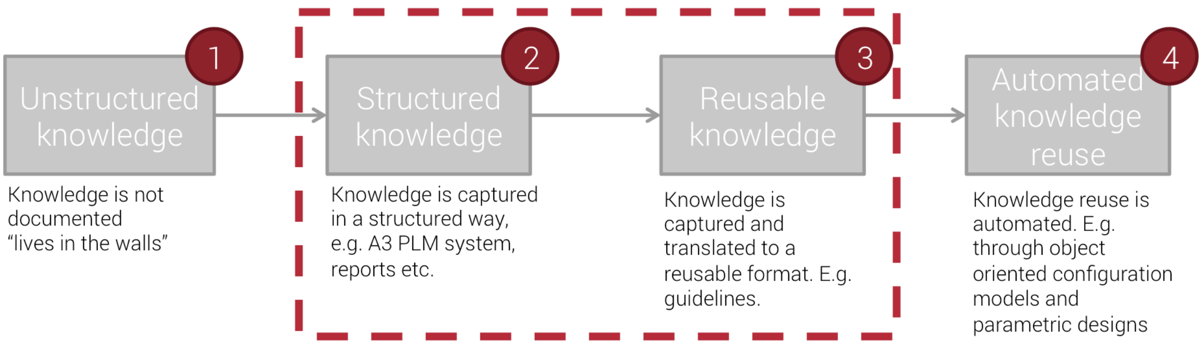

Figure 2. Describing different reuse capabilities for knowledge through the spectrum of unstructured knowledge, structured knowledge, reusable knowledge and finally automated knowledge reuse.

1.6 Thesis Structure

This thesis consists of seven chapters and the chapters subsequent to this introduction (*Chapter 1*) are outlined as follows:

Chapter 2 presents the theoretical background of the thesis, including general product development methodologies, the knowledge dimension of product development, the theory of knowledge, knowledge management, the knowledge management cycle and knowledge reuse support. The sources have been collected over the progression of the studies and have continuously been contributing new ideas and perspectives.

Chapter 3 presents the research strategy and methodology applied for conducting this research and the rationale for selection. The various forms of data collection and analysis are discussed along with important considerations for evaluating the quality of the 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 synthesized and discussed in relation to the research questions and criteria for research quality from Chapter 3.

Chapter 6 elaborates on the validity of the research results and their generalizability to other domains and industries.

Chapter 7 summarizes the overall conclusions of the findings and highlights both the academic and industrial contributions of this thesis.

Chapter 8 elaborates on some interesting aspects for advancing this research topic and continuing to support the research goals outlined to address both methodological and technological issues.

2 FRAME OF REFERENCE

This chapter presents the theoretical background and frame of reference that form the foundation for the research presented in this thesis (Figure 3).

2.1 Product Development – Knowledge Work

Product development has been a vital part of our civilization for as long as anyone can remember. The term involves the creation of products as incremental development, including the modification of existing products or the innovation of entirely new products. Product development is often described as satisfying customer needs with new or additional benefits.

As the increase in global competition and market segmentation accelerates the pace during which changes take place in many industries, product development capabilities are becoming critical to companies. The product development capability is generally defined as the integration or combination of differentiated functional knowledge (Grant, 1996a; Kogut and Zander, 1992). Successful product development is achieved by organizations 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).

For organizations to keep their depth of functional knowledge as well as cross-functional collaboration, organizations commonly apply a matrix structure in the automobile, electronics and aerospace industries (K. Ulrich and Eppinger, 2011). The matrix organization is conceived as a hybrid of functional and project organizations in which individuals are associated with both cross-functional projects and their functions. Each individual has typically two supervisors, a project manager and a functional manager. Ulrich and Eppinger (2011) highlight that when an organization is moving in the direction of becoming a project rather than a functional organization, issues evolve such as how to maintain functional expertise over time and how to share learning from one project to another.

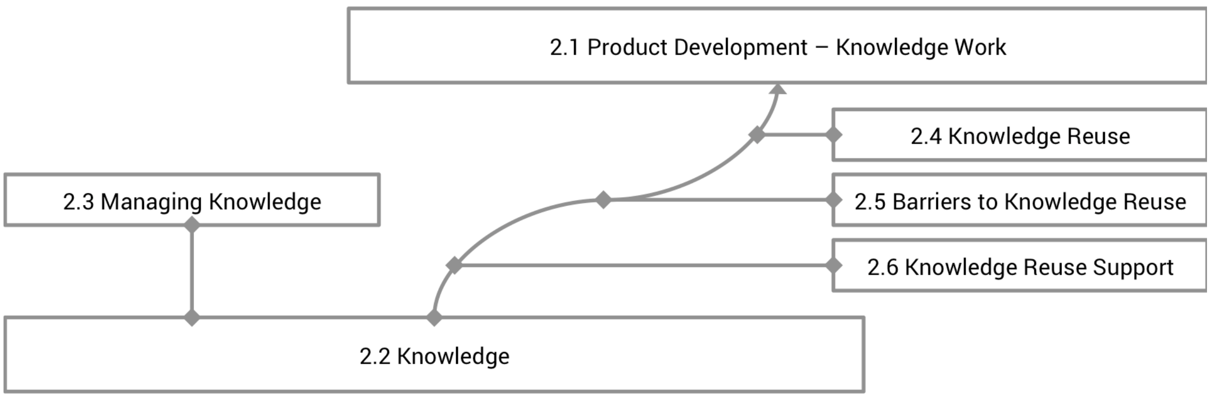

Figure 3. Overview of the topics presented in frame of reference

That organizational structures highly impact product development is known, along with a broad imperial study that has underlined that most products are developed across generations while pointing out a couple of important factors that need to be considered when investigating development methods and processes to make existing knowledge available for increased efficiency (Albers, et al., 2015). A new product generation is always based on at least one existing product and these products, such as precursor products or products of competitors, are called 'reference products' (Albers, et al., 2015). The subsystems are either adapted to new product generations by means of carryover or are newly developed based on shape or principal variation. It has been proven that independently of the degree of incremental or innovative development, the products strongly remain dependent on the knowledge of reference products (Hoppmann, et al., 2011). Each product development project aims to bring one new generation of products to market while parallel and following projects focus on other products/generations. In order to use the full organizational capability for innovation, knowledge needs to flow between projects through cross-project integration. Consequently, the management of knowledge must reach further than the project in progress.

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

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).

2.1.1 Lean Product Development

Lean thinking has attracted a wide variety of organizations and supported them in eliminating all non-value-adding activities and consistently aligning all required activities to external and internal customers by focusing on two value streams, the knowledge value stream and the product value stream (Morgan and Liker, 2006). The concept of knowledge value stream illustrates the cross-project knowledge flow (Kennedy, 2008).

Problems addressed in the Lean Product Development literature may be grouped into two classes. The first class includes challenges dealing with the effectiveness of the development process in terms of the market success of newly developed products (Hines, et al., 2006). Problems within this class include a lack of alignment between product development strategy and the wider business strategic plan, unnecessary development activity, a lack of understanding of customer requirements and a high degree of new product failure rates (Bauch, 2004). The second class of challenges is concerned with the efficiency of the development process itself. These problems include the lack of a formal or standardized processes, the 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). The latter two categories can also be seen as doing the right things and doing things right to enhance effectiveness and efficiency, respectively (Drucker, 1994). A major topic in the Lean Product Development literature is the identification of best practices that may lead to the mitigation of the challenges presented in the two classes (Hoppmann, et al., 2011).

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

Hoppmann et al. (2011) present a framework of 11 Lean Product Development Components, in which one of them is *Cross-Project Knowledge Transfer* is also known as project-to-project knowledge transfer. Table I presents the other ten components and how they may affect Cross-Project Knowledge Transfer and vice versa.

These contributions outline a strong relationship between Lean Product Development and knowledge. However, as stated by Lindlöf et al. (2013, p. 1128): *"Despite all this focus on notions like knowledge and learning in lean product development, the literature review did not reveal examples of studies that put the lean concept in the light of Knowledge Management Research*", thereby increasing the need for further investigation.

2.1.2 Knowledge Workers

Practitioners of product development can be defined using different terms, such as product developers, product designers and knowledge workers. Knowledge workers often perform a wide variety of tasks and the outcome is regularly improved given their collective experience. However, it is not solely the building of experience and creation of knowledge that is valuable for the organization, it is essentially when that knowledge is applied and used to improve the design that the real value will be gained.

Knowledge workers are regularly switching between being learners and the teachers. While being teachers, it is important to adjust how the knowledge is packaged in relation to the receiver in order to increase its strength of application and thus also its potential for reuse (Szulanski, 1996). Hence, what type of knowledge is needed and the way in which the acquirer 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 in which knowledge reuse takes place and suggests that these situations dictate the particular needs of knowledge transfer (

Table II).

Because of the focus on incremental product development in this thesis, *Secondary Knowledge Minors* are generally omitted. 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, whereas those reusing the work as *Shared Work Producers* probably will use the context as a reference for the new design.

Table I. Ten Theoretical qualitative interdependency of cross-project knowledge transfer and the ten other Lean Product Development Components (Hoppmann, et al., 2011).

Component	**How does component in row require *Cross-Project Knowledge Transfer?***	**How does *Cross-Project Knowledge Transfer* require component in row?**
Strong Project Manager	More reliable project planning, cost and time estimation	Enforcement of use of checklists and knowledge transfer
Specialist Career Path	Enhancement of technical expertise through ever increasing knowledge base	Higher ability for reflection and documentation of lessons learned
Workload Leveling	Reduced variability through avoidance of unnecessary steps, iterations and learning	Time for reviewing past project findings before project start, time for reflection and documentation of lessons learned
Responsibility-based Planning and Control	More reliable planning of tasks due to large amount of interaction with manufacturing	Higher incentive for using past knowledge due to accountability and ownership
Simultaneous Engineering	Transfer of manufacturing requirements and best practice solutions	Documentation and reuse of knowledge on requirements of and design for manufacturing
Supplier Integration	Documentation of supplier performance, preferred suppliers and their strengths and weaknesses	Integration of supplier requirements and ratings in documentation
Product Variety Management	Availability of knowledge on feasibility of part reuse, module and interface design from past projects	Easier documentation of best practices for structures and designs due to lower part variability and clearly defined interfaces
Rapid Prototyping, Simulation and Testing	Best practices in testing and prototyping; documentation of failure modes	Generation of objective test data through early and short problem-solving cycles
Process Standardization	Gathering of best practice milestones and procedures; best practice standard tools	Better reuse of knowledge due to similarity of subsequent projects and tools employed
Set-based Engineering	Freezing and re-use of design sets from previous projects; generalization of solutions in trade-off curves	Increased rate of knowledge creation and documentation through the consideration of a wide range of possible solutions

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

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 work similar to the knowledge source but in a different setting*, e.g. during a subsequent project, cross-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 on 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 the 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 that of the authors of the records*. Their main challenges are to locate the right repositories for their purposes and precisely defining the content for which they search.	- Store context information as metadata - Provide training on how the knowledge base is structured - General training on how to analyze and validate results

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 acquiring knowledge from earlier projects (Oehmen, et al., 2012).
- To overcome deficiencies in product development 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, KM and organizational learning (Rossi, et al., 2012).
- Lean Product Development emphasizes the need for a system perspective rather than focusing on individual activities to change organizational behavior

(Browning, 2000), thereby forcing some unlearning of bad habits in order to welcome change (Leon and Farris, 2011).

- Hoppmann et al. (2011) present and propose an organization to follow the eleven Lean Product Development Components to increase *Cross-project Knowledge Transfer*.
- Making sure that you know the receiver of your knowledge to be able to adapt it for increased possibilities of knowledge acquisition (Markus, 2001). Recommendations to improve reuse in cross-project knowledge 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 giving a common understanding of its applied context. In this thesis, the key characteristic of knowledge is its application 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 and 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 as a pyramid starting with data from the bottom and followed by information and knowledge. Occasionally, wisdom and intelligence are added at the top (Rowley, 2007).

The definitions between data, information and knowledge differ between authors and there exist several variants 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.

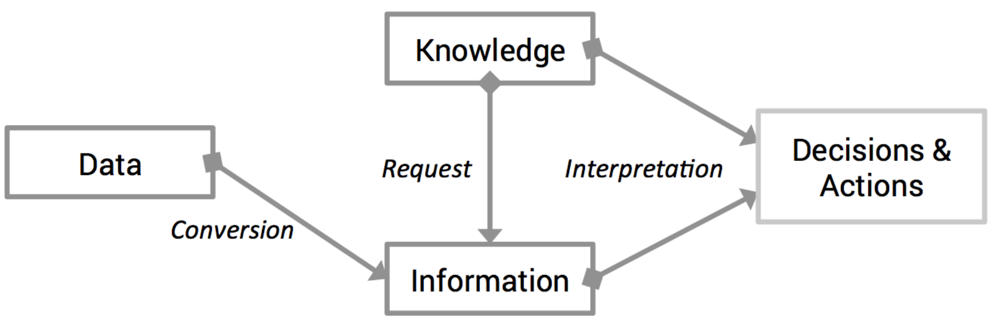

Figure 4. Relationship between data, information and knowledge adapted from Lehner & Maier (2000)

Knowledge represents the understanding of situations and their context, insights into the relationships within a system, the ability to identify leverage points and weaknesses and understand the 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 4 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 into 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 and 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 expressed in writing without incurring undue losses of information (Evans, et al., 2014) and allows for greater fluency, especially in its dissemination. This form of knowledge allows it to more easily, rapidly and extensively be disseminated throughout the organization than other forms (Grant and 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, in which the codification is a process that takes place in the design and functionality of artifacts (Gorga and Halberstam, 2007; Van den Berg, 2013; Wiig, 1993) Some common examples include technical drawings, models, software codes, prototypes, tools, products and patents (Kogut and 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 investigation before being able to support actions in order to resolve problems. In this context, it is often treated as information.

Tacit knowledge is uncodified knowledge (Ikujirō Nonaka and 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 this format non-conscious knowledge as ‘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 and tacit knowledge by arguing that tacit knowledge is not possible to articulate whereas implicit knowledge is.

Further, in attempting to codify or encapsulate tacit knowledge, it is important to understand that some remnants in the human mind remain (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, thereby allowing for the application of tacit knowledge in a collective setting.

In addition to these forms of knowledge, researchers also divide knowledge into different types often used to categorize knowledge: declarative (know-what), procedural (know-how) or casual (know-why) (Alavi and Leidner, 2001; Lundvall and 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 refine in documents. Procedural knowledge represents an understanding of the generative processes that constitute phenomena and often describes a process by which something is accomplished 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 taxonomies and examples

Knowledge types		**Examples**
Declarative knowledge (Alavi and Leidner, 2001)	Knowledge About (Alavi and Leidner, 2001) Know-What (Lundvall and Johnson, 1994) Know-Who (Lundvall and Johnson, 1994)	What battery type is appropriate to a specific situation
Procedural knowledge (Alavi and Leidner, 2001)	Know-How (Alavi and Leidner, 2001; Lundvall and Johnson, 1994)	How to apply best design-practice depending on battery type
Causal knowledge (Alavi and Leidner, 2001)	Know-Why (Alavi and Leidner, 2001; Lundvall and Johnson, 1994)	Understanding why this would be the best battery type and best-practice for design
Conditional knowledge (Alavi and Leidner, 2001)	Know-When (Alavi and Leidner, 2001)	Understanding when to decide battery type
Relational knowledge (Alavi and Leidner, 2001)	Know-With (Alavi and Leidner, 2001)	Understanding how the choice of battery type interacts and consequences for other systems

2.2.2 Knowledge Value, Quality and Actionability

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

The literature defines knowledge as a "justified true belief" that "increase an entity's capacity for effective actions" (Alavi and Leidner, 2001; Ikujirō Nonaka and Takeuchi, 1995). 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". Thus, knowledge that is not used has low value, whereas knowledge that leads to decisions and actions has higher value and it should be prioritized for dissemination.

With the growing amount of captured knowledge the importance of understanding knowledge quality increases and here have been some studies to empirically examining knowledge quality or similar concepts (e.g. Durcikova and Gray, 2009; Kulkarni, et al., 2006; Majchrzak, et al., 2012; Poston and Speier, 2005). 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, in addition to convincing 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, trade-offs and other argumentation evaluated (Lee 1997) that 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 towards 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 (Cross and Sproull, 2004):

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 knowledge provided and its design rationale)

5) *legitimation* (similar to validation but convinces others that the knowledge is correct, providing proof thereof)

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, it needs to be categorized in a way that supports the intended user in understanding its context and applicability.

