THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Technology Platforms

Organizing and Assessing Technological Knowledge to Support its Reuse in New Applications

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Cover:
Schematic illustration of how technologies are
developed, integrated, stored and reused (see p.5).

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ABSTRACT

Companies that develop a wide range of products often strive to exploit opportunities for synergy among them. Many products that cannot share components can still offer opportunities for synergy as they build upon the same technologies and know-how for their development and production. 'Technology platforms' is an approach focused on how to systematically leverage technologies across different applications, but prior research has mainly treated it as a business strategy, without providing support for the engineering work required to realize it.

This thesis explores how a technology platform approach can be realized with methods and tools at the engineering level by seeking to answer three research questions: (1) what barriers exist to effective technology reuse, (2) how to organize technological knowledge, and (3) how to assess feasibility of a planned case of technology reuse. Three main research methods were used to answer these questions. Firstly by interviews with managers and engineers at a case company that operates in the aircraft engine industry, secondly by reinterpretation of existing literature into the field of technology reuse, and thirdly by the development of methods and tools for engineers.

The findings related to the first research question suggest two important barriers to efficient reuse of technologies at the engineering level; the difficulties of creating, locating, transferring and deploying reusable knowledge from previous development, and the need for adapting technologies before introducing them in new applications.

Two types of support for organizing technological knowledge are proposed as answers to the second research question. The first is to represent technological knowledge in a digital 'technology catalog' to increase awareness about existing technological capabilities within a company and provide a starting point for finding detailed knowledge. The catalog would feature pages of basic knowledge about technologies and provide links to detailed reports and contact information to relevant experts. The second proposed means is to model technologies in a relational database with specific fields for the design parameters and conditions they support, as well as their relations to other technologies and systems. This method supports a development methodology referred to as a 'technology-based configurable platform approach' that automates the generation and analysis of design concepts based on platform models. Technological knowledge modeled in the database would be used as boundary conditions for the configurator software to ensure that generated concepts are valid.

In response to the third research question, an assessment methodology referred to as 'TERA', TEchnology Reuse Assessment, is proposed to support the identification of potential challenges of reusing technologies in new applications. The methodology features a scorecard that probes factors found in previous research to be inhibiting or supporting of technology transfer and reuse.

The proposed methods and tools have so far only been subjected to initial tests at the case company, and although they show great promise, further tests will be required to validate their usefulness.

Keywords: technology platforms, technology reuse, technology management, technology development, technology transfer, platform thinking, core capabilities, knowledge reuse, knowledge management, knowledge repositories.

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Alingsås, Sweden, 2015

Daniel Corin Stig

APPENDED PUBLICATIONS

Paper A

Corin Stig, D., Högman, U. & Bergsjö, D. (2011). Assessment of Readiness for Internal Technology Transfer – A Case Study. *Proceedings of the 21st Annual International Symposium of the International Council on Systems Engineering* (*INCOSE 2011)*, Denver, CO, USA, June 20-23, 2011.

Paper B

Corin Stig, D. & Bergsjö, D. (2011). Means for Internal Knowledge Reuse in Pre-Development – The Technology Platform Approach. *Proceedings of the 18th International Conference on Engineering Design (ICED 2011*), Copenhagen, Denmark, August 15-18, 2011.

Paper C

Levandowski, C., Corin Stig, D., Bergsjö, D., Forslund, A., Högman, U., Söderberg, R. & Johannesson, H. (2013). An Integrated Approach to Technology Platform and Product Platform Development. *Concurrent Engineering – Research and Applications*, 21(1), pp. 65-83

Paper D

Levandowski, C., Corin Stig, D. & Raudberget, D. (2015). Accommodating Emerging Technologies in Existing Product Platforms. *Proceedings of the 24th International Association for Management of Technology Conference (IAMOT 2015)*. Cape Town, South Africa, June 8-11, 2015.

Paper E

Corin Stig, D., Högman, U., Isaksson, O. & Bergsjö, D., (2015). TERA - An Assessment of Technology Reuse Feasibility. *Proceedings of the 2015 Conference on Systems Engineering Research (CSER 2015)*. Hoboken, NJ, USA, March 17-19, 2015.

DISTRIBUTION OF WORK

The appended papers resulted from the contributions of multiple authors. The distribution of work for each paper is outlined below.

Paper A: Daniel Corin Stig planned the study, conducted the primary interviews for the study and performed the analysis with the support of Ulf Högman. Recordings of interviews conducted by Daniel Bengtsson and Stefan Stetz for their MSc thesis (2009) were used as additional sources of data. Corin Stig wrote the majority of the paper, with support and contributions from Högman and Dag Bergsjö.

Paper B: Daniel Corin Stig and Dag Bergsjö jointly planned the study, developed the software prototype, conducted the interviews, performed the analysis and wrote the paper.

Paper C: Christoffer Levandowski coordinated the project and wrote the paper together with Daniel Corin Stig, Dag Bergsjö, Anders Forslund and Ulf Högman. Levandowski created the system architecture and set up the case together with Bergsjö and Corin Stig. The planning, analysis and writing of the paper was supported by Rikard Söderberg and Hans Johannesson.

Paper D: Christoffer Levandowski initiated the research together with Dag Raudberget and coordinated the work. Levandowski and Daniel Corin Stig jointly developed the technology information model and wrote the majority of the paper, while Raudberget contributed with parts of the ideas and content.

Paper E: Daniel Corin Stig planned the study, conducted the literature review, developed the process and scorecard and wrote the paper. Ola Isaksson and Ulf Högman participated in discussions that shaped the design of the proposed solutions and provided feedback on the written content. Dag Bergsjö supervised the work and provided ideas and feedback.

ADDITIONAL PUBLICATIONS

The following publications were also developed during the course of this research, but have not been appended as core contributions to this thesis.

Nawaz, K., Corin Stig, D. & Bergsjö, D., 2012. Technology as a Product. *Proceedings of the 21st Annual IAMOT Conference*, Hsinchu, Taiwan, March 18-22, 2012.

Corin Stig, D., 2013. *Platform Thinking for Technology Management – Supporting Knowledge Reuse in Technology Development*. Licentiate Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Corin Stig, D., 2013. A Proposed Technology Platform Framework to Support Technology Reuse. *Proceedings of the Conference on Systems Engineering Research 2013*, Atlanta, GA, March 19-23, 2013.

Bergsjö, D., Levandowski, C. & Corin Stig, D., 2015. Multi-Level Product Platform Strategy for a Multi-Level Corporation. *Proceedings of the 25th International Symposium of the International Council on Systems Engineering*. Seattle, WA, July 13-16, 2015.

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1 INTRODUCTION

New technologies are often highlighted as selling points when industrial companies market their new products. Such ‘new features’ might be what most people think of as ‘technologies’, but many technologies will not be highlighted in sales brochures. Instead, they work in the background, perhaps to indirectly enable the features that customers value or to reduce the cost of manufacturing. Regardless of whether a technology can be marketed as a product feature or not, possessing the capability to use a technology appropriately in the development and manufacture of a product can be highly valuable to companies. Hence, companies invest vast amounts of resources in developing new technologies and refining existing ones, expecting to get a return on their investments by selling more products or reaching higher profit margins.

A natural way for companies to leverage their investments in research and development (R&D) is to reuse product architectures, components, manufacturing equipment and technologies between different products, or from one generation of products to the next. The knowledge gained in one development project can then be reused to avoid repeating similar design tasks and help reduce both cost and development time, while at the same time improving the robustness of the solutions by building upon previous experience.

Companies and engineers intuitively exploit opportunities for reusing previous results when conducting new development, but to do so systematically remains a challenge. Previous research has provided insights into how engineering work can be conducted in ways that help companies reuse product architectures, components and design concepts across applications by means of ‘product platforms’ (Meyer & Lehnerd, 1997; Jiao et al., 2007). Another stream of research has praised the potential benefits of systematically reusing technologies across applications (Prahalad & Hamel, 1990; Kim & Kogut, 1996; Schuh et al., 2015), but it has mainly focused on the business and strategy level and has not yet reached the engineering level to show how such strategies can be realized in practice.

Integration of technologies in products and production can be a great challenge in itself (Leonard-Barton, 1988; Eldred & McGrath, 1997b; Iansiti, 1998; Magnusson & Johansson, 2008), and when companies reuse technologies in new applications, they face a number of additional challenges. Even small changes in the requirements for a technology can prompt new development efforts that might be both costly and time consuming due to the inherent uncertainties of technology development. Also, the distance in time between the first and subsequent technology application projects induces challenges to the transfer and management of the knowledge involved. If a team reuses their own technology in a new application, they will likely remember much of what they did previously. But the greater the distance in time, the greater the risk that they forget things or have trouble locating and understanding existing documentation. To reuse a technology previously developed and applied by other people is even more difficult. Some elements of the knowledge gained by the previous team might be impractical or even impossible to document and transfer. The other knowledge elements, which can be transferred, will induce a transaction cost that increases with the distance between the source and recipient of the knowledge.