2.2.3 Organizational Knowledge

The preserved and accumulated knowledge through time is called Organizational Knowledge and the means by which organizations can learn from their past by avoiding repetitions of past mistakes and by adopting proven successful practices (Barros, et al., 2015; Johnson and Paper, 1998). Organizational Knowledge 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 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 and 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 and Paper, 1998; Kransdorff and Williams, 2000). In this thesis, the focus is on codified Organizational Knowledge, stored in e.g. information systems & other artifacts. One might assume that the likelihood that codification is used as a strategy for learning among projects decreases in correlation to the degree of innovativeness of the product developed. This hypothesis was tested by Cacciatori et al. (2012) but was not supported.

Based on Nonaka and Takeuchi's work, Spender (1996) elaborated further on Organizational Knowledge and divided explicit and tacit knowledge into a matrix with individual and social knowledge as columns. Although all fields are part of Organizational Knowledge, 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).

2.2.4 Summary

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

- Knowledge is often heavily dependent on data and information and, together with information, forms our understanding to be able to take legitimate actions and make appropriate decisions (Davenport and Prusak, 1998; Lehner and Maier, 2000; Wiig, 1993).
- Codified knowledge can be more easily, rapidly and extensively disseminated throughout an organization than other forms (Grant and Baden ‐ Fuller, 2004; Van den Berg, 2013).
- Encapsulated knowledge often needs further effort before it can support actions in order to resolve problems and is in this context 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 and 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 and Sproull, 2004).
- 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 and Paper, 1998).

2.3 Managing Knowledge

2.3.1 Knowledge Management

For centuries it has been known that knowledge has a great potential in product development. 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 through such factors as problem-solving, dynamic learning, strategic planning and decision-making (Herschel and Jones, 2005) in order to increase innovativeness and responsiveness (Hackbarth, 1998; Mills and Smith, 2011).

Effective knowledge management requires an infrastructure made up 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, et al., 2011; Gold, et al., 2001; Kamsu Foguem, et al., 2008; Sanchez and Mahoney, 1996; Teece, 2000). The success of knowledge management initiatives and activities is highly dependent on the infrastructure, i.e. the processes, tools and structures through which they are implemented (Heisig, 2009; Phaal, et al., 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 may not be true today and knowledge needs to continuously adapt to new factors, data, inventions and problems (Wenger, et al., 2002). On the topic of what makes managing knowledge a challenge, Wenger et al. (2002) elaborates on the necessity for organizations to no merely reduce knowledge to an object, but 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. Examples of KM implications for different perspectives are provided in Table IV.

Table IV. Knowledge perspectives and implications for KM (adapted from Alavi & Leidner (2001))

Perspectives		**Implications for Knowledge Management**
Knowledge vis-à-vis data and information	Data include facts, raw numbers. Information is structured data that are provided some context. Knowledge is information interpreted for specific situations.	KM focuses on exposing individuals to potentially useful knowledge and facilitating assimilation of knowledge.
State of mind	Knowledge is the state of knowing and understanding.	KM involves enhancing individual learning and understanding through provision of knowledge.
Object/asset	Knowledge is an object/asset to be stored and manipulated.	Key KM issue is building and managing knowledge assets.
Process	Knowledge is a process of applying expertise.	KM focus is on knowledge flow and thus the whole KM cycle.
Access to knowledge	Knowledge is a condition of availability.	KM focus is to systematically maximize knowledge accessibility and availability.
Capability	Knowledge is the potential to influence action.	KM is about building core competencies and understanding strategic know-how.

2.3.2 Knowledge Management Cycle

Commonly, knowledge management is viewed as a process within a conceptual framework that produces knowledge using a sequence of stages within which are designated different tasks and techniques. The terminology used for presenting the sequence of stages differs widely in literature and some of them are summarized in Table V. This section provides a compact overview of some of the most influential models that exist. The models introduce valuable elements to be considered in understanding how Organizational Knowledge is processed throughout its valuable applicability across the organization. There have been numerous models that describe the relationships between the key processes of KM. Early models include the Wiig KM Cycle (Build, Hold, Pool & Use) (Wiig, 1993), the Meyer and Zack KM Cycle (Acquire, refine, store distribute & present) (Zack, 1999) and the McElroy KM Cycle (Knowledge production, Organizational Knowledge and knowledge integration) (McElroy, 2003). KM cycles are typically described from a broad perspective outlining the activities that are intended to have a dynamic KM work inside an organization (Davenport and Prusak, 2000; Ward and Aurum, 2004).

Several KM models are summarized in Table V which highlights the width of terminology used.

Table V Summary of models representing sequences of stages in KM

Reference	Title	Sequence of Stages
Wiig (1993)	Knowledge Management Cycle	Build, Hold, Pool, Use
Bukowitz and Williams (1999)	Knowledge Management Process Framework	Get, Use, Learn, Contribute, Assess, Build/Sustain, Divest
Zack (1999)	Knowledge Management Cycle	Acquire, Refine, Store/Retrieve, Distribute, Present
Bhatt (2000)	Knowledge Development Cycle	Knowledge Creation, Knowledge Adoption, Knowledge Distribution, Knowledge Review and Revision
Nissen et al. (2000)	Knowledge Management Life Cycle	Create, Organise, Formalize, Distribute, Apply, Evolve
(Davenport and Prusak, 2000)	KM 3-stage model	Generate, Codify/Coordinate, Transfer
Alavi and Leidner (2001)	Organizational Knowledge Management Processes	Knowledge Creation, Knowledge Storage/Retrieval, Knowledge Transfer, Knowledge Application
Birkinshaw and Sheehan (2002)	Knowledge Life Cycle	Creation, Mobilization, Diffusion, Commoditization
Schaefer et al. (2002)	Knowledge Life Cycle	Creation, Documentation, Transfer and Reuse
McElroy (2003); Firestone and McElroy (2003)	Knowledge Life Cycle	Individual and Group Learning, Knowledge Claim Formulation, Information Acquisition, Knowledge Validation, Knowledge Integration
Paukert et al. (2003)	Innovation Knowledge Life Cycle	Select Relevant Knowledge, Apply Knowledge, Gather Experience, Rate Experience, Share Experience
Ward & Aurum (2004)	KM 7-stage model	Create, Acquire, Identify, Adapt, Organize, Distribute, Apply
Salisbury (2003; 2008)	Ongoing Lifecycle of Knowledge in Organisations	Knowledge Creation, Preservation, Dissemination and Application
Jashapara (2004)	Knowledge Life Cycle	Discovering Knowledge, Generating Knowledge, Evaluating Knowledge, Sharing Knowledge, Leveraging Knowledge

King (2009) argues 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 5). King (2009) also argues that KM initiatives sometimes forget that organizational performance improvement is what KM is ultimately all about. In this thesis, the KM cycle from King (2009) has been further adapted, utilized and is represented in Figure 6.

The KM cycle is a general model that it is dependent on the situation and the emphasis and/or level of detail with which each stage is performed. The cycle addresses a broad range of learning from all types of sources: personal experience, formal education and training, peer review, and intelligence from all sources.

Although the stages are presented as independent and sequential, the process is not always uni-directed, which means that going back and forth is common as stages are performed in parallel or even left out.

The flow of knowledge goes through different stages that together build up the KM cycle. The base is in Organizational Knowledge and external knowledge followed by the KM loop represented by *acquire, assess, apply, create, identify, refine and disseminate* as described on 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 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. In order to identify the knowledge gap, it is common that some sort of knowledge request needs to be triggered and depends on numerous reasons, some of which include decision-making, knowledge gap analysis, problem-solving or innovation. If the knowledge is known, either by the organization or externally, the process starts with acquiring, or creating the following behavioral theory of the firm, whereby "search is stimulated by a problem and is directed toward finding solution to that problem" (Cyert and March, 1963, p. 121). Most often some knowledge is known from before but needs to be expanded to solve the request.

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

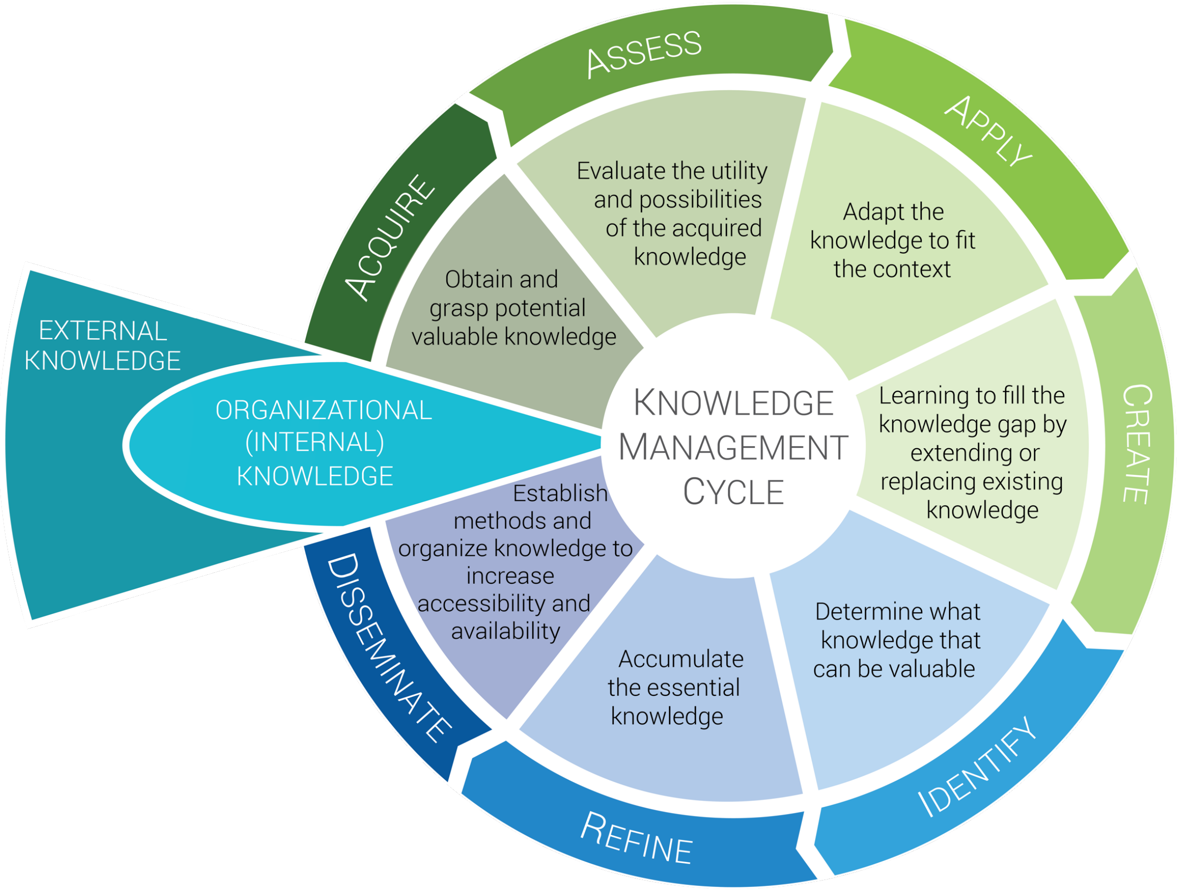

Figure 6. Knowledge Management Cycle including seven stages. The first four are integrated into individual learning, whereas the final three need to be added for organizational learning (Noruzi, et al., 2018).

2.3.3 Organizational Learning

Organizational Learning is a supplement to KM. An early picture of Organizational Learning was "…encoding inferences from history into routines that guide behavior" (Levitt and March, 1988, p. 319). In other words, Organizational Learning standardizes what has been learned across an organization.

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

In line with this view, Organizational Learning should be considered the goal of KM (Lehner and Maier, 2000). By motivating the creation, dissemination and application of knowledge, KM initiatives create 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 means by which Organizational Learning may be supported to sustainably improve the utilization of its 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" (N. M. 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 with 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 Organizational Knowledge to effectively gain knowledge reuse 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 Summary

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

- Organizational Learning is a supplement to KM and can be explained as the goals and processes whereas KM focuses on managing the content and flow of knowledge (Easterby-Smith and Lyles, 2003; Lehner and Maier, 2000).
- KM activities aim to support the organization in effectively utilizing 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 and 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.

2.4 Knowledge Reuse

Whereas knowledge creation and dissemination do not necessarily lead to performance enhancement, effective knowledge reuse (acquire, assess and apply) does (Alavi and Leidner, 2001; Gressgård, 2014). Effective knowledge reuse can improve the quality of work of employees, enhance organizational innovation capability, allow for better service and enhance organizational performance (Cacciatori, et al., 2012; O'Leary, 2001; Yang, et al., 2013). However, despite its importance, very little research has focused on knowledge reuse or utilization (Cheuk, et al., 2017).

From an organizational perspective, knowledge reuse can be understood as putting knowledge into productive use to deal with challenges and achieve organization goals. Therefore, knowledge reuse is usually driven by the recipients of knowledge to better address business needs (Petter and Randolph, 2009). Indeed, a KM initiative should be considered a success only when it leads to knowledge reuse (Baxter, et al., 2008; Liu, et al., 2013) because the value of the knowledge is mainly realized whenever knowledge is used (Alavi and Leidner, 2001). Accordingly, this thesis adopts the following definition of knowledge reuse effectiveness: *a value judgment made by the knowledge user regarding both the efficiency of the accomplishment and the degree of the fulfilment of its goals (effectiveness) by reusing knowledge* (Cheuk, et al., 2017) which further stretches the definition of knowledge value to be based on the judgment of the user.

In product development engineers intuitively reuse previous designs and knowledge when performing new design tasks, either by a complete carryover of reference products or through the reuse on an abstract level, such as concepts or knowledge (Schulz et al. 2000; Smith & A. H. B. Duffy 2001). 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 reuse is a way to balancing and coping with eternal technological uncertainty, which accompanies market uncertainty results in knowledge gaps. Knowledge workers are continuously striving to close knowledge gaps in the quest to satisfy the customer needs and minimize risks. In this pursuit of success, the existing knowledge is one of the most important resources inside the modern organization. According to Albers, the success and competitiveness of a company will increasingly depend on how quickly it can absorb knowledge and thus expand its Organizational Knowledge, disseminating it inside the organization and applying it through knowledge reuse. Albers (2017) argue that as a prerequisite for the development of innovative products, there is a continuous process of closing knowledge gaps performed through the KM cycle.

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 the costs during the latter stages (Boothroyd, 1994; Duverlie and Castelain, 1999; K. T. Ulrich and Pearson, 1993). These decisions often rely on uncertain information (Augustine, et al., 2010; Kihlander and Ritzén, 2012; Pomerol, 2001) and knowledge to evaluate which decisions are the "right" ones (Verworn, et al., 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 reworks negatively affect both time and cost.

To make fewer design changes late in the product development process, concurrent engineering and front-loading have been proposed by researchers (Morgan and Liker, 2006) and in many companies, they have been interpreted as necessary for making a greater number of more explicit decisions early. In practice, this has been implemented through a requirement to involve people from late-stage functions early on. In most companies, however, this poses a problem as the amount of resources in the form of employees is much lower in the latter phases which means that a manufacturing engineer would need to server as the manufacturing representative in a greater number of projects than can be handled by a single individual. 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 that require personal attention upon request. Making knowledge from experts available to more people are what Dixon (1999a) called a shift from an expert to a distributed model.

Front-loading pulls unavoidable decisions up front in order to proceed towards upcoming development activities, such as prototyping, testing and manufacturing. The importance of decisions that highly impact both the effectiveness and efficiency of the product development process can sometimes be neglected because their consequences are seen later on and are thus 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 in efforts at the front-end.