Thus, in order to reduce the effects of challenges inherent in technology reuse, engineers need to use purposeful practices that support this special case of technology integration and knowledge transfer. This thesis aims to contribute to research on how companies can systematically manage their technologies as reusable assets, referred to as a 'technology platform' approach, by exploring how companies can organize and assess their technological knowledge to support engineers in the reuse process.

1.1 Case Company

This research originates from the conclusions of a previous initiative at the company GKN Aerospace Sweden AB[1] (GKNA), where the use of a technology platform approach was identified as a viable opportunity to improve the efficiency of its technology development projects. GKNA develops and manufactures components and subsystems for aircraft engines, with the majority of its operations at the headquarters in Trollhättan, Sweden. It operates across three different business areas: space propulsion, military aircraft, and commercial aircraft, which were managed quite independently until a reorganization in 2003 when they became integrated. Its products are characterized by advanced technology and low volumes, and the strategy of GKNA has been to focus on developing strong capabilities within a number of key technological areas and working with multiple engine makers as risk-and-revenue sharing partners.

While their specialized competence can be leveraged across various products to different customers or partners, the reuse of the detailed designs is complicated by a number of factors (Högman et al., 2009). One factor is that designs developed in alliances may have elements that are the property-rights of their partners, which must not be reused in products developed with other partners. Another factor is that in order to make components reusable in different products, trade-offs are required with regard to their design that make it impossible to meet expected high performance requirements. Instead, when industrial researcher Ulf Högman together with his colleagues analyzed the potential for reusing components using a product platform approach at GKNA, they found that most of the assets shared between products consisted of technological knowledge (Berglund et al., 2008). However, they found few examples of research focusing on how to manage technologies as a platform of reusable assets, which initiated the research reported in this thesis.

1.2 Research Goal

The goal of this research has been to explore how a strategy to increase the internal leverage from a company's technological capabilities can be realized by means of

[1] When the research was started, the company was called Volvo Aero Corporation but changed its name after having been acquired by the company GKN. Since GKN encompasses several divisions, this thesis uses 'GKNA' as an abbreviation for GKN Aerospace Sweden AB or just 'the case company' for simplification. For further reading about the division, an extensive description of the company and related research on its technology development processes are provided in the dissertation by Ulf Högman (Högman, 2011).

support for engineers to reuse technological knowledge more effectively across applications.

The work has been performed within two different research projects, which have guided the ways in which this goal has been pursued. The majority of the work was done within the project ‘Sustainable Technology Platforms’, which was a collaboration between Chalmers University of Technology and the case company GKNA. The project goals included to define an approach for working with technology platforms, and to develop methods and tools deemed necessary to support it.

During its final year, the work continued within another research project called ‘Virtual demonstrators for parallel product and production system development’. The case company was one of the partners in this project as well, and the objective was to demonstrate how a platform approach including models for product families, manufacturing resources and technologies can be integrated to automatically generate and analyze multiple detailed concepts for the design of an aircraft engine component. This thesis primarily addressed the work package of defining which elements of reusable knowledge should be represented in a technology platform to support configuration of viable design concepts.

1.3 Delimitations

The empirical data in this research have been gathered from only one company, whereby the study is aimed at and delimited to technology reuse in companies resembling GKNA—such as other suppliers developing and producing low-volume products for high-technology industries. Companies working primarily with software-based technologies have not been addressed and it is likely that the challenges and proposed solutions would have been different if they were.

Our focus has been on activities and assets that exist *within* firms. Thus, the possibility of accessing technological knowledge through relations with other companies has neither been acknowledged nor discussed. Research on ‘open innovation’ and joint development of products and technologies in alliances or across the supply chain has, therefore, been deliberately excluded from the literature reviewed.

While technology reuse can be supported on many levels, ranging from corporate strategy to design solutions, this research has not explored all of them equally. For instance, strategic management topics that could have bearing on technology reuse have not been included except for in the review of literature. Aspects relating to the details of specific products that would require technical expertise to assess have also been disregarded, including the choice of technologies to acquire for the technology portfolio and practices for creating versatile and flexible designs that allow reuse on an engineering level. Instead, this thesis has mainly covered issues about how to use methods and tools that guide such decisions and stimulate such practices, which are likely to be most closely related to the challenges facing technology managers and people responsible for the design of development processes within companies.

1.4 Outline of the Thesis

The subsequent chapters of the thesis are outlined as follows:

Chapter 2 includes an introduction to literature relevant to the study of this topic, as well as the derived research questions. The literature has been collected over the course of the project and has continuously contributed new ideas and perspectives.

Chapter 3 presents the methodology and methods used for conducting this research, as well as 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 to discuss in subsequent chapters.

Chapter 5 is where results are discussed in relation to the research questions and the existent literature. Answers to the research questions are provided and comments are made regarding their implications for theory and practice. The validity of the results is also discussed based on the criteria for research quality presented in Chapter 3.

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

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

2 FRAME OF REFERENCE

This chapter presents the results from a review of literature related to the studied topic. Figure 1 illustrates schematically the activities and elements that are central to technology reuse, which are covered in the theory presented in this chapter. The figure shows how technologies are developed in technology development projects, then transferred to product development projects to be integrated in product applications and at the same time become stored in a virtual ‘technology platform’ as capabilities. Later, the technologies can be reused during subsequent product development projects, and the factors affecting the success of this reuse activity are of particular interest for this thesis.

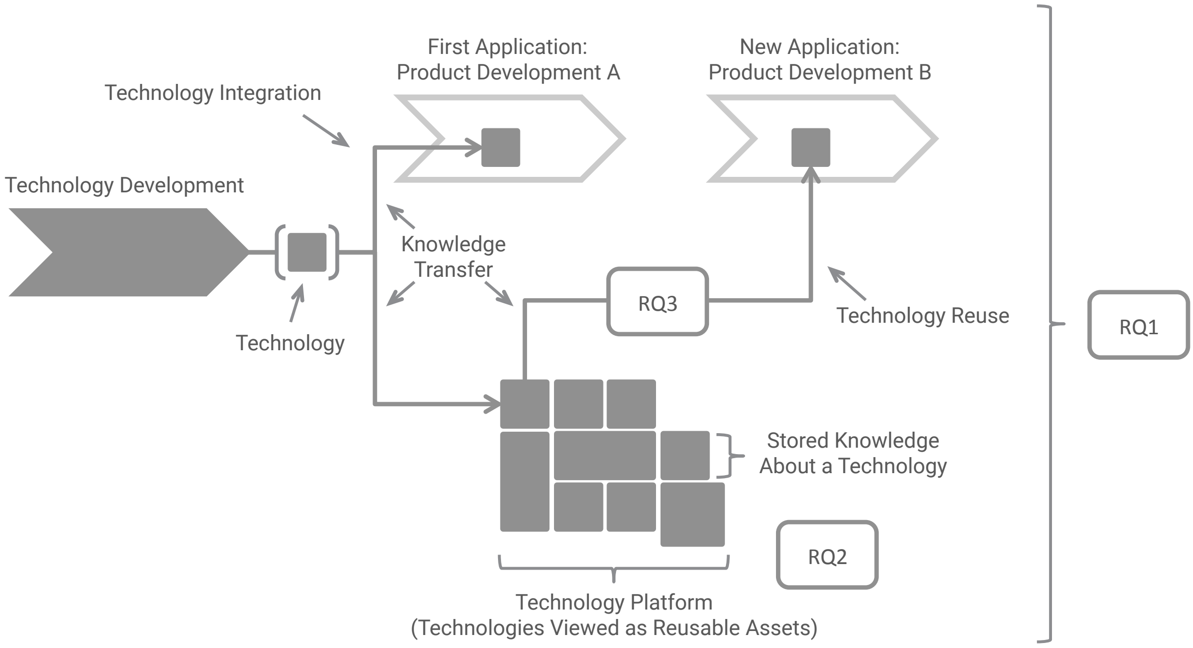

Figure 1. Schematic illustration of the studied context including key terms used and mapping of the research questions.

The literature review uncovered three research questions (discussed in more detail in Section 2.5): RQ1: What barriers to efficient reuse of technologies can be identified at the engineering level within companies? RQ2: How can a company organize its technological knowledge to make it more accessible to internal reusers? RQ3: How can the feasibility of reusing technologies in new applications be assessed in order to predict and prevent potential complications?

In order to establish the frame of reference for answering these research questions, this chapter starts by clarifying how the ambiguous term ‘technology’ is defined in this research, and continues with theory on how technologies are developed and transferred within industrial companies. This helps clarify the setting in which technologies are normally developed and applied, and provides certain characteristics that are relevant for answering all of the research questions.

Next follows theory from management research and engineering management research that treats technologies as capabilities and reusable assets. The literature reported on in this section provides insights into what elements a strategy for reuse should include and what the common issues are when working with reuse in general. This is closely related to the first research question, and the findings guided the formulation of the second and third research questions.

Last is a section on knowledge management and reuse, which are key areas for answering the second and third research questions since technologies in essence constitute a type of knowledge.