According to a number of studies, front-loading is one of the major factors of product development team performance (S. L. Brown and Eisenhardt, 1995). Front-loading, referred to as problem-solving (S. Thomke and Fujimoto, 2000), up-front homework (R. G. Cooper and Kleinschmidt, 1994) or as detailed pre-development planning (S. L. Brown and Eisenhardt, 1995; Tatikonda and Rosenthal, 2000) and is a countermeasure against expensive waste later on in the product development process 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 during which most problem-solving activities take place. The notion of front-loading suggests that project-specific knowledge should be acquired or generated as early as possible in order to reduce late engineering modifications and fill in relevant knowledge gaps. Thomke and Fujimoto (1998) underline two methods by which product development 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 and Liker, 2006). Regarding the empirical effect of front-loading, it has been suggested that, by implementing rapid prototyping and cross-project knowledge transfer at the front-end, Toyota could deliver new designs with 30% less lead time (S. Thomke and Fujimoto, 2000).

The literature on Lean Product Development and total quality management deals with efficiency issues in knowledge-intensive tasks. A study of lean principles suggests the standardization of product development process 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 and Liker, 2006; Reinertsen, 2009). Hence, these studies propose using simple tools to support product development decisions to standardize common elements in the product development process. Reinertsen (2009) suggests that a systematic front-loading method would ensure that product development 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 is in product development naturally reused either by people, artifacts or documents.
- The knowledge owner from the latter product development 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 product development teams resolve problems early on 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 KM cycle that relate 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, their accessibility and ease of use (Watson & Hewett 2006). Employees who find such practice useful are more likely to make contributions to them and making 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, et al., 2013; Kotnour, 2000; Weber, et al., 2001). Some authors argue that the lack of motivation to receive lessons learned is in fact a greater obstacle than motivating experienced project members to disclose what they have learned (e.g. N. M. 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 become organized and not just remain piles of information (S. M. Duffy et al. 1995). There may be inappropriate technology integration depending on a mismatch between the need of engineers and such factors as IT project management, upgrades and costs (BenMoussa, 2009). Any method implemented must support the knowledge to be updated, accessible and available to the personnel within the organization (Davenport and Prusak, 2000).

There exist different typologies to group 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 sharing barriers related to SMEs and MNCs (Table VI); however they changed the word “people” to “individual”.

Table VI. Knowledge sharing barriers (Riege, 2005)

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

2.5.1 Summary

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

- A common way to categorize barriers is by three groups: people, organization and technology.
- Individual barriers mainly involve motivation (not understanding the benefits to 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.

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 to KRS, have been developed and deployed (Lehner and 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 and Engineering Checklists.

The objective of a KRS, including the knowledge repository, is to support organizational learning and increase organizational effectiveness by supporting the KM cycle and in that sense assisting individuals in their decisions inside the organization (Alavi and Leidner, 2001). This objective 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, et al., 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. Because of the uncertainty in the trade-off between knowing what, how and when you might need such assets in the future, KRS follows a number of challenges in the optimization of such knowledge assets.

The knowledge taken care of by the knowledge repository is exclusively describing product and manufacturing systems is performed by the communication between individual-computer, computer-computer and computer-individual. 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 (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 and Staples, 2001).

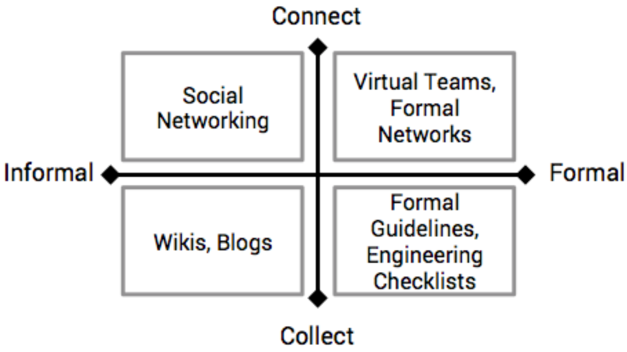

Figure 7. Knowledge reuse support can be roughly categorized across the spectrum of connect-collect and informal-formal.

2.6.1 Informal and Formal Knowledge Codification for Building Knowledge Assets

Researchers distinguish between two main strategies for routing knowledge from its creation to reuse: a personalization and a codification strategy (Hansen et al., 1999). The codification strategy is based on the document-to-individual approach, in which people retrieve codified knowledge from knowledge management systems, databases, books, data warehouses, decision support systems and enterprise resource planning systems (Hansen, et al., 1999). The personalization strategy is instead based on individual-to-individual learning, in which knowledge is shared with other people (employees) through face-to-face communications, including on-the-job learning, storytelling, training activities and communities of practice (Brown & Duguid, 2001). Two types of KRS have been developed for supporting these two strategies: electronic knowledge repositories supporting the codification strategy as they store codified knowledge for future adoption, whereas knowledge directories (e.g. yellow pages) and knowledge networks (e.g. electronic communities of practice) support the personalization strategy (Hansen, et al., 1999; Markus, 2001). Electronic knowledge repositories are documents or repositories that facilitate knowledge and information search, storage and retrieval (Wu and Wang, 2006). Repositories are used by companies to enable employees dispersed across different locations to access the company's best practices, lessons learned and know-how instantly as well as over time. The former are supported by KRS for **connection** while the latter, which is in focus in this thesis, is supported by KRS for **collection;** Figure 7 (Hansen, et al., 1999). The KRS can also be divided into different segments, whether formal or informal.

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, et al., 2004). In all cases, KRS plays an important function without which 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 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 and Wallace, 2000). A codification strategy can benefit from referring to experts or document authors to support the interpretation of the codified knowledge in cases when its application is not straightforward, as well as increasing knowledge validity (Cross and 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 it on a larger scale. IT for KM is commonly referred to as KM Systems. Related to KM Systems is Organizational Memory System which is generally characterized by the fact that a whole bundle of tools is used, not an isolated single tool (Lehner and Maier, 2000). Corin Stig (2015) 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.

Do not forget that in the quest to enhance knowledge flow, it is easy to primarily focus on IT; however, its purpose and needs must be defined and shared in order to achieve basic trust by the users to achieve expected outcomes (Firestone and McElroy, 2002).

Every KRS exists along a different scale between technical solution (tool) and method (Figure 8). People tend to view Wikis as more of a tool than a method, even if there is a method behind them whereas the opposite pertains to A3-reports.

A common misconception of KM tools is that the "implement and they will come" strategy will satisfy all needs and will automatically generate good knowledge work. Sadly, many KM initiatives fail due to an insufficient understanding and the implementers then wonder why employees do not make use of this potentially great new KRS system. 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).

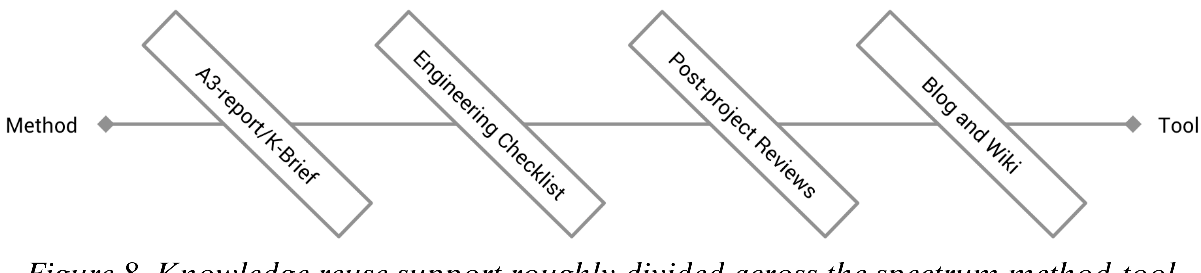

Figure 8. Knowledge reuse support roughly divided across the spectrum method-tool.

Even if this thesis is skewed towards the collection of knowledge, a balance between all circumstances is recommended. There is a risk of having too 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 and Kumaraswamy, 2005). Ideally, a KRS is only populated with knowledge that may be retrieved, rather than everything known to man (L. Blessing and 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 lost
- 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 and Turner, 2006; Schindler and Eppler, 2003; Von Zedtwitz, 2002)

The concept of post-project reviews might be a useable model since it considers constructing individual into Organizational Knowledge. However, it must clearly be further elaborated upon. 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 continuous knowledge repository between projects. This deduction is, however, not revolutionary. The concept of continuous improvements is known and thoroughly deliberated upon 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 accomplished, 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 are 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 adviseble to divide them into a number of separate checklists.
- The checklists are unique to every company and adapted to their 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 future projects.

2.6.4 Web 2.0

Knowledge repositories based on Web 2.0 solutions, such as blogs and wikis, have been proposed as means of facilitating knowledge-sharing (Levandowski, et al., 2013; Standing and 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 and 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 and 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 Lean Product Development 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 and 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 originator. 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 and Liker, 2006; Shook, 2008; Sobek II and 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 Lean Product Development literature, different types and purposes of A3-reports have been suggested, although only problem-solving A3s are highlighted in this thesis (Morgan and Liker, 2006; Sobek II and 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 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 and 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 may 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, 2015).
- 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 lost
    - 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 and Turner, 2006; Schindler and Eppler, 2003; Von Zedtwitz, 2002)
- The Engineering Checklist aims to remind the engineer of things that must be completed throughout the product development process (Morgan and Liker, 2006).
- Morgan and Liker (2006) point out a crucial part of utilizing Engineering Checklists effectively 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 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, in order to be effective they still require a culture of sharing and collaboration (Wagner and 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 form (Shook, 2008).

2.7 Sustainability

Sustainability in a product development 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 with which to improve the resource efficiency of products by focusing on reuse, refurbishment, remanufacturing and recycling (Allwood, et al., 2010; Chen and Graedel, 2012). An instrument by which to achieve this is Product Service Systems 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 small an 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.

During the product development 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 and 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 and Van der Vorst, 2003). Remanufacturing places requirements on product design to facilitate disassembly and upgrading, whenever necessary (Sundin and 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, et al., 2011).

A fully functioning KRS has the potential for moving knowledge from all product life-cycle phases to product development 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, these data 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 product development 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 deficiency points up a need for a functioning knowledge flow from latter phases into product development (Figure 9), 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).

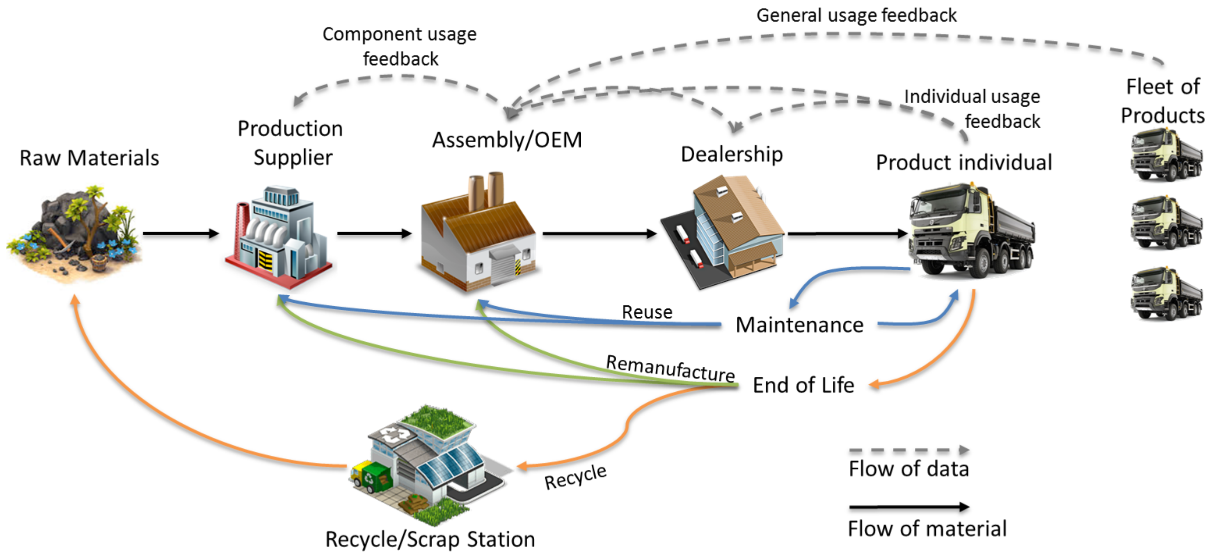

Figure 9. Component and information flow from latter to earlier phases. The figure also illustrates the data from individual products and fleet of products, which can be used in different ways in earlier phases.

3 RESEARCH APPROACH

This chapter briefly outlines different approaches for scientific study. Further, it discusses the research approach and methods applied in this thesis.

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 product development 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, overlapping phases: experimental, intellectual and empirical (L. T. Blessing and 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 with empirical studies in the 1980s. 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.

3.1.1 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 (2009) 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 the tools, methods or guidelines that can be applied. Therefore, there is greater freedom for the researcher to find new ways to deal with the questions studied during the creative part of the research process. 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 10). It is not often possible to perform all four within the boundaries of a single research project (L. T. Blessing and Chakrabarti, 2009).

The first stage is research clarification (RC) and main goal is to define a success criterion for evaluating research success. The main source of information and method at this stage is existing literature. 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 on which 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.

3.2 Applied Research Methodology

All appended papers are preceded by a literature review. Paper A is furthermore a deeper review of existing theory. Paper B is a two case study introducing a potential solution to an identified research gap, whereas Paper C is a deeper evaluation of a long-term implementation in industry setting. Especially Papers B and C are based on case study research, not solely single but sometimes multiple units, involving "intensive study of a single unit for the purpose of understanding a larger class of (similar) units […] observer at a single point in time or over some delimited period of time" (Gerring, 2006). As such, case studies provide an opportunity to gain a deep holistic view of the research case and may facilitate describing, understanding and explaining a research problem or situation.

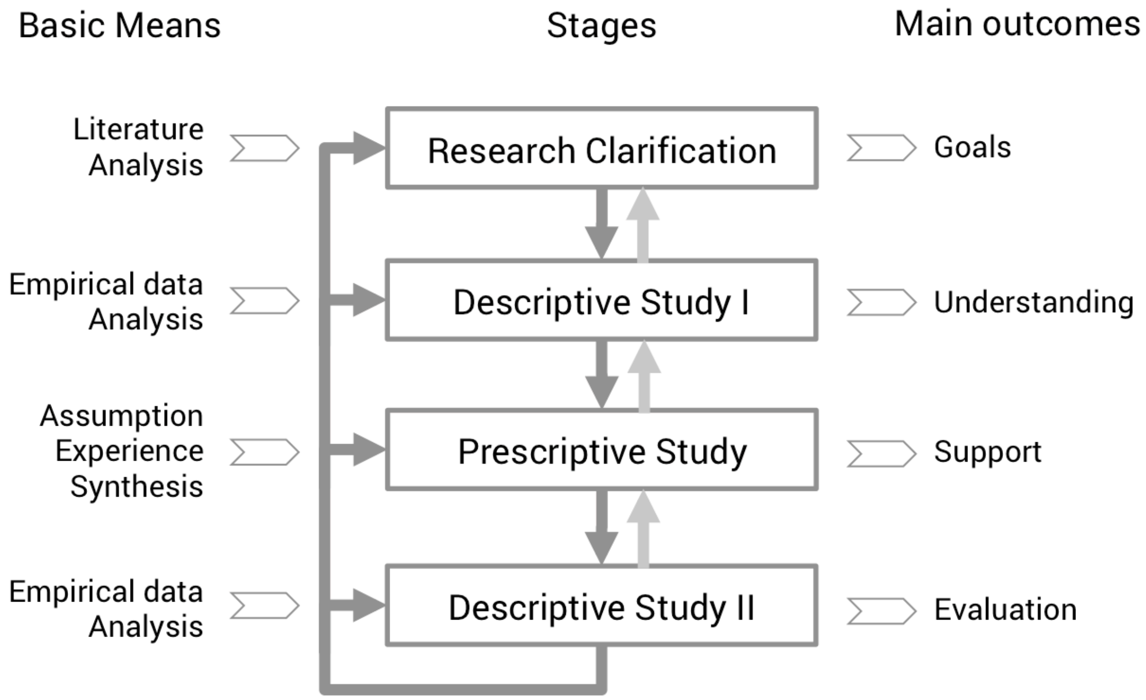

Figure 10. The framework, redrawn from Blessing and Chakrabarti (2009)

Paper A is what Blessing and Chakrabarti (2009) refer to as Type 1 Studies including RC and DS-I, Paper B Type 2 Studies including RC, DS-I and initial PS, whereas Paper C is Type 5 including RC, DS-I, PS and initial DS-II (Table VII).

Table VII. Overview of the conducted studies and their relations to the research questions.