2.1 Defining Technology

A 'technology' can be defined as "the theoretical and practical knowledge, skills, and artifacts that can be used to develop products and services, as well as their production and delivery systems" (Burgelman et al., 2008), or more simply as "organized knowledge for practical purposes" (Mesthene, 1979, cited in Herschbach, 1995)

It can be concluded from these definitions that the study of technology is closely related to the study of knowledge. Technologies are composed by knowledge, but have specific properties that differentiate them from other types of knowledge—stronger links to artifacts, better possibilities to codify their knowledge, and a clear practical purpose—which makes such knowledge easier to record and organize into a system (Granstrand, 1998). However, Herschbach (1995) argues that because of its close connection to specific practical activities, technological knowledge is not as easy to categorize and codify as scientific knowledge.

In essence, there is no significant difference between a 'technology' and a 'technological capability', other than the focus in the latter term on the knowledge behind the application rather than the application of the technology itself. For technology-based companies, technologies are the most significant type of capabilities and they grow from the development of products and processes (Leonard-Barton, 1995). Within the literature on capabilities in R&D, there is some confusion about the use of the terms 'capability' and 'competence' (Prahalad & Hamel, 1990; Leonard-Barton, 1995), but they will be treated as interchangeable in this thesis.

Technological capabilities take the form of knowledge assets that can reside in individual knowledge and skills, physical assets such as machinery and databases, managerial systems that can support or inhibit the flow of knowledge, and the values of a company which guide behaviors (Leonard-Barton, 1995).

Technologies do not work in isolation and need to be regarded as elements that only bring value when integrated in an application context, which makes the study of technology integration of particular interest (Iansiti, 1998). A useful categorization of technological capabilities that builds upon this characteristic of embeddedness is provided by Drejer and Riis (1999), who distinguish between three different types of technologies based on their scope and level of embodiment in the processes and interactions among different resources:

(1) A single technology, which can be embodied in a limited number of employees and equipment and is easy to identify.

(2) A network of interwoven technologies that are not meaningful by themselves, and for which knowledge on the interactions between the technologies is important.

(3) A complex system involving many departments and organizational units, where an even larger share of the competence resides in the synchronization and synergies among activities and resources.

In this thesis, a technology is defined as *a set of knowledge that forms a capability to achieve a practical result when applied to the design or development of a product, service or its manufacture or delivery*. This definition stresses three different technology characteristics that are relevant for this thesis. Firstly, technologies are possible to identify as sets of related knowledge. Secondly, they constitute capabilities or assets that companies can nurture and utilize to make better products and services. Thirdly, they need to be integrated in an application context in order to realize their values as assets.

2.2 Technology Development

'Research and Development' (R&D) is commonly used as a collective term to describe the organization and processes that generate new knowledge and products within companies. Several different terms are used in the literature to differentiate the early stages of R&D, i.e. the phases of 'research', including, but not limited to, 'basic research', 'applied research', 'fuzzy front end', 'technology development', 'advanced engineering' and 'pre-development'. The common theme is that all these terms, although they cover different ranges of the research phase, refer to activities that occur prior to the phases of 'development' or 'product development'. In this thesis, the term 'technology development' is used broadly to cover all of the above terminology for the early development phases, except for those types of basic research that are exploratory to the extent that underlying intentions exclude the application and commercialization of the results (see Table I).

Table I. Summary of terms used for R&D. (Karlsson, 2004)

<table>
<tr><td colspan="5">R&D</td></tr>
<tr><td colspan="3">Research</td><td colspan="2">Development</td></tr>
<tr><td>Basic Research</td><td>Applied Research</td><td>Advanced Engineering</td><td>Product Development</td><td>Engineering</td></tr>
<tr><td></td><td colspan="2">Technology Development</td><td></td><td></td></tr>
</table>

2.2.1 Characterizing Technology Development

Working fast and effectively when developing new technologies has become an important source of competitive advantage (Katz & Allen, 1985; Wheelwright & Clark, 1992). However, the development of new technology is often mismanaged and efforts often fail to produce their intended effects (Eldred & McGrath, 1997a; Cooper, 2006). A common reason is that technology development is performed using the same set of processes and methods as were used for product development, which leads to poor innovation, less robust solutions, and potentially missed deadlines and cost targets (Schulz et al., 2000). Instead, less formal processes and organizational designs are needed for the development of technology, during which the pressure for productivity and control is reduced to make room for innovation (Katz & Allen, 1985).

Iansiti (1998, p.12) neatly summarizes the traditional model of an R&D process and clarifies the different characteristics of 'research' and 'development':

> "Research projects, aimed at the creation of technological possibilities, are optimized for the investigation of rapidly changing knowledge domains. Once enough is learned about these knowledge domains, research defines the technological possibilities available, which are transferred to the development organization. Development activities are optimized to execute complex tasks. These involve adapting the (now stable) set of technological possibilities to the complex requirements of the application context."

Technology development and product development are often managed separately in order to equip them with suitable methods and process models (Schulz et al., 2000). There are multiple reasons to keep them separate: (1) to allow time for creativity, (2) set up a creative environment, and (3) steer development toward flexible technologies that may be used in multiple products (Clausing, 1994).

Whereas some literature presents the alignment of technology development and product development as a temporal division of the same process (Eldred & McGrath, 1997b; Cooper, 2006), albeit with some overlap, Clausing and his colleagues (Schulz et al., 2000) prefer to model them as two parallel streams, from which product development collects, or "fishes out", appropriate technologies from the technology stream (Figure 2).

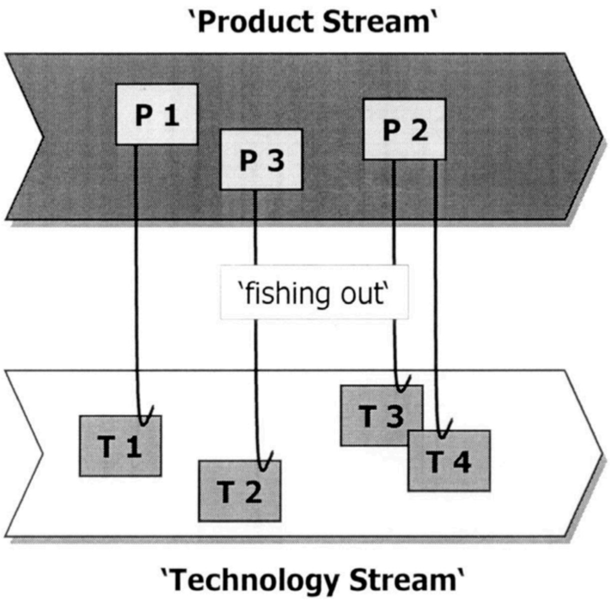

Figure 2. Product development and technology development as separate 'streams' (Schulz et al., 2000).

McGrath (2000) also models the product development and technology development processes as parallel and loosely coupled. However, he places more emphasis on the importance of mapping evolving technologies to their planned applications beforehand so that technical dependencies between them can be resolved prior to technology integration.

Based on his review of the literature, Nieto (2004) concludes that a technological innovation process, which corresponds to the technology development process, is primarily characterized by being continuous, path dependent, irreversible and affected by uncertainty. Further, Nieto (2004) argues that uncertainty is the most important characteristic and distinguishes between three different types:

(1) Technical uncertainty – whether a technical solution will work as intended.
(2) Uncertainty about future use – for what applications a specific technology will be suitable.
(3) Uncertainty about future evolution – how the usefulness and characteristics of a technology will evolve during its development.

Process models have been designed specifically for dealing with uncertainties in technology development. Cooper (2006) has proposed a model adapted from his original 'Stage-Gate' model, which was created for product development, to fit the unpredictable nature of technology development (Figure 3).

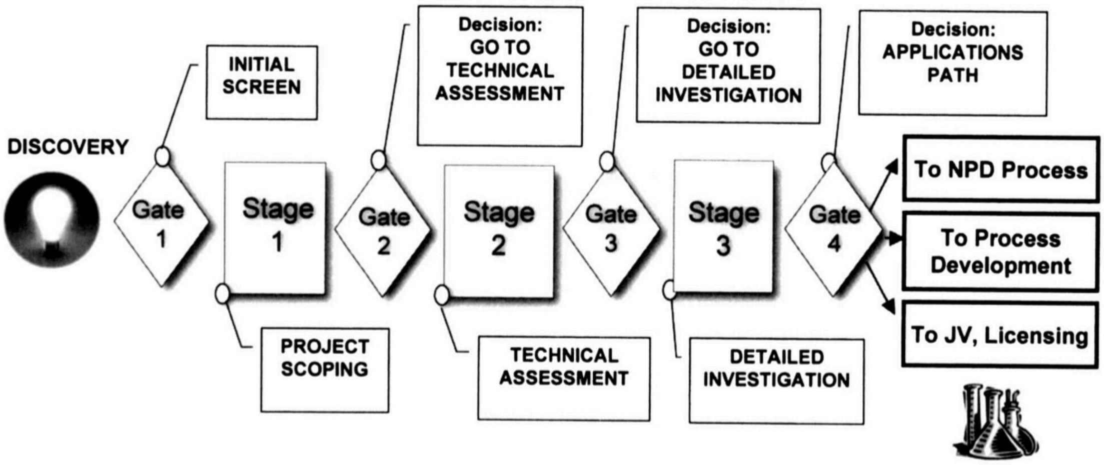

Figure 3. The technology development Stage-Gate model by Cooper (2006).