Study	Purpose	DRM phase	Data collection methods used	Resulting paper	Related RQs
Study 1: Literature review	Identify prior research related to knowledge reuse barriers and create a framework for the studied topic	DS-1 – type 1	Literature review	Paper A	RQ1
Study 2: Support development and implementation, case study	Develop and introduce a tool for supporting knowledge reuse within incremental product development	PS – type 2	Semi-structured interviews, observations of workshops	Paper B	RQ 2, RQ 3
Study 3: Support and implementation evaluation, case study	Evaluate the true effect of the implemented support and identify potential engineering implications.	DS-2 – type 5	Semi-structured interviews, long-term observation, document analysis	Paper C	RQ 2, RQ 3

I. Paper A

The goal of this descriptive study was to examine the KM literature to discover barriers inhibiting knowledge reuse of existing codified knowledge in product development. For this purpose, a content analysis study of articles was conducted that presented a host of barriers to successfully reusing knowledge in different contexts. The approach used followed the model suggested by Vom Brocke et al. (2009), as it is suitable to structure the knowledge accumulated in a specific domain through the principles of quality relevance of the publication and methodological rigor. The literature review identifies publications of interest to researchers through the data-gathering process and then describes the choice of relevant publications for the preparation of the article. This literature search follows a five-phase approach so as to be systematic, transparent and replicable; (1) Definition of the context and scope of the review, (2) Identification of keywords and search string, (3) Database selection, literature search and filter application, (4) Analysis and synthesis of the results obtained and (5) Future research.

The first phase is the definition of context and scope of the review. The pre-study resulted in the identification of a set of papers that together summarized and synthesized the topic of interest (Cleveland and Ellis, 2015; Riege, 2005; Yih-Tong Sun and Scott, 2005). However, all articles identified investigated barriers across a wider spectrum whereas this article focuses specifically on the knowledge reuse of codified knowledge. The scope of this review was consequently to contribute to and delve into the theme of knowledge and knowledge reuse within product development so as to identify existing barriers to reusing codified knowledge. Further, the literature findings were synthesized into a framework of barriers condensed to the topic studied.

Paper A was hence driven by the following research question:

What potential barriers can be identified that restrains the successful reuse of codified knowledge in product development?

II. Paper B

Paper B is based on confirmatory research of knowledge reuse focusing specifically on synthesizing the experience of overcoming knowledge reuse barriers with the use of Engineering Checksheets (ECS's) that evolved throughout the research process. The evolvement of ECS's has been supported by the focus and ability to digitalize Toyota-based lean KM methodology, tools and processes while keeping its user-friendly, visual and easy-to-use attributes. The topic of interest called for a deeper understanding of the real-life context of engineers in order to explore what could be important factors that might affect knowledge reuse. This approach favored the use of qualitative case study research, seeking to both generate and verify the existing hypothesis (Gerring, 2006; Yin, 2013). The set-up of the research project as a partnership involving case companies also gave access to a detailed inquiry into the topic in a real-life setting. This access to data was the main rationale for selecting a two-case design, i.e. an opportunity to study a situation otherwise inaccessible to researchers, which Yin (2013) refers to as a 'revelatory case'.

Throughout the research project, data were collected from case companies using semi-structured interviews, document analyses, informal meetings, internal seminars and long-term observation. The interviews, 24 in total, were conducted primarily with product developers, production developers, product managers and knowledge managers and specifically focused on knowledge reuse. The questions often revolved around how knowledge was stored and disseminated, how decisions for reuse were made and what challenges were experienced when recontextualizing knowledge for reuse to new applications. Analyses were based on the coding of statements in the interview transcripts and the identification of patterns, as well as hypotheses testing experiments using both results from case studies and related research.

Reviews of existing literature were conducted primarily in the academic fields of KM, OL and the pragmatic field of Lean research, which helped positioning the empirical findings within a larger context and generalizing the observations. Another field, Cognitive Psychology, contributed to the scientific basis of this research, even though we did not claim to be experts in that field.

This was generalized in a concept that corresponds to the industrial needs reflected in two different case companies expressing the need for Lean and practical approaches to KM and reuse.

These industrial needs were expressed as the following research question in paper B:

How can organizations in an easy, lead-time shortening and visual manner document, store and disseminate product and process-related knowledge?

III. Paper C

Paper C is primarily focused on evaluating of the implementation of ECS's which is performed by applying the proposed Initial Descriptive II procedure in the Design Research Methodology (L. T. Blessing and Chakrabarti, 2009) and through a strong collaboration with a large industrial company which has been applying ECS during more than five years within various groups. The aim for the chosen methodology was to provide a generic statement about the partial implementation.

The topic of actionable thin-sliced knowledge items in an engineering context called for a deeper understanding of the real-life context of engineers in order to explore the applicability, usability and usefulness of the support, as well as issues, factors and links that needed further detailed evaluation. The setup of the research project as a partnership with the case company gave access to a detailed inquiry about the topic in a real-life setting.

The implementation was initiated in 2012 and throughout the research project, data were collected from the case company using semi-structured interviews, document analyses, informal meetings and internal seminars, along with long-term observations performed by one of the researchers. The study culminated in 21 interviews performed in early 2018 focusing primarily on ECS even if more general KM-related questions were included and conducted primarily with product developers, production developers, product managers and knowledge managers. Interviews lasted from .4 hours to 2.5 hours.

Questions regarding what needs the ECS is set out to fulfill, effects on capture and reuse, the process for using the method and the usefulness of thin-slicing were formulized as open-ended questions and were followed up by questions based on the researchers' former experience in the case depending on the direction of the answer. Analyzes were based on audio recordings from interviews and the coding of statements in the interview transcripts. Further, the interview data were noted and organized by each protocol question and the identification of patterns and their relation to the research studied. The interview transcripts were communicated and approved by each participant. The analysis was presented during a workshop with outside researchers and representatives from the case company.

Reviews of existing literature were conducted primarily from the academic fields of Engineering Design, Knowledge Management and Organizational Learning.

The research question that guided the process in Paper C was:

What effects can be seen by implementing actionable thin sliced knowledge items in product development to foster knowledge reuse?

3.2.1 Approach to Validation of the Results

Developing support systems for engineering through design science comes with several challenges. Moving between reality to theory and back to theory again is inconsistent; one of the challenges is that the solution may not correspond to reality, i.e. the real need. It is therefore important that the research is validated to ensure that the correct problems are solved. By applying and testing the method and system in design reality.

Design science is not an exact research field and findings from real-life development projects are difficult to validate because of the large complexity and number of variables affecting the result. According to Buur (1990), there are two major ways of verifying the validity of a design research result: *logical verification* (i.e. that the research results are based on related research and that there do not exist any contradictions with accepted theories and methods) and *verification by acceptance* (i.e. the research is acceptable/adopted by experienced practitioners within the scope of the research).

It is possible to some extent to use logical verification regarding the KRS developed by asking the question: Is it possible for practitioners to adapt the developed system in order to fulfill the identified need? However, for applicability and for the need and use of the research results in industry, verification by acceptance is a reasonable method. Verification by acceptance can be performed by presenting, demonstrating, and possibly implementing the IT system in a real-life setting and discussing the problems and solutions with representatives from the industry, interviewees, and research colleagues.

Validating a design method also calls for evaluating of its purpose by demonstrating its usefulness (Pedersen, et al., 2000). Pedersen et al. (2000) further present the validation square as an approach to validate design methods which is believed to be applicable to this research project. The validation square contains four views in order to address the aspects relevant for validation purposes. The four views are supplemented by empirical and theoretical dimensions, as well as the structural and performance dimensions. The performance variables can be connected to the efficiency of the method developed, i.e. the ability of the method to perform what it is intended for. This validation is advantageously conducted with a quantitative evaluation of the method. The structural dimension of the validation square is more related to effectiveness and is best validated by qualitative evaluation (Pedersen, et al., 2000).

In order to ensure the theoretical validity, the research work has to reflect related areas to knowledge reuse and explain possible deviations from these fields. The studies must focus on areas where knowledge reuse is applicable and useful.

These views can be related to knowledge reuse research according to the following:

• Theoretical structural validity: Correctness of constructs, both separately and integrated, consistency, similarities and applicability of theory in adapted knowledge management practices.

• Empirical structural validity: Appropriateness of problem examples (case studies) and the usefulness of the method applied, for example industrial projects where incremental product development and thus a high degree of knowledge reuse can be studied.

• Empirical performance validity: Performance of the solutions with respect to problems, for example the measured performance according to increased knowledge reuse, ultimately leading to reduced lead time in product development while maintaining or increasing quality.

• Theoretical performance validity: Performance of the method beyond the example solutions, for example transferability of the solution to other cases. Knowledge reuse through ECS in other industries.

Further, Maxwell (2012) recommends an eight-step checklist that can be used for testing validity in qualitative research:

1. *Intensive, long-term involvement*, which provides more robust data and opportunities to test hypotheses.
2. *Rich data*, e.g. through comprehensive transcripts of interviews that cover different aspects of a situation.
3. *Respondent validation*, i.e. letting subjects review the data and conclusions derived based on their responses.
4. *Intervention* into the research setting to examine the effects of proposed solutions.
5. *Searching for discrepant evidence and negative cases* to avoid ignoring data that do not fit a theory.
6. *Triangulation*, by which information is collected using a variety of methods and sources to mitigate the risks of bias.
7. *Numbers*, whereby quantitative claims can be tested and data made more explicit.
8. *Comparison*, e.g. using multiple case studies, which provide the opportunity to isolate variables in order to study causality.

4 SUMMARY OF APPENDED PAPERS

This chapter will provide a short summary of the results gained from the work that formed the basis of the appended papers in this thesis.

The three appended papers cover different aspects on how to support knowledge reuse in product development. Several case companies were studied and two of them worked as pilots for implementation of a KRS based on the method developed for the purpose of increasing knowledge reuse. Further, one of the case companies fully adopted the method even beyond the research pilot. In all cases, a basic understanding of work methods was investigated to set the basis for further research.

To give an overview of the contents of the three papers and how they relate to each other before going into details, an executive summary follows:

Paper A focused on reviewing literature regarding knowledge reuse of codified assets and mainly investigated potential barriers that might challenge this action.

Paper B introduced a KRS, ECS, for the purpose of being a lightweight system to efficiently share knowledge of succeeding projects. ECS's are piloted in two case companies and the procedure is presented as well as the reasons for different choices taken during each implementation.

Paper C continued the work of Paper B by evaluating one of the two initiated pilots which was further adapted during the five years (of writing this thesis). The evaluation is based on factors related to the KM cycle.

4.1 Paper A

Stenholm, D. & Bergsjö, D. (2018). Barriers to Reuse of Codified Engineering Knowledge in Product Development – A Literature Review.

The purpose of Paper A was to explore and extend prior research on barriers to KM by limiting and deepening the objective of the research to review barriers to the reuse of codified knowledge in product development. In this study, we thus focused on the consumer of knowledge, who has received less attention compared to the producer of knowledge (N. Dixon, 2002; Kankanhalli, et al., 2005; Markus, 2001; Zhang and Jiang, 2015) and the process of acquiring and applying codified pre-existing knowledge within a repository.

Reusing experience-based knowledge with the support of documentation is often known as a codification strategy within the organization and is based on the document-to-individual approach, in which individuals retrieve knowledge from KM Systems, databases, books, data warehouses, decision-support systems and enterprise resource planning systems (Hansen, et al., 1999). Experience-based knowledge is referring to a mixture of framed experiences, values, contextual information and expert insights, providing a framework for evaluating and incorporating new experiences and information (Davenport and Prusak, 2000). However, the effects of inefficient knowledge reuse of codified knowledge become apparent when individuals resist capturing knowledge because of the low degree of value it brings, thus leading to valuable knowledge being lost over time.

The overwhelming strategy and balance between short-term and long-term effectiveness and success are viewed as critical. It is commonly known that product development projects are not measured on the rate of knowledge reused but primarily on time, cost and quality. Even if the acquisition of "knowledge documents" are stressed as important, it commonly become an *ad hoc* approach not directly tied to project process. The study resulted in the identification of 18 barriers inhibiting knowledge reuse mapped into the typology of people, organization and technology, presented in Table VIII.

The study contribute by providing insights for the future design and implementation of Knowledge Management Systems allowing practitioners to develop strategies to overcome identified potential barriers and improve the engineering knowledge reuse strategy.

Table VIII. 18 barriers to knowledge reuse identified in Paper A

People	
P1	Lack of capability to find knowledge
P2	Lack of time/low prioritization to acquire codified knowledge
P3	Lack of understanding of knowledge content
P4	Lack of motivation for reusing knowledge due to attitude, moral reasons or lack of incentives
P5	Lack of awareness and realization of the value and benefit of reusing knowledge
P6	Lack of trust in the accuracy and credibility of knowledge
P7	Difficult to adapt knowledge to new context
P8	Difficult to "unlearn" previous knowledge in order to accept new knowledge
Organizational	
O1	Integration of knowledge reuse into the company's goals and strategy is missing or unclear
O2	Practices, leadership and managerial direction that hinder knowledge reuse
O3	Organizational structure inhibits or slows down most reuse practices
O4	Lack of a transparent rewards and recognition systems that would motivate people to reuse more of existing knowledge
O5	Existing organizational ethics (culture, norms and assumptions) hinders reusing practices and people to reuse knowledge
Technology	
T1	Mismatch between the needs and requirements of individuals and integrated IT systems that impedes reuse practices
T2	Lack of compatibility between diverse IT systems and processes
T3	Lack of availability and accessibility to integrated IT systems obstruct work routines and knowledge flows
T4	Unrealistic expectations of employees as to what technology can do and cannot do
T5	Reluctance to use IT systems due to lack of familiarity and experience with them

4.2 Paper B

Bergsjö, D., Catic, A., Stenholm, D. (2018) A Lean Framework For Reusing Knowledge – Introducing Engineering Checksheets.

The purpose of Paper B was to bring several knowledge management theories and practices together and throughout the research adapting ‘enabling knowledge reuse’ to be a guiding principle in order to formulate an improved method for documenting knowledge. The focus has been to create ***actionable and reusable knowledge*** *presented at* ***the right time****, to the* ***right audience*** *in a* ***digitally condensed format*** *that will hopefully lead to* ***improved decision-making****, thereby potentially driving* ***innovation*** *and effectively reducing overall product realization* ***lead-time****.*

By combining positive aspects, the results led to the introduction of the concept of ECS’s with the following definition of ‘Checksheet’:

A Checksheet is a tool that presents an extended checklist of condensed, actionable and experience-based pieces of knowledge the aim of which is to direct knowledge users towards decisions or actions relevant to a predefined context. The Checksheet traces its origins on the checklist-based Know-what and is often complemented by guidance using one or several alternative Know-how’s for performing the specific action along with the Know-why rationale under which circumstances the actions become relevant.

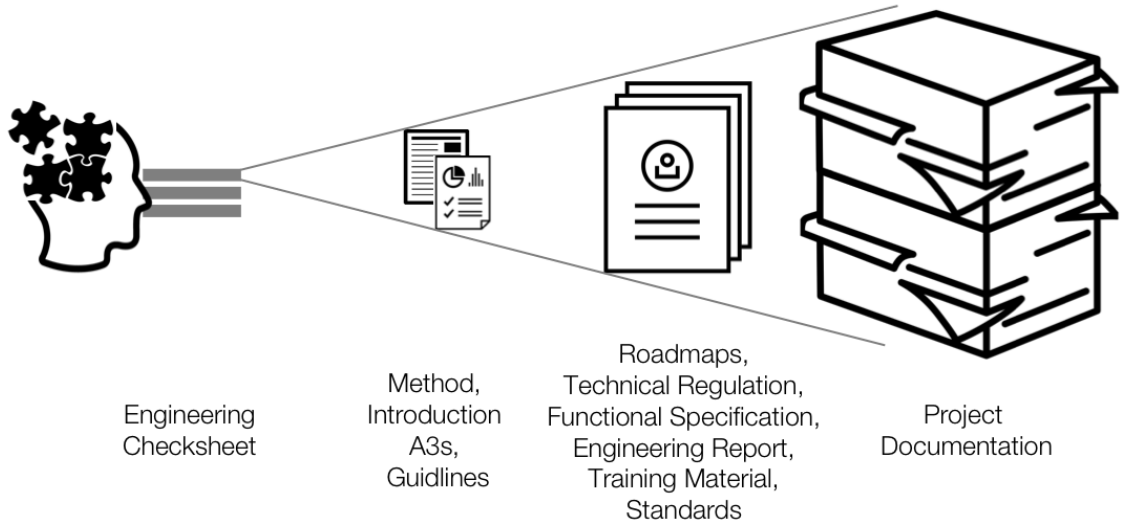

Figure 11. Engineering Checksheet visualizing the thinnest slice of knowledge.