The traditional Stage-Gate model assumes that there is a target market, defined customers and a clear view of potential future product features, and requires detailed analyses to pass a project on to the next stage. A technology development Stage-Gate, on the other hand, uses qualitative assessment about the potential value of the concepts to support decisions on whether further experimentation and testing is worthwhile (Cooper, 2006).

2.2.2 Technology transfer and integration

The transfer of technology between technology development and product development projects is complicated for various reasons, and the effort required is often underestimated (Eldred & McGrath, 1997a). In a study of 32 internal transfers of manufacturing technologies, Galbraith (1990) found that almost all the interviewed employees had underestimated how complicated the transfers would be and thus gave insufficient attention to planning and controlling them. Rather than a simple handover of documents and prototypes, a continuous process of transferring knowledge is generally needed to ensure a successful transfer, as is mutual adoption of the technology and application environment between the transferring parties (Leonard-Barton, 1988; Eldred & McGrath, 1997a). Further, when technologies are integrated in applications, the domain-specific knowledge that technology experts possess needs to be combined with context-specific knowledge related to the application, which can be both novel and complex (Iansiti, 1998).

A firm or business unit that wishes to integrate external technology in their products or manufacturing need to go through four steps of technology transfer: (1) identify a source, (2) reach agreement to transfer the technology, (3) transfer the technology and (4) incorporate the new technology in its processes (Stock & Tatikonda, 2008). Eldred and McGrath (1997a) discuss three important dimensions of the transfer activity; 'program synchronization', 'technology equalization' and 'technology transfer management'. Program synchronization refers to the temporal alignment of the development processes, during which an optimal transfer would imply that a technology is ready for transfer at the same time as the product concept is about to be decided. Technology equalization is the process by which issues related to the enabling of a technology for its intended application are addressed, e.g. by preparing and developing the interfaces to other technologies and systems. Such enabling can be highly problematic since technologies can seldom be tested in a fully representative environment in advance (Leonard-Barton, 1988) and since the feasibility of the system solution needs to be evaluated already at a concept level (Kihlander & Ritzén, 2011). Also, product developers often perceive the results transferred as being insufficiently prepared for implementation (Eldred & McGrath, 1997a; Nobelius, 2004). Finally, the dimension technology transfer management deals with the operational details of defining roles, conducting technology assessments and making plans for managing the transfer.

While new technologies may provide technical advantages, firms face more uncertainty and higher risk of failure when applying them than when reusing technologies for which they have prior experience (Green et al., 1995). Novelty has been shown to affect time-to-market even more for process technologies than for product technologies (Tatikonda & Rosenthal, 2000). With experience, the potential problems and contingencies of a technology's behavior in various application environments become better known, which helps predict potential problems in future applications. Similarly, an integral part of the process of knowledge reuse is to understand the contextual factors of the setting in which knowledge was created, in order to be able to recontextualize it and make it useful in a new setting (Markus, 2001). Technologies that are new to the world most certainly bring uncertainty, but technologies that are new to the firm can display the same characteristics regardless of the existence of prior knowledge in the scientific community (Green et al., 1995). With novel requirements for the technology in a new application comes the need for an innovation effort to close knowledge gaps and make sure the technology and product system work together. It also means that the recipient is likely to face new problems, which imposes higher requirements on the recipient's internalization of the new knowledge to be able to commit to, re-create and use it (Cummings & Teng, 2003).

There is strong agreement in research that any technology integration shall be preceded by a technology readiness assessment to ensure that the downstream product development project does not risk its objectives by taking on too much technical uncertainty (Mankins, 1995; Eldred & McGrath, 1997b; Ajamian & Koen, 2002; Nolte, 2008; Clausing & Holmes, 2010), which is the topic of the next section.

2.2.3 Technology maturity assessments

By measuring the maturity of a technology, the remaining risks and costs of further development can be estimated to facilitate the decision of when the technology may be ready to be transferred to product development (Nolte, 2008; Olechowski et al., 2015). The most widely adopted metric for assessing technology maturity is Technology Readiness Levels (TRLs), originally developed by NASA in the 1970's (Olechowski et al., 2015) and later introduced to a wider audience through the publication of a White Paper by Mankins (1995). The metric features a scale with nine levels (1-9), where the highest levels indicate the existence of a complete prototype that has been verified in environments that closely resemble its intended application. At the other end of the scale, technologies with the lowest TRLs are still undergoing stages of basic research, whereas the middle levels usually correspond to there being proof-of-concepts in lab environments. A full overview of the scale is presented in Figure 4.