Table IX. Structural description of a knowledge element.

	Know-what	Know-why	Know-how
One knowledge element includes	Action/decision that needs to be taken	Why does this specific action/decision need to be made? Why is it important?	How will the action/decision preferably be performed? What is important to keep in mind/consider?

In two separate case studies, we introduced ECS as a methodology and tool using spreadsheets and a web-based system. We identified success in the adoption and growth of the methodology in the first case study, whereas the second case study provided insights into the reuse of knowledge and human interaction of a web-based ECS system. Case Study 2 successfully demonstrated the application of a web-based ECS as a means of reducing and avoiding repetitive problems.

Further findings and reflections on the case studies have uncovered the following:

- ECS's possess the ability to function as carriers of engineering knowledge, supporting both experienced and novice users, by filtering and representing important aspects focusing on the know-what, know-why and know-how. In this way, ECS's serve to educate inexperienced engineers in the most critical engineering decisions and their potential impact, as well as supporting experienced engineers in recalling essential aspects of product and process delivery.
- ECS's have proven to be dependent on the organizational structure in which the availability of knowledge managers has become a significant success factor in Case Study 1.
- The superior benefits of the web-based IT-tool over the spreadsheet prototype in terms of complexity management, analysis capability and general user experience. However, motivating users to employ a prototype spreadsheet has a lower internal threshold as it does not require a new tool and may be an enabling factor for testing and evaluating the general ECS methodology.

4.3 Paper C

Stenholm, D., Catic, A,. & Bergsjö, D. (2018). Knowledge Reuse in Industrial Practice: Evaluation of Implementing Engineering Checksheets in Industry.

The purpose of Paper C was to evaluate the implementation of Engineering Checksheets for managing knowledge within an engineering company. The tool was introduced stepwise starting in 2012 and had at the point of our evaluation grown to incorporate about 100 knowledge areas. The perspective taken in the analysis of this evaluation was from the engineering viewpoint, benefits and challenges with practical knowledge reuse experienced in daily engineering work, hence the ambition of this paper to expand literature beyond the traditional, management view on organizational learning and knowledge dissemination.

The framework was evaluated on factors mapped according to the Knowledge Management cycle; acquiring, assessing, applying, creating, identifying, refining and disseminating (Table X). During the study, a commercial and file-based spreadsheet tool was used as an IT-system for supporting the implementation.

Table X. Evaluation factors affecting the success of Knowledge Management System based on the steps for knowledge reuse

	Evaluation factors
Acquire	• Findability - Knowledge is found with minimal effort and time • Understandability – Content and rationale is understandable with minimal effort and time
Assess	• Validity and reliability - The knowledge is trustworthy and replicable • Content evaluability - The knowledge is easily assessed based on its value to the current context
Apply	• Applicability - The knowledge is reused in a current context • Actual value (e.g. decision taken, problem solved) - Applying the knowledge leads to bringing development forward
Create	• Knowledge gap identification – A knowledge gap is easily identified between existing knowledge and the necessary knowledge required • Expandability - Possibility to build upon existing knowledge
Identify	• Identifiability - New knowledge is easily identified • Extractability - New knowledge is easily separated from existing codified knowledge
Refine	• Createability of new records - New knowledge is easily codified • Manageability - Existing knowledge record is easily updated and managed
Disseminate	• Shareability - The knowledge can easily be prepared for availability and accessibility to an arbitrary receiver • Transferability - The knowledge can easily be transferred to a specified receiver

Within Paper C several positive effects was identified throughout the evaluation with various types of knowledge workers in a development setting. We concluded that the ECS is particularly beneficial for inexperienced knowledge workers as compared to *previous, adhoc and dispersed practice* when quality assuring a delivery, identifying the most critical design parameters and identifying critical inputs from others in the chain of development. In relation to the implementation process, and the perceived maturity of the ECS document, we concluded that an early draft of the ECS is supportive and often "good enough" for engineers to start using. A draft ECS further encourages the update process and contact with knowledge owners. Hence, the ECS should be put into practice as soon as possible, rather than waiting until engineers, or knowledge owners, feel that it is perfect, as this is unlikely to ever happen due to the continuous evolution of the organizational knowledge.

For experienced knowledge workers, the perceived gains was related to less stress as they used the ECS to make sure that necessary actions had been taken according to existing knowledge without necessarily relying on their mind. In practice the ECS's contained an average of 35 KEs, and even experienced engineers will eventually forget to check or implement a few of them. However, this necessitates the ECS to be agile towards experienced engineers as they seldom have the patience to go through long and tedious documentation, whereas experienced engineers often only need to glance on the "Know-What" and can thus finish an ECS in a few minutes.

During the extraction of knowledge into ECS, it was concluded that the format is not appropriate for either collecting all existing or all types of knowledge. Therefore, it was important to highlight the necessity of not duplicating detailed knowledge existing in other forums, but instead reference these sources. Multiple times in the evaluation of ECS's, it was stated that to be kept relevant, minimalistic and up-to-date, knowledge needs to be systematically reviewed by everyone involved through a shared responsibility to report issues with a single knowledge owner being the main professional responsible for the complete content of the ECS.

Regarding knowledge owners and organizational structure, we concluded that there was a need to define responsibility for making sure that knowledge is captured in the project and shared globally, in both the Community of Practice, as well as in the general documentation and specifically the ECS. In the study, some successful cases were highlighted where the knowledge in each domain was shared during regular meetings reviewing the ECS through the combination of local knowledge owners (responsible for the project) and a global knowledge owner connected through the Community of Practice. From the organization level, there was still a lack of formalized governance structure for managing the creation, maintenance and reuse of codified knowledge. This was to some extent managed by the knowledge owners and Community of Practice, but were not formalized as routines integrated in the general development process.

In the organizations, the balance between codification (in this context the ECS) or the personalization approach (represented by knowledge owners and the Community of Practice) was not explicitly discussed and some cases witnessed about potential issues. Even if the process of codifying the knowledge had been completed, the knowledge owner responded to a knowledge request from a colleague by spending time and verbally providing guidance in front of referring to the asset. However, if guidance beyond the captured knowledge would be necessary, the knowledge owner should be available to provide such guidance but first and foremost refer to existing codified assets. From the engineer's perspective of applying existing knowledge, the personalization approach is perceived as easier and thus naturally becomes a threat to the codification approach unless that habit is changed.

From the knowledge manager's perspective, we concluded that much of the knowledge captured in the ECS was not codified before or existed in project-specific documents of lessons learned. The ECS fulfilled the task of systematically carrying learning from past projects to new projects to be stored connected to engineering tasks in an available format. In the role of Knowledge Manager, the study also highlighted the need for continuous education and management follow-up of the tool for making sure that new employees understand its objective and the basic demand it fulfills. In a few cases, the ECS had found its own pace to the extent that ECSs were being created and filled out without managers or Knowledge Owners pushing the tool. Further, the study showed that the experiment was successful without focusing on a specific IT system since the tool survived changes and updates of IT support systems, such as the introduction of a new Wiki system for managing the detailed development guidelines. Further findings are summarized in Table XI.

Table XI. Summary of the main evaluation results from Paper C regarding the ECS implementation related to phases in the KM cycle.

	Evaluation results
Acquire	• The implemented timeline in the spreadsheet is valuable support to guide what is important in what step in the process. • Implementation of ECS witnessed less phone calls to experts to ask basic questions that are now captured in the ECS. • The ECS provides advice based on experience and knowledge from different key colleagues. • ECS is a document that is especially valuable in the beginning of the project, and thus valuable to include early on in the process. • Easy-to-understand content due to several factors. First of all, the amount of knowledge is condensed, the structure is clear with Know-what, Know-why and Know-how and each KE holds a single purpose from the perspective of the work to be performed. • Basic knowledge about the topic is preferred before being able to understand the content in the ECS. • The structure helps ECS holding a lot of information in relation to its size. • Valuable to have personal contact with the creator of the knowledge in order to ask questions to minimize the risk of misunderstanding.
Assess	• Being able to see the date when the knowledge was captured/created, along with source and references is valuable in order to assess the validity of the contents. • Including Know-why in order to assess if it is applicable to the current case together with Know-what.
Apply	• Front loading the ECS supports a process of "check-do" instead of "do-check". Describing in which order the knowledge is consulted, either before or after the action is performed. • Experienced engineers find ECS valuable as a reminder to making sure that all aspects have been considered. • Structure of Know-what and Know-how guides engineers to make decisions and take actions on existing knowledge. • Being able to visually convey that knowledge has been applied or not in order to monitor the progress both for purposes of self-assessment, as well as external assessment from other stakeholders, such as managers.
Create	• Include Know-why in order to know the rationale behind the action or decision in order to expand or revise the knowledge. • The inclusion of Know-why makes the validity of the knowledge transparent and can stimulate a dialogue around the apparent lack of knowledge and the need to create new knowledge for the sake of solid decision making.
Identify	• It is easier to see how new knowledge fits into the captured knowledge due to the structure that provides a holistic view of the knowledge area.
Refine	• Easy to input knowledge in text, but due to the IT solution, managing images became a struggle.

	• Including references to other documents and webpages through a specific placeholder for references and attachments decreased the time for refining and the need for duplicating while still capturing valuable knowledge in one place. • Refining the knowledge was not done without effort but the template supported the process and was quite self-explanatory. • The structure of Know-what, Know-how and Know-why required some initial time to grasp, but was valuable while capturing the knowledge in a structured form. • The Know-why forced a deeper clarification about the reasons behind the proposed action and decision. • The initial ECS in each case was mainly created due to instructions from managers and not by decision from the knowledge expert themselves. • Refining the knowledge between groups working with similar activities forced differing "best practices" into converge to a common agreement. • Setting up a process that continually brought involved engineers together to make sure that the ECS became updated built trust in its content.
Disseminate	• Support sharing knowledge to a unknown receiver, as well as transferring knowledge to a known receiver, by storing the ECS in the PLM system or shared workplace, for example as an attachment to an email. • Easy to share limited knowledge by being able to refer to a specific KE.

5 SYNTHESIS

This section combines the results from the appended papers and prior literature to answer the research questions of this thesis to outline the journey towards increasing knowledge reuse through improved practice.

5.1 Quality Characteristics of Codified Knowledge for Reuse

RQ1: What are the characteristics of captured codified knowledge that empowers knowledge reuse in product development?

A systematic literature review was conducted to identify relevant capabilities (i.e. enabling methods and technologies) to foster knowledge flow through representing Organizational Knowledge in a manner more convenient for knowledge reuse.

The research performed for Paper A provided insights into the challenges to knowledge reuse that could be identified. The findings from this research summarize and structure existing literature on the challenges to knowledge reuse, such as the willingness of employees to reuse (Watson & Hewett 2006), the ability to acquire the knowledge within an appropriate time frame (Weber, et al., 2001), seeing the practice as useful (Watson & Hewett 2006) and investing the time for exploration (Riege, 2005).

A precondition for effective knowledge reuse is that a reusable knowledge asset has been created in the first place. Literature indicate that efforts have been undertaken to create knowledge assets, but that sufficient focus has not been on *reusable* knowledge assets. Creating knowledge assets in the hopes of someone finding them valuable has been seen as inefficient and for knowledge transfer, finding the right receiver and context is troublesome (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 amount of challenges that are present varies, as well as to which degree they affect the final result. The value of the knowledge asset can be measured by how often it is visited and reused together with the benefit provided from reuse. Some common challenges are that individuals are rapidly switching positions, knowledge is dynamic and continuously in a state of flux and prioritizing knowledge reuse is not always viable.

The challenges identified in Paper A along with the literature review become the basis for identifying characteristics to increase knowledge quality in order to support more efficient KRS. Further summarized in Table XII are characteristics meant to support knowledge reuse in product development, along with the mapping of challenges related to people from Paper A repeated in Table XIII.

Table XII. Characteristics that were identified to increase knowledge quality

Characteristics of Knowledge Reuse Quality
(1) – Relevance of content

Captured knowledge should consist of critical knowledge to ensure organization competitiveness.

Critical knowledge that is significant to value generation that might be retrieved should primarily be captured, rather than everything known to man (L. Blessing & Wallace, 2000), to minimize the risk of information overload while still capturing the most relevant knowledge to ensure organizational competitiveness (Garud and Kumaraswamy, 2005). This is in line with both P1 and P2 because some types of knowledge are more important/critical/relevant to an organization than other types depending on the significance of the task than they are used for, capturing too much knowledge might lead to excessive cost for finding and making use of the knowledge (Garud and Kumaraswamy, 2005).

(2) – Ease of application

Captured knowledge should foster actions and/or decisions because it is evaluated based on the result of application.

Davenport & Prusak (1998) argue that knowledge should be evaluated by the decisions or actions to which it leads and knowledge should thus be structured in a way that fosters actions and/or decisions. Actionable knowledge is explained by Cross & Sproull (2004) as representing a pragmatic view of knowledge creation and application toward specific ends. The search for knowledge is often stimulated by an upcoming issue and is pursued in finding a solution to that problem (Cyert and March, 1963). One can thus argue that knowledge should include Know-What (declarative knowledge) and Know-How (procedural knowledge) as guidance to support its usage (Lundvall and Johnson, 1994).

Declarative knowledge describes the kinds of phenomena worth pursuing (Alavi and Leidner, 2001). Procedural knowledge on the other hand represents an understanding of the generative processes that constitute phenomena and often describes a process by which something is performed and can therefore often be codified as process-steps and practices. Procedural knowledge has also elements of tacit knowledge that is acquired only by extensive experience and "learning by-doing" (Alavi and Leidner, 2001).

This characteristic has the possibility of increasing the speed at which knowledge can be applied and thus decreasing the P5 challenge. By minimizing the time between acquisition and use of the knowledge through clear guidance, its value becomes more rapidly apparent and thus provides incentives for future reuse (Markus, 2001).

(3) – Completeness

Captured knowledge should include richer contextual details to support understanding.

Knowledge should include richer contextual details to support an understanding of the problem and help the knowledge acquirer redefine the problem and understand the factors that need to be addressed (Ahn, et al., 2005; Markus, 2001). Contextual knowledge should also describe the potential effect on related systems (know-with – relational knowledge) (Alavi and Leidner, 2001). The completeness/coverage can either be seen as the percentage of real world knowledge, the number of business rules represented, the extent to which the codified knowledge represents the full knowledge domain, i.e. the knowledge of all relevant sources and level of full description of the specific task. However, considering that too much contextual information would not necessarily benefit users because they may be distracted by unnecessary and unhelpful contextual information without leading to maximum clarity which is difficult but important to balance in order to cope with the challenges P3 and P7.

(4) – Traceability

Captured knowledge should include a design rationale to support the reapplication to a new context.

A recurring comment on how to make codified knowledge reusable is to capture its design rationale containing the justifications for a design, alternatives considered, trade-offs evaluated and other argumentation (Busby, 1999; Lee, 1997; Markus, 2001). The foregoing explains the 'Know-why' of knowledge and supports the evaluation of how conditions may be different when that knowledge is reapplied (P7) to a new context and the value brought by it (P5) (Alavi and Leidner, 2001; Duffy, et al., 1995). The traceability of knowledge creation can be a valuable component in assisting in the determination of knowledge credibility.

(5) – Shareability

Captured knowledge should focus on the generic level and follow a standardized structure to boost knowledge sharing between different user groups and other applications.

In order to use the full organizational capability for innovation, the knowledge needs to flow between and through cross-project integration (Kennedy, 2008). A generic level and standardization of structure boost knowledge reuse between different user groups and perspectives and other applications (K. G. Cooper, et al., 2002). A more generic level of knowledge addresses the P1 challenge as a way of increasing the possibility of wider sharing and a familiar structure increasing the speed of acquiring the knowledge (P2).

(6) – Interpretability

Captured knowledge should be visualized and written in a language/terminology that matches the reuser to support and increase the speed of interpretation.

It is important that the knowledge to the greatest extent possible is captured and packaged in relation to the potential receiver in order to increase understanding (P3), stickiness and thus also the potential for reuse (Szulanski, 1996). To increase interpretability, understanding and maximize clarity in spite of the compact form, visual aids are recommended to the largest possible degree along with a written language/terminology that matches the reuser (Shook, 2008).

(7) – Accuracy

Captured knowledge should provide high validity through assuring correctness of reuse.

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, et al., 2002). Thus, a certain degree of organizational unlearning must be pursued so that old beliefs regarding procedures and measurements are deconstructed and change welcomed (Leon and Farris, 2011). Dixon (1999b, p. 7) states that "accumulated knowledge… is of less significance than the processes needed to continuously revise or create knowledge".

Thus, is it a necessity to continually provide a high degree of validity through quality assurance in order to ensure correctness of reuse even in a dynamic environment. High validity can be achieved through various methods, including references to and author, the date of creation and updates can guide the user to further explore and define validity. Further, if the validity of the knowledge were to be limited to a certain time period, this should be stated. Accordingly, the process of building and maintaining accuracy is important to overcome the challenge of a lack of trust in the knowledge (P6).

(8) – Relevance in time

Captured knowledge should indicate when in time the knowledge should be reused to promote front-loading of knowledge.

To make fewer design changes late in the product development process, front-loading has been proposed by researchers (Morgan and Liker, 2006) and in many companies, it has been interpreted as a necessity of making a greater number of more explicit decisions early which has great effect on the costs of the latter stages (Boothroyd, 1994; Duverlie and Castelain, 1999; K. T. Ulrich and Pearson, 1993). Thus, knowledge should include time aspects, conditional know-when, maximizing the possibility of front-loading knowledge and guiding the acquirer of knowledge on time (Alavi and Leidner, 2001), which can help knowledge reuse overcome the P2 challenge as a way of prioritizing between knowledge assets.

(9) – Minimality

Captured knowledge should be integrated with existing complementary knowledge assets to increase the potential reuse of all available knowledge.

New knowledge is most often generated by combining existing knowledge and therefore, pointers should exist to reference knowledge independently of the degree of incremental or innovative development (Albers, et al., 2015). It has been shown that independently of the degree of incremental or innovative development, products remains strongly dependent on the knowledge of reference products (Hoppmann, et al., 2011). The amount and number of concepts or relationships representing the same thing can be limited by including references to other experts and expertise in order to redirect further knowledge if needed i.e. through referrals/pointers to relevant people or databases (Cross and Sproull, 2004; Markus, 2001). This also increases the possibility of finding the necessary knowledge that already exists and is available (P1).

(10) – Degree of coherence

Captured knowledge should maintain a high level of coherence of the knowledge to avoid confusion.

Coherence of knowledge can have high impact on the process of understanding the knowledge and a low degree of coherence will result in confusion. Additionally, coherence can be viewed from two perspectives; (1) knowledge from various sources may contradict one another, (2) knowledge items extracted from the source may contradict a set of rules of the organization (Rao and Osei-Bryson, 2007). Accordingly, a low degree of coherence will thus lead to reduced trust in the accuracy and credibility of the knowledge asset (P6).

Table XIII. Findings from Paper A on challenges for knowledge reuse related to people extracted from Table VIII

People	
P1	Lack of capability to find knowledge
P2	Lack of time/low prioritization to acquire codified knowledge
P3	Lack of understanding of knowledge content
P4	Lack of motivation for reusing knowledge due to attitude, moral reasons or lack of incentives
P5	Lack of awareness and realization of the value and benefit of reusing knowledge
P6	Lack of trust in the accuracy and credibility of knowledge
P7	Difficult to adapt knowledge to new context
P8	Difficult to “unlearn” previous knowledge in order to accept new knowledge

5.2 Development of Knowledge Reuse Support

Throughout this research, KRS has been developed as a support for a more efficient way of organizing and working with knowledge assets to promote a higher degree of knowledge reuse in product development and as response to the second research question.

RQ2: How can organizations structure its knowledge to make it more reusable?

The KRS developed based on the research performed, combining past research in the field with new case studies, is named ECS's. An ECS takes the positive aspects of the common KRS to succeed in managing lessons learned based on experience, such as Engineering Checklists, Post-Project Reviews, A3-reports, blogs and wikis. It also includes aspects of the theory underlaying, e.g. actionable knowledge. Especially Catic and Malmqvist's (2013) model for Engineering Checklists lays a foundation due to its similarities and aims to serve the same purpose.

From an industrial perspective the main objective of the ECS is to increase the overall return on time invested into KM. This primarily means that the "apply" phase of the KM cycle is in focus to ensure that knowledge has an actual effect on the decision-making in a product development organization. The reason for focusing on the apply phase was not only rational from a return on investment perspective but also from a motivational perspective. The occurrence of knowledge application is likely to have a positive effect on the further motivation for capturing and refining knowledge as those individuals who witness this can observe the value to others or to themselves.

The design of the ECS was guided by the characteristics identified as research results from answering Research Question 1 and from evaluation factors in Paper C. An important aspect among the evaluation factors is the absent factor related to the absolute volume of knowledge contained. As the purpose of the ECS was to closely align with the KM cycle, this also meant that the focus was more on the flow of knowledge than on the volume. Therefore, the intention is not to capture and manage all existing knowledge. Instead, the aim of the ECS is to guide the engineer towards decisions and tradeoffs known from previous work in a predefined context so that the engineer can be aware of what awaits him in the engineering process depending on targets and scope.

The definition of the Checksheet concept is worth repeating:

A Checksheet is a tool that presents an extended checklist of condensed, actionable and experience-based pieces of knowledge the aim of which is to direct knowledge users towards decisions or actions relevant to a predefined context. The Checksheet traces its origins to the checklist-based Know-what and is often complemented by guidance using one or several alternative Know-how's for performing the specific action, along with the Know-why rationale under which circumstances the actions become relevant.

The ECS structure enables each thin slice or knowledge element (KE) to be described in three dimensions in the definition and based on work by Alavi & Leidner (2001) and Lundvall & Johnson (1994): *Know-what*, *Know-why* and *Know-how* to foster knowledge reuse and continuous improvement. This is similar to the engineering checklist in which each KE starts to explain what to do (*Know-what*) (Catic and Malmqvist, 2013). In Figure 12, an information model describes the ECS structure with attributes, operations and their internal relationship. Figure 13 illustrate an example on how the structure is implemented in a spreadsheet system from paper C.

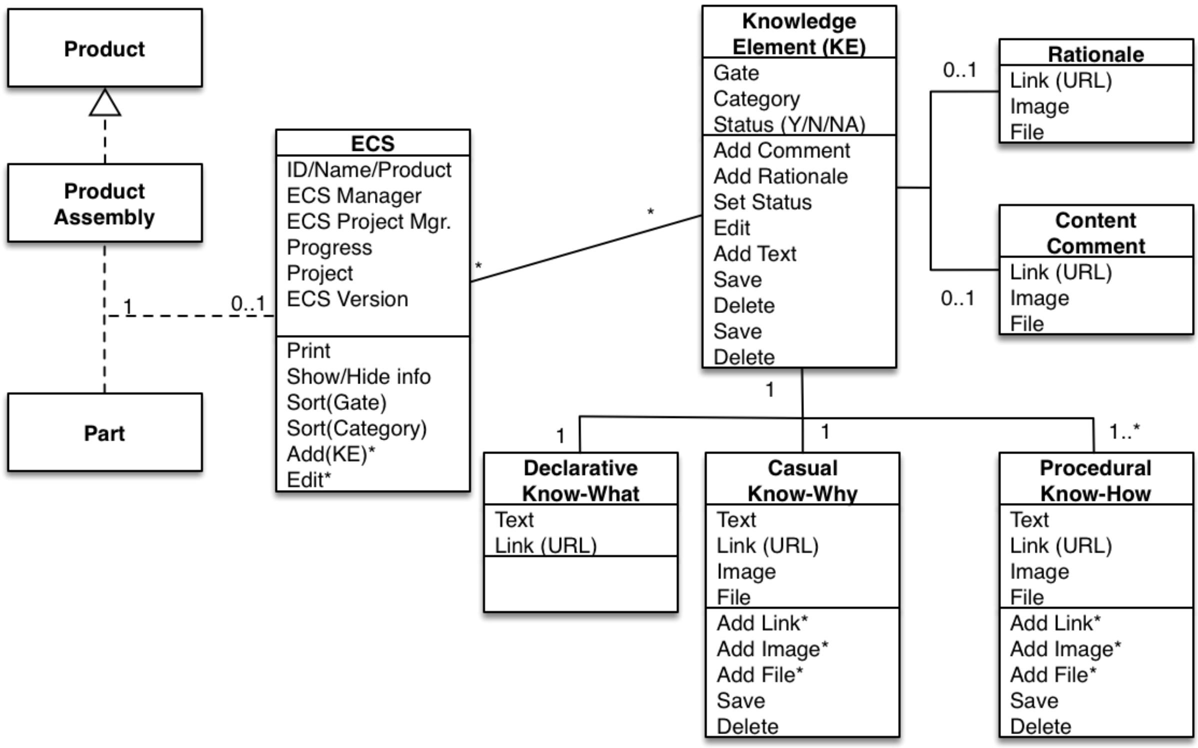

Figure 12. Information model for Engineering Checksheet

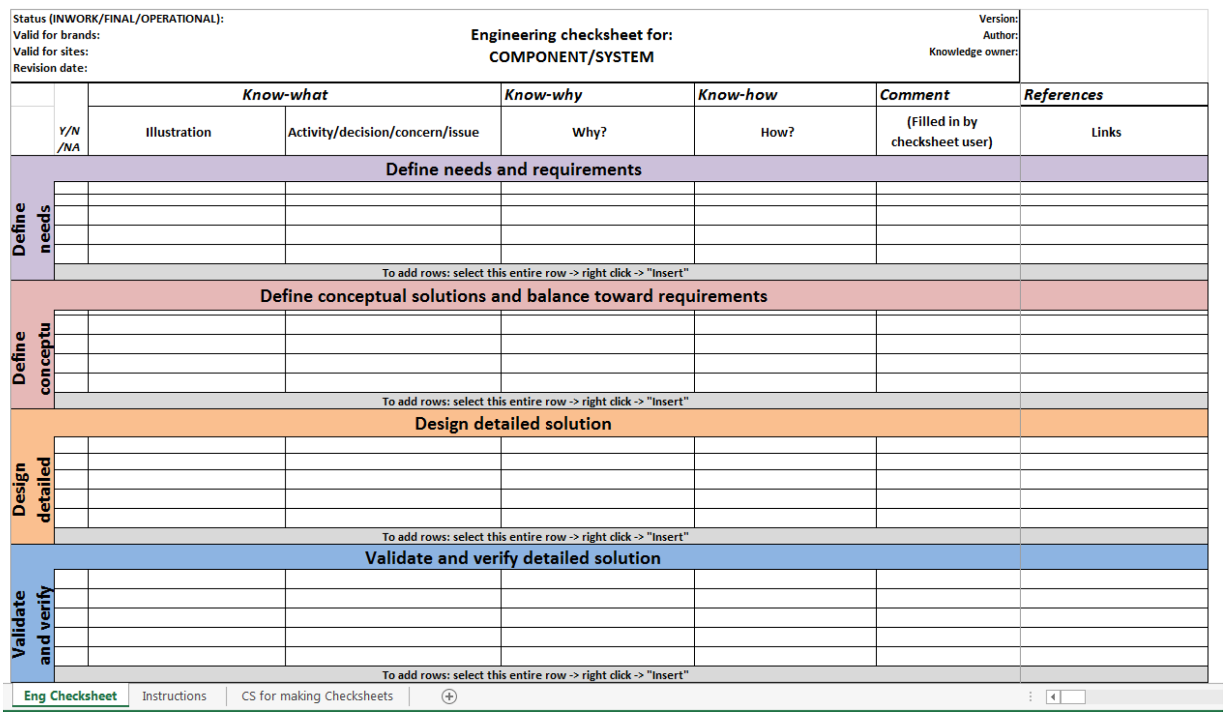

Figure 13. Engineering Checksheet structure implemented through the use of spreadsheets (Paper C)

5.2.1 Addressing the Characteristics

In this section, the characteristics identified from RQ1 are elaborated on in relation to ECS in order to present the rationale for a justification of the tool. The development of ECS is an ongoing process and still in early stage even if it has been iterated within real-life settings (Papers B and C).

1 - Ease of application

The structure of ECS divides the knowledge into KE's which should lead to one single (or a few) actions/decisions. Initiating each KE with knowledge about Know-What instantly describes what the supposed actions are to be accomplished. When the individual reusing the knowledge does not know the procedure on how to perform the action or may just want a short reminder, each KE also includes Know-how as a separate field to view in a supportive capacity.

By focusing on decisions, actions and considerations known from previous work, the ECS aims to provide predictability in terms of scoping, planning and executing the engineering work because it reveals the degree of challenge that different concepts, technologies, suppliers and processes for testing or manufacturing in the past.

In a checklist, each check tends to reflect backwards, what has been accomplished, compared to the ECS in which the KE is described in terms of upcoming decisions/actions (compare "have you/did you" to "be sure/keep in mind/be aware that").

2 – Relevance of content

The ECS builds on the procedure of interviewing individuals with a high degree of expertise in a certain domain, thus asking their specific knowledge in order to add to the ECS. Similar to the A3-method, the ECS is focused on being condensed in order to provide an overview of the necessary knowledge to consider.

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 the 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 company specific knowledge is the most valuable knowledge to capture—the knowledge that has been built up through mistakes and experience, often during a long time and not just through a few clicks away. ECS aims to pinpoint the knowledge upon which an expert bases his decision, even if it is based on a gut feeling. The studies in Papers B and C have shown that there is often something behind a gut feeling that can be described and codified.

3 – Completeness

ECS is set to balance the completeness along with the amount of captured knowledge in order to still be condensed. The clarity is provided through the structure of its content, as well through the process during which involved individuals are promoted to continuously refine the content captured in order to include necessary surrounding information to become applicable while removing unnecessary items. Furthermore, the KE follows the "less is more" rule and quality rather than quantity as it may be confusing and difficult to quickly assess overly extensive descriptions. There is still a tricky balance in maintaining a quick assessment of the content while providing as complete information as possible, which is important because decisions based on incomplete knowledge are often revisited as detailed product/process design and verification testing uncover problems with the decisions (Augustine, et al., 2010).

4 – Traceability

In order to understand other alternatives considered, as well as necessary background information to grasp the design rationale, each KE consists of a separate field for the inclusion of Know-why. The methodology also encourages the reuser to leave a comment to the KE if the knowledge is considered in any way different from that proposed.

An engineering checklist that only tells someone what to do is easy to use but is not reusable in giving a deeper understanding and in facilitating the possibility of continuous improvements (Morgan and Liker, 2006).

5 – Shareability

Documents that capture expertise tends to fluctuate between being on a general or a detailed level which makes it difficult to share. The ECS can hold different levels on each KE to share only a portion of the entire ECS. The structure is set to help the potential reuser to quickly get a good understanding of whether or not the knowledge is applicable in the new context. Each KE can also be separately tagged with appropriate key-words to increase knowledge sharing possibilities.

6 – Interpretability

As the ECS creation process is performed through a mixture of interviews, workshops and group work, the language becomes a blend of the individuals contributing. Novices that are recommended to draft the ECS tend to capture the knowledge in a way that more easily explains its meaning by using easier language than that used by experts. Each KE is also encouraged to include text, symbols, images, illustrations and trade-off curves if they provide a further understanding of the subject.

7 – Accuracy

An important aspect related to disseminating best practices is that even if they represent a current standard, they will eventually become updated and changed. In Lean Product Development, continuous improvement is highly sought after which also applies to best practices. As ECS is a methodology that provide support during development it foster a more dynamic approach to the content and stimulates changes if necessary. The ECS encourages practitioners to comment on the content in close connection to when it is applied if any new lessons have occurred which have not been captured before.

As part of quality assurance, references will be provided to the author of the knowledge, date of capture and latest update along whether or not the knowledge has been verified as valid by a knowledge manager. To succeed with the maintenance and validity of the ECS, a "knowledge owner" responsible for the content and ensuring its correctness was assigned to each ECS. This is not always easy to coordinate because in concurrent engineering, there are often several people involved in designing each part. Thus, the update can come either directly from the Knowledge Owner or as a proposal from the executor of the ECS for better support of the refinement process, i.e. maintaining ECS based on new knowledge. By instantly updating the ECS, solutions to recent issues are fresh in the minds of product designers and knowledge is instantly captured and made reusable. Therefore, it might be beneficial to detect learning cycles and identify possible ECS elements as outcomes as early as possible in the ECS implementation process.

8 – Relevance in time

Increased value of ECS comes from the use of knowledge a engineers are made aware of decisions early on in the product development process to be able to support the process with appropriate knowledge. 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 gates, the ECS helps to divide these into smaller decisions to support them with related knowledge.

Each KE in the ECS can be connected to a timing aspect such as time plan, process phase, process step or milestone/gate to predict when in time the knowledge should be considered as support for the executor to prioritize. This can be performed in either just a top-to-bottom approach of KE or through different types of categorization, for example according to the phases in the development process.

The case studies in Paper B show that product designers want openness, support and the opportunity of getting free hands when it comes to the order in which things are accomplished. They tend to feel constrained when forced to follow a strict process, which in many cases is the way they feel about checklists, believing that their innovation capacity may be held back. The ECS can thus be organized into different categories with which related KEs fit, e.g. needs & requirements, concepts, detailed designs, as well as verification & validation.

9 - Minimality

As related to (2), each KE must not duplicate already existing codified knowledge if other more appropriate forms for capturing knowledge are applicable. Instead, the KE should refer to other sources to support the localization process of that knowledge. The same is applicable for the depth of knowledge; if the reuser would need extended knowledge of the domain, other relevant references should be provided to databases or individuals.

The ECS is best described as a "virtual advisor" which, beside predictability, also provides the knowledge user with guidance on how to acquire information by providing links and references to relevant standards, design data, contact people and templates.

10 - Coherence

It is necessary for the ECS to have a high degree of coherence of the knowledge to avoid confusion with other sources. The ECS promotes the use of references to other codified assets or individuals to minimize the duplication of knowledge as a way of decreasing the risk of ending up with diversified guidance.

Further, capturing important aspects of when restrictions to the reuse of knowledge may exist due legal reasons can be valuable. However, this is not specifically considered in the ECS structure.

5.3 Implications from Implementing Engineering Checksheets

RQ3: What can be learn from implementing a support developed based on a knowledge reuse perspective?

By drawing on the empirical findings of implementing a KRS in a real industrial setting from Papers B and C, along with prior literature, the research question can be answered by presenting three implications in this Section.

Considering the exploratory research question and overlap between papers, the key contributions will be presented in the next section according to each synthesized implication and its relation to theory. Table XIV, Table XV and Table XVI summarize the key contributions from each paper in relation to the three implications presented.

5.3.1 Implications

During this research, the engineering level has primarily been studied and from our findings implications can be drawn in order to foster an improved and functional knowledge flow inside large organizations. Implication number one:

Implement a conscious KM strategy for balancing between a personalization (KRS for connecting) and codification (KRS for collecting) approach based on organizational need; however remember to align the company culture with the strategy.

As knowledge is the most important asset during product development, it is necessary to decide on a KM strategy in order to set the current Organizational Knowledge in valuable motion while making sure to minimize any losses. The findings in Paper C highlight the necessity to understanding the current organizational culture and should the strategy differ, the culture needs to follow the new direction or else, it may run the risk of undermining initiatives implemented. For example, the company may decide on moving against a codification strategy forcing individuals to create knowledge assets within the organization, while colleagues simultaneously routinely using personalization approaches for acquiring knowledge as part of past behavior and culture. Further, in all cases studied there were not solely personalization or codification approaches but always a mixture of the two.

Independent of the size of a strategy, cultural change or complexity of a KRS, there is always a necessity for management to provide support when necessary and continuously focus attention on the change, including implementing measurements (Key Performance Indicators – KPI's) that are in line with what the benefits of the change are intended to provide. To clarify, in Paper C one of the KPI's implemented was for each Knowledge Owner to create one or several ECS's connected to their component(s) and checked in to the company database. When accomplished, the KPI would be fulfilled and management satisfied. However, this measurement does not reflect any real value and in some cases, the ECS was never used and thus lost all its potential value which primarily resulted in a waste of time, possibly leading to increased resistance against future KM initiatives.

Table XIV. Summary of the key contributions related to Implication No. One from the papers appended.

Item #	Result	Paper
I1.1	Only measuring project success based on time, cost and quality decreases the focus on creating knowledge assets for future use.	A, C
I1.2	In the case companies, engineers often felt that the need for decisions or actions drive the need to first acquire knowledge.	A, C
I1.3	The not-so-successful cases had a tendency to focus on capturing knowledge even if they understood that the real value was gained until reusing that knowledge.	C
I1.4	The case company used the method as a way of having new recruiters collect knowledge in a certain domain or when the document already existed as a way of more quickly getting up-to-speed.	B, C
I1.5	Collecting knowledge into one document by referring to other existing knowledge assets or individuals was valuable by increasing the speed of finding the knowledge related to a certain component.	C
I1.6	The case company expressed the viewpoint that the way in which to locate valuable knowledge documents is to often to ask colleagues.	C
I1.7	Valuable to have personal contact with the source of the knowledge in order to ask questions that minimize the risk of misunderstanding.	C

While bringing attention to knowledge flow, do not focus too much on IT-tools because they will always change. A continuous focus on the mindset, behavior and organizational structure from a manager's perspective is necessary to succeed and thus, focus must not be limited to a specific method or process, which will eventually change.

During the implementation of the ECS tool in one of the case companies in Papers B and C, attention to the supporting IT-system was low, only making sure that necessary functionalities existed even if they were not optimized for the specific methodology. The study revealed that even if some comments during the interviews specifically related to IT infrastructure, most challenges seemed to exist in the areas of mindset, behavior and organizational structure. Individuals who truly understood the benefits of working actively with KM did not care of which IT-system they used. But paid greater attention to the fact that the process worked on a daily basis for the team. In one example from Paper C, the team changed IT tools twice after implementing ECS while still keeping most of the aspects of the methodology intact.

A common knowledge-sharing barrier from literature regards the hoarding of knowledge due to making an individual stand out from his colleagues and thus securing his position in the organization. This cause was not identified in either of the Papers B or C however, in one group, they acted passively in sharing their documented knowledge because they felt that people tend to believe they become experts after they had gained access to the knowledge assets. Even though it was impossible to capture *all* knowledge regarding a certain domain.

Independent of the IT-tool, the study found that, it is difficult for both experts and novices to initiate knowledge-sharing because experts tended to think that most of the knowledge was trivial, whereas novices were unsure on where to start and what to initially ask, calling for a knowledge intermediator to initiate the process. In the studies researchers acted as initial intermediators to draft the first baseline of the ECS.

Even if it has been mentioned by several researchers before and is supported by this study to create an effective flow of knowledge inside an organization a continuous process towards KM is necessary such as highlighted in paper C in which teams frequently come together to share and capture lessons learned. Other examples to increase knowledge-sharing was the initiation of meetings specifically to share current issues in order to obtain input and references from colleagues to existing documents or individuals.

Table XV. Summary of the key contributions related to Implication No. Two from the papers appended.

Item #	Result	Paper
I2.1	Creating knowledge assets with a time distance from when the knowledge was created requires more effort and the result is often less than anticipated because people tend to forget, leading to missing pieces of knowledge.	A, B
I2.2	In the cases when the view of KM was more of an *ad hoc* approach often led to lower prioritization with a lower level of reuse.	C
I2.3	The case company showed a difference in the long-term goals communicated (increased knowledge refinement and reuse) regarding KM and what was measured as success criteria in terms of time, cost and quality.	C
I2.4	The managers stressed the importance of creating knowledge documents without stressing the need for reusing them to the same degree.	C
I2.5	The low possibility of interacting with codified knowledge limits the possibility of editing and commenting on the content, thus affecting its validity in an ever-changing environment.	C
I2.6	Making sure that KM is a daily routine makes the process run more smoothly when someone changes position.	C
I2.7	"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.	C
I2.8	A lack of routines for when to use/search for different knowledge documents interrupts the flow. The heavy volume of documents makes it difficult to acquire them all.	C
I2.9	Efficient KM is not so much about the IT system as it is about the process however, the method supports the process to a high degree.	B
I2.10	Experts saw benefits of collecting their collective knowledge into a single document that was continuously visited for support during development in order to not have to solely rely on their minds.	C
I2.11	The case companies experienced the need for connecting the knowledge documents to the development process which resulted in categorizing them according to the different phases of the product development process.	C
I2.12	The case company saw benefits of continuously capturing new lessons learned due to the simple fact that people tend to forget with the consequence that more specific knowledge with greater technical depth could be captured without becoming a major challenge.	C

I2.13	Company interviews and success cases supported the need to set up a process of regularly reviewing, evaluating, and standardizing lessons learned and preparing them for implementation.	C
I2.14	Organizational commitment is necessary when adapting the process to a new way of working which represents a change both physically and in the mindset of all parties.	C

Separate project-specific knowledge and knowledge to be captured for future use.

In Paper C, several aspects provided evidence that new learning from projects should be added to the flow of valuable knowledge inside an organization. The organizational structure in the case company regularly defined an individual responsible for applying existing knowledge to a project, as well as identifying new knowledge gained. The new knowledge should further be shared together with the individual responsible for that specific domain on an organizational level as well as individuals responsible in other projects within the same domain. Individuals responsible for a domain within a project is thus accountable to create a healthy knowledge flow in the project, while the responsible for the domain on an organizational level is accountable for making sure that the knowledge is kept inside the organization over time, as well as making sure it is accessible and available to other relevant projects.

While using the ECS, engineers made a couple of different type of comments, either content updates due to new learning or misspellings and comments related to how they perceived the KE and potential deviations made in the project. The latter was counted as project-specific knowledge, whereas the former was used as input for potential updates to the ECS. Further, at the case company in Paper C one ECS for each domain served as a master document, whereas a copy of the master was created as a duplicate for each project. After the project had been finalized, the copy was stored as a project document while potential edits or updates was made to the master.

Table XVI. Summary of the key contributions related to Implication No. Three from the papers appended.

Item #	Result	Paper
I3.1	The case company tended to differentiate between project-specific knowledge and knowledge valuable over time as different parts of the Organizational Knowledge.	C
I3.2	While deciding on what constitutes company-specific knowledge some groups that had enjoyed strong collaboration with suppliers became unconscious about ownership of the knowledge.	C
I3.3	As both the ECS IT system and spreadsheet allowed for direct editing into the master ECS, such editing was more restricted on a process- than on an IT level.	B, C
I3.4	Project-specific deviations from original best practices presented in the ECS were stored as comments to each KE.	B, C
I3.5	Traditional lessons learned practices tend to become ad-hoc processes and seldom resulted in future use.	C

6 VALIDATION

In this chapter, the results in the form of answers to the research questions and research approach will be discussed and evaluated in terms of validation and verification.

This chapter is based on *3.2.1 Approach to Validation of the Results* and sets out to support the goal of research by aspiring and bringing results that are as truthful as possible while using an approach and methodology that support this goal. The goal should also be transparent in terms of its limitations and potential threat to the validity of its claims, which are provided in the following discussion on the quality of this research.

Verifying the validity of research results can be performed by *Logical verification* and *Verification by acceptance (Buur, 1990)*. Research can be considered logically verified when there exist no contradictions with accepted theories and methods. Verification by acceptance focuses on having new scientific contributions accepted by experts within the field.

Further, validation can be discussed from the perspectives of the four views presented in Chapter 3 as the validation square; *theoretical structural validity, empirical structural validity, empirical performance validity and theoretical performance validity*.

The frame of reference and literature review laid the foundation for the *logical verification* and *theoretical structural validity*. As the identified results including barriers to knowledge reuse, characteristics of codified knowledge for improved reuse and the KRS, ECS's, have been based on research within the field of KM or related domains. The author sees the results as an extension of existing research and models with particular application on the engineering level supporting external consistency as it agrees with established theory and internal consistency when no conflicts are found between individual elements in the theory.

The development and implementation of ECS's made it possible to validate that the theory and methodology created actually work and can be used in a real engineering environment. The continuous feedback during implementation together with evaluation made it possible to further improve the KRS. The IT system especially developed to support the ECS methodology is still under development and has been implemented in a limited demonstration setting; however, it is still performed in a real industrial environment, which is important to note when discussing its applicability.

The results presented in this thesis have been shared with and analyzed by a broad range of experts both within industry and academia to reach *verification by (external) acceptance* and discover relevant input from other studies and related research. More explicitly, all papers have been undergoing peer reviews as part of the publication process. Results have been presented and elaborated on during the collaboration with case companies in which company experts within the field and other disciplines have had opportunity 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 and research partners of the Wingquist

Laboratory. 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).

The appropriateness of case studies and usefulness of the method applied form the basis for the *empirical structural validity*. Reflecting on the cases, the case studies were relevant for testing the support for knowledge reuse as the case studies behind all papers primarily were carried out in incremental product development at larger organizations. The KRS was tested in domains with a high degree of reference knowledge and with people of various level of expertise and age.

The KRS introduced and implemented have primarily been evaluated on its performance through a qualitative procedure and thus providing a low possibility of statistical analysis. However, the KRS has to large extent been confirmed as being capable of identifying the right problems with respect to increasing valuable knowledge reuse through discussions in groups and interviews with company experts. Papers B and C show the possibility of assessing the introduction of KRS as part of *empirical performance validity*. In both papers, examples have been provided where reuse of knowledge has led to not repeating past mistakes, the quality assurance of components and cross-project learning, as well as cross-plant learning in production. With the approach taken, engineers and managers can more easily ensure that captured knowledge is consulted before designing. Even if this part of the validation square is difficult to validate by using before-and-after measures, many of the results can offer higher performance as pointed out in Papers B and C.

Generalization of the results, *theoretical performance validity*, to transfer to other industries and cases is highly relevant to this kind of research. It is believed that the results of this research are generally applicable to all industries developing Mechatronics products. The KRS has been developed based on the existing theory on barriers and challenges to knowledge reuse which was further shaped into characteristics for knowledge quality that formed the basis of this thesis. The different groups applying the method within case companies witnessed a high degree of applicability within various groups, thus arguing that similar applicability will be found in other organizations. Nonetheless, the empirical data gathered throughout this research have been limited to and primarily been collected from two companies, one in Sweden and one in Norway. Both companies develop technical products and are aligned with our research focus but are still considering a few cases that limit the ability to make general statements.

The research approach taken, involving interviews, seminars, workshops, document reviews and demonstrations, reflects a broad research approach. However, managing threats that follow qualitative research, which is the case with the studies performed, is an issue that needs to be considered after the research has begun (J. A. Maxwell, 2012). The perspective and possibility of design research within industries and of individuals at different hierarchical levels in product development at large organizations, have provided the opportunity to reach a research depth within a broader domain which calls for further generalization of the research results.

The list below summarizes the extent to which the eight techniques proposed by Maxwell (2012) and described in Chapter *3.2.1* were used to strengthen research validity:

1. *Long-term involvement* has been a key element in this research. One of the case companies has been involved for several years as part of this research, whereas the other company hosted parallel and shorter study which have been used as comparison. Repeated observations and interviews along with sustained presence among the researchers in the setting studied have helped to rule out spurious associations and premature theories.
2. *Rich data* have been gathered by interviewing both managers and engineers from different parts within the organizations and by using recordings and detailed transcripts of the answers.
3. After the interviews and workshops had been held at the case company, transcripts were used for *respondent validation* to discuss findings and proposed solutions to plan the next step.
4. *Intervention* in any form is often, if not always, present when performing field research. Even if the researchers have attempted to influence the study as much as possible, a discussion on how to improve, develop or test ideas about the groups and topics studied has been present. This has mainly been performed as part of the KRS implementation corresponding to the second descriptive stage of the framework of Blessing and Chakrabarti (2009).
5. *Searching for discrepant evidence and negative cases* has been performed through a broad literature review and a critical analysis of whether the expressed needs of the case companies were in fact real needs based on a comparison of cases from the literature. Also, the negative feedback from the pilot of the chosen IT system (spreadsheet) for implementation in one of the cases, along with the negative response around ECS from some individuals/departments, has been reported and the issues anticipated during the implementation have been discussed.
6. *Triangulation* was partly employed by asking a variety of stakeholders in the case companies by interviewing them both before and after demonstrations to avoid biased answers. However, a more thorough examination of reports and other documentation would have deepened our understanding of the content of codified knowledge and its potential for actual reuse. Instead, statements by interviewees have been our primary source for drawing conclusions about the availability and accessibility of knowledge, which may be subjective and not representative of the organizations as a whole.
7. *Numbers* have only been used to a limited extent when reporting findings from interviews by indicating whether an opinion was shared by a few or the majority of respondents. Asking for numeric ratings of statements and employing larger samples would have increased the validity of our findings.
8. Multiple cases have been studied with relatively homogenous groups of respondents. However, due to the nature of implementing demonstrations in real organizations, numerous aspects can vary, calling for less formal *comparisons* and interpretations of results. The multiple cases support generalizability, to a limited extent, and provide an indication of further opportunities for testing the external validity, as well as examining the causal impact of implementing the proposed solutions by comparing the situation before and after such intervention. The research was primarily conducted in two different product development organizations of which one of them are active in the automotive industry and the other in oil and gas.

The secret of getting ahead is getting started. The secret of getting started is breaking your complex overwhelming tasks into smaller manageable tasks, and then starting on the first one.

- Mark Twain

7 CONCLUSIONS

This chapter outlines the thesis outcome in the form of conclusions and recommendations.

Knowledge reuse is an approach for companies to systematically maintain product quality and standardization while enabling continuous improvement. This method has previously been studied mainly from a business strategy and management perspective. This research has attempted to contribute to theory by studying the implications of knowledge reuse on the engineering level, with particular emphasis on existing challenges to the effective reuse of experience-based knowledge. The research also led to a proposed KRS, ECS, based on identified characteristics of knowledge that supports reuse, which was further evaluated through implementation in a real industrial setting.

Two different companies were principally studied in connection with this research. Both companies perform product development on the sites studied; one is working in the automotive industry whereas one is active in oil and gas industry. The overall approach of the research was guided by the 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 identification of characteristics for reusable knowledge and further development of ECS for the prescriptive parts of the research were based on both findings from empirical studies and existing literature, mostly from the academic field of knowledge management.

The first of three research questions posed in this thesis concern the characteristics on codified knowledge in order to be prepared for efficient reuse on the engineering level. Initially, this was studied by identifying barriers to efficient knowledge reuse. A mismatch was observed between the knowledge sources available to designers and the those accessed by designers. The possible reasons for this mismatch are a lack of accessibility, availability and trustworthiness. All case companies state and confirm that knowledge is often stored in another form than current practice suggests.

A barrier commonly mentioned is the lack of time for acquiring and applying existing knowledge. However, this activity should be compared to other activities performed by engineers and is thus a matter of prioritization. The barrier might then instead be the perceived value of finding and reusing knowledge compared to the effort necessary to be invested.

Various knowledge assets are often not optimized for knowledge reuse which can probably be linked to such traditional success factors in product development as time, cost and quality. Neither of these factors include the creation of valuable knowledge assets for future use. Managers seem to focus mainly on the fact that if knowledge is codified, it would automatically be reused, something that is seldom supported by studies performed.

Based on the identification of potential challenges , several recommendations have been found for supporting knowledge reuse that are derived in the form of ten characteristics defining knowledge quality. Captured knowledge should:

1 - *consist of critical knowledge to ensure organization competitiveness.*
2 - *foster actions and/or decision because it is evaluated based on the result of application.*
3 - *include richer contextual details to support understanding.*
4 - *include a design rationale to support the reapplication to a new context.*
5 - *focus on the generic level and follow a standardized structure to boost knowledge-sharing between different user groups and applications.*
6 - *be visualized and written in a language/terminology that matches the reuser to support and increase the speed of interpretation.*
7 - *provide high validity through assuring the correctness of reuse.*
8 - *indicate when in time the knowledge will be reused to promote front-loading of knowledge.*
9 - *be integrated with existing complementary knowledge assets to increase the potential reuse of all available knowledge.*
10 - *maintain a high level of coherence of the knowledge to avoid confusion.*

The final research question focuses on the knowledge learned from implementing and evaluating a KRS. Based on the identification of capabilities of the above characteristics, a KRS, the ECS was developed, piloted to further implemented and run for as long as five years in one of the case companies.

In the company which most widely adopted ECS, it was implemented through the use of a spreadsheet IT system. The idea was that ECS should work as a bridge between large codified knowledge assets based on experiences and mistakes (often stored in people's minds), while being connected to specific product. The pilot has shown positive outcomes and great potential. ECS aims to visualize the knowledge into KE's to make it easier for the engineer to make sure that all aspects of the knowledge asset have been considered. Each KE is also divided into separate layers to guide the engineer through Know-What, Know-How and Know-Why in each decision or action point, providing a deeper understanding and opportunity for improvement. Due to the limited sample size in our study, it obviously limits our ability to draw broad conclusions. Therefore, the findings should be considered exploratory and preliminary, but they nevertheless serve as an indicator of a model for supporting the knowledge management cycle inside an organization.

7.1 Academic and Industrial Contributions

The academic contribution of this study touches upon research themes related to knowledge management and organizational learning in general and knowledge reuse support in particular. At a general level, this thesis contributes to the second wave of knowledge management, in which the focus is on conditions that stimulate collective knowledge sharing, especially tacit dimensions, on a daily basis. With increasing shifts towards lifecycle responsibility and cross-functional and cross-organizational settings, this is becoming increasingly critical. However, few methods and tools have been published for these purposes, especially for knowledge reuse processes related to procedural knowledge. Literature stresses the importance of capturing procedural and contextual knowledge to support knowledge reuse. Nevertheless, there has been little focus on identifying a practical approach or framework capable of capturing such knowledge that might be applicable in product development settings. Most relevant research has been limited to proposing recommendations for improving the knowledge capturing process with a secondary focus on reuse.

As an academic contribution, this thesis has described potential barriers to knowledge reuse, using the KM cycle stages acquiring, assessing and applying as guidance. Further, investigating potential barriers to knowledge reuse and derive the characteristics of knowledge supporting reuse have been a successful approach, which other researchers in the domain could potentially apply to elucidate knowledge reuse practices in order to derive supportive actions and methods to cope with emerging product development trends. Another major contribution of the thesis is the proposed KRS based on the characteristics identified. The evaluation showed that the KRS provides valuable support for reusing contextualized knowledge related to product development. The theory and empirical findings from the studies have also established foundations for academic researchers to continue investigating knowledge reuse in product development. The evaluation framework could also help other researchers in the domain to evaluate different settings.

In terms of industrial contributions, this thesis has explored contemporary knowledge reuse practice in primarily a product development setting within automotive and oil & gas industries and proposed a number of suggestions to improve such practice. Given the inherent complexity, an important exploratory step has been taken towards elucidating experience, as well as knowledge capturing and reusing processes. The methodology and KRS from these case studies have also contributed an understanding of studying, deriving and implementing methodology and concepts in an industrial setting. The study has initially proven to be applicable to other industrial sectors, such as disseminating experience-based knowledge from the field to early development phases.

This thesis has pointed out that engineers often decide not to retrieve knowledge from codified assets; instead, they prefer to source the necessary knowledge from other colleagues within their organization. Thus, contrary to what is often stated, the access to and use of a KRS do not necessarily enhance knowledge reuse in an organization. Rather, engineers still favor people-to-people interactions to solve complex problems. This habit seems dependent on the degree of complexity and innovation of the knowledge needed during product development. Knowledge complexity seems to act as a moderating factor in the relationship between knowledge quality and knowledge reuse meaning that, in conditions of high knowledge complexity, organizations cannot completely rely on a document-to-people approach as some degree of interaction will always be necessary. With the present findings, we also advance the literature on the benefits of knowledge codification within the product development process. Codification has been considered an important vehicle for transferring knowledge (Davenport and Prusak, 1998). Its presence or absence is considered either an enabler or a barrier to knowledge sharing (Hansen, 2002; Kogut and Zander, 1992). However, the literature has not considered the effects that poorly codified knowledge and knowledge complexity have on knowledge reuse. Indeed, researchers have adopted an unproblematic approach to the process of codification (Hall, 2006) and have often assumed that the quality and ease of codified knowledge use is high. Accordingly, they suggest that companies have to enhance knowledge reuse activities in order to increase performance (Haas and Hansen, 2007; Kogut and Zander, 1992). Further, this thesis adds, in conditions of high knowledge complexity, companies should balance codification and personalization strategies (Hansen, et al., 1999) and must closely monitor the quality and ease of decision/action regarding the codified knowledge.

The findings show that having high quality knowledge is not enough to improve business performance; engineers should be properly supported and eager to efficiently reuse knowledge. Potential inefficiencies and barriers may otherwise decrease knowledge reuse. Although vast amounts of knowledge can be created, codified and archived into repositories, the difficulties of reusing knowledge can create dissatisfaction and unwillingness to reuse the repository in the future (reuse intentions). It is well-known that the reuse of existing design knowledge is the key to realize rapid product design (Hoppmann, et al., 2011). During our studies several engineers preferred to reach out to colleagues or recreate a solution from scratch rather than searching for existing knowledge. This dynamic produces a duplication of efforts and knowledge and increases the time needed during the product design stage, with the result that such inefficiencies can negatively affect first-mover advantages (Hoppmann, et al., 2011).

It has been argued that the capacity to rapidly designing new products that meet market needs is crucial in highly competitive markets, and the design of a new products is a costly process in any manufacturing company. Research shows that approximately 80% of the manufacturing cost of a product is determined by its design (Clark and Fujimoto, 1991). In this thesis, we have acknowledged that if efficient codified knowledge reuse can be applied, positive consequences can be seen both in terms of quality and time. For example, by decreasing the time needed to solve technical problems when experienced key employees leave the company and their knowledge and expertise can stay as Organizational Knowledge instead of leaving with them (March, 1991). In fact, the problems of incorrect codification of knowledge also offset the potential benefits of repositories, which are generally created to retain the knowledge held by employees who leave a company (Dalkir, 2013). Accordingly, if an organization does not establish clear, shared guidelines and norms throughout the organization about the way knowledge should be codified and archived into an organizational repository, the risk that the repository will not be used effectively and will not fulfil the purpose for which it was created is high.

Finally, the results highlight the inadequately met needs of end-users in workplaces who usually rely more on personal contacts than structured reports for identifying and reusing knowledge; these end-users could instead draw upon the proposed tool to support their daily work.

8 LIMITATIONS AND FUTURE WORK

This chapter will present potentially valuable directions for future research to address both methodological and technological issues within KM and ECS.

Regarding the development and integration of effective knowledge reuse through ECS within product development, some key work remains to be performed. The work outlined in this thesis is of initial Descriptive II type following the Design Research Methodology, thus concluding in some further proposals for improvement. Future research is proposed to more deeply investigate the concepts explored in this thesis, verifying them in broader industrial contexts and extending them to new endeavors.

The present research has some limitations. First, the limited industry focus and depth could limit the findings to the context investigated. Further research could undertake a comparative study for the purpose of getting a broader cross-company and cross-industry validation of results. Although the findings of this research come from a limited group of case companies, the belief is that many other product development organizations can learn valuable lessons from this thesis.

Second, this study has adopted a qualitative method of investigation based on primarily interviews, observations and review of codified assets, which limits the possibility of quantifying the fulfillment of characteristics considered in this thesis. Therefore, a quantitative validation of the framework developed through this thesis is needed.

Third, another limitation of this research could be that it has not tested the influence of environmental conditions and characteristics of individuals, which have been found to be important factors when trying to understand the impact of KRS (Kane and Alavi, 2007).

8.1 Methodological

The studies focused on identifying the opportunities to improve knowledge reuse in the product development environment within primarily global industries by initiating research on existing challenges. Further, a KRS was developed in the form of a methodology and system to address current deficiencies. Hence, preliminary evaluations have focused on testing the proposed KRS and guidelines for capturing (i.e. preparing and formulating) experience-based knowledge, the primary objective being to determine if and how the proposed methodology may facilitate knowledge reuse.

As highlighted in Paper C, bottom-up approaches, like the proposed methodology, pose new challenges to organizations from both methodological and technological perspectives. A major concern is the requirement for active user participation in all stages fulfilling a vibrant knowledge repository. Industrial experiments revealed that practitioners favor the adoption of new methods and tools when assisted by a suitable process and guidelines and when they are integrated into routine business procedures (Paper C). Accordingly, the proposed methodology has been implemented and applied in various settings depending on which group is practicing the methodology. However, in some of the cases, the KRS has proven to be efficient for extracting procedural knowledge from complex issues.

Further research is needed to thoroughly evaluate the methodology in terms of the time required to refine and disseminate, as well as acquiring, assessing and applying the knowledge compared to other methods. The studies presented have indicated that the time required to refine and thus keep the ECS up-to-date decreases over time and is seen as being more valuable when frequently used. In future studies, the effort required to those involved in contrast to the value of the outcome needs to be measured in order to further assess and evaluate the ease and usability of the proposed methodology quantitatively.

The ECS evaluated in a real industrial setting has shown to support knowledge workers in recalling critical knowledge, faster coming up-to-speed and to possessing a natural place to store new knowledge. However, the generalizability of the study is limited because the sample size was small and was performed in limited industry sectors. Thus, broader industrial studies with implementation through various sectors to assess the effectiveness of ECS, relative to other methodologies, are called for to improve the reuse of knowledge gained from past experiences, thereby facilitating the execution of faster and more accurate decision-making. The following questions are proposed to be addressed in future research:

To what extent does an introduction of a knowledge-reuse-centric Knowledge Management System increase the reuse of engineering knowledge?

The partial validation in this research has not measured quantitatively the value of introducing ECS, rather limited to observations and semi-structured interviews by asking engineers about their own awareness of knowledge reuse after the introduction of ECS.

How can the level of knowledge reuse influence organizational effectiveness?

Throughout the studies in this thesis the main focus has been from the engineering level, with the logical reasoning and by consulting earlier research, assume that increased knowledge reuse will lead to increased organizational effectiveness. It is not without difficulties to measure this correlation, nonetheless, an important future work.

How can ECS help organizations to find the optimal balance between personalization and codification within product development?

The implementation of ECS within industry has shown that different team settings results in various ways of usage. Some teams tend to use it as a support for discussion during knowledge sharing sessions, while others apply a more firm codification approach. A general proposal of such practice has not been comprised by this research but would be valuable for future application of ECS within different settings. A deeper cross-case study could potentially reveal how different team settings might benefit from applying ECS together with the two types of knowledge sharing strategies.

8.2 Technological

Papers B and C have illustrated two different ways of implementing the developed ECS framework. During the most widespread implementation, a spreadsheet IT system was used for support, in which the basic ECS structure and functionalities were tested. In future research the dedicated system should be developed further, permitting participants to access ECS content without distracting functionalities and maximizing the method in order to refine, disseminate, acquire, assess and apply the knowledge. In this way other practitioners are allowed to get a better understanding of the methodology and its value in order to reuse knowledge more efficiently. To improve knowledge quality, a process has been derived, in which captured knowledge would need approval from a "validator" i.e. an expert or specialist in the area related to the knowledge captured, before being placed into the ECS to ensure quality and reliability as part of a future IT system. In Paper C, the responsible individual on organizational level for each domain took the role as validator as part of the implemented process. To support the process of making sure that knowledge of high quality is captured, potential functionality of the IT system should be investigated. To avoid the risk of knowledge leakage, secrecy procedures should be considered; however, to increase the cross-functional sharing of knowledge, a "tagging" procedure is proposed for each KE to make it more searchable and thus not restricting KE to belong to a specific ECS. The validation of these concepts, i.e. knowledge validation, knowledge security and KE sharing, need to be tested in a future industrial environment.

The results of this thesis are limited to proposing a methodology, a spreadsheet-template and an initial IT system for improving knowledge reuse, referred to as ECS, based on current industrial practices and observations. From a technology perspective, the first step is to improve the developed and dedicated IT system based on an evaluation of the implemented spreadsheet-based ECS and further improve its functionality to foster cross-functional knowledge sharing and reuse.

The most important, and indeed the truly unique, contribution of management in the 20th century was a fifty-fold increase in the productivity of the manual worker in manufacturing. The most important contribution management needs to make in the 21st century is similarly to increase the productivity of knowledge work and knowledge workers.

– Peter F. Drucker (1999)

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