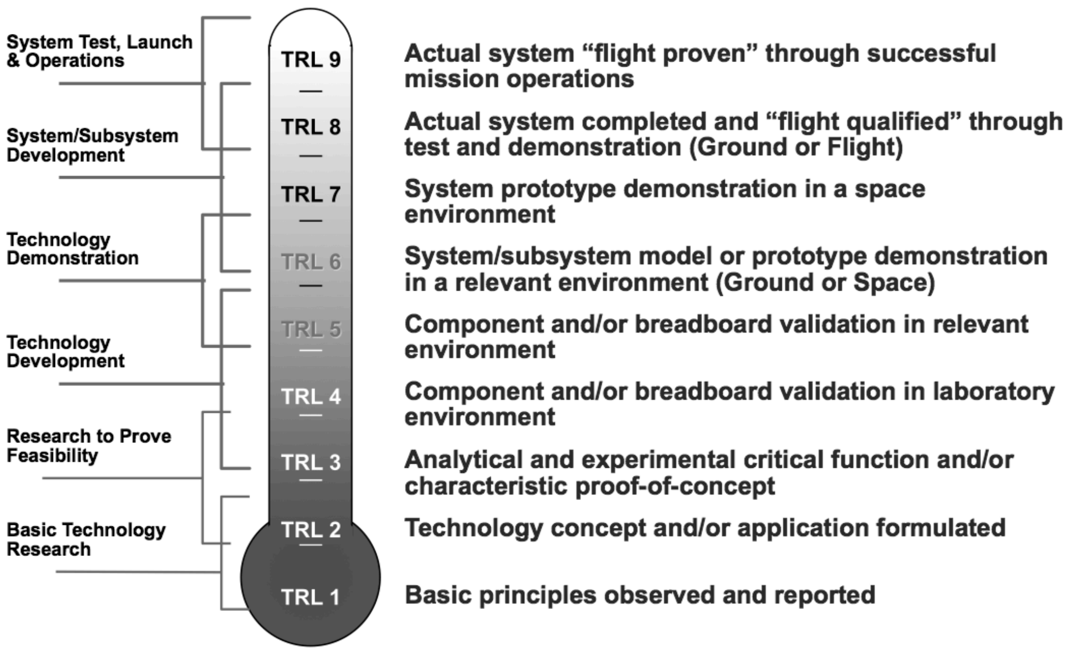

Figure 4. Technology Readiness Levels (TRLs) (Mankins, 2002).

Extensions to the TRL scale have been proposed by various researchers to account for other factors that are important when assessing the readiness of a technology. Sauser et al. (2008) address the uncertainties derived from interrelatedness between technologies and propose a separate readiness metric called Integration Readiness Level (IRL), intended to be used for the interfaces between related technologies. Together with their TRLs, these IRLs add up to a System Readiness Level (SRL). The dependence on environmental factors for technology maturity was also noted by Högman (2011), who found that the TRL for a technology dropped a few steps on the scale when its target application changed. Mankins, who published the first White Paper about TRLs, later released an extension to the original metric in order to account for the varying difficulty of advancing through the TRL scale and differences in technology criticality (Mankins, 2009). From their study on the challenges experienced by organizations that use TRL practices, Olechowski et al. (2015) conclude that even the most experienced users still struggle with three important issues: measuring system readiness, making decisions based on TRL assessments, and validating the quality of the derived metrics. An exception to the omnipresence of TRLs is provided by Clausing and Holmes (2010), who exclude the TRL scale and focus on assessing risks along different dimensions, including failure modes and manufacturability, to provide a holistic picture of technology readiness.

2.2.4 Summary

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

- Technologies constitute sets of practically useful knowledge that can be applied in development projects to improve products, their manufacturing and their delivery (Herschbach, 1995; Leonard-Barton, 1995; Burgelman et al., 2008).
- Technological knowledge can exist in many different shapes, including individual knowledge and skills, machinery, documents, databases, managerial systems, and company values (Leonard-Barton, 1995).
- Technologies differ in the extent to which they need to be synchronized with other technologies to function as intended (Drejer & Riis, 1999).
- The development of technology has different goals and characteristics than product development and thus needs to use different processes and methods (Eldred & McGrath, 1997b; Iansiti, 1998; Nieto, 2004; Cooper, 2006).
- Technology development is less predictable than product development (Cooper, 2006) and is characterized by three types of uncertainties: whether the technology will work, where it will be used and how it will evolve (Nieto, 2004).
- Technology development can be seen as a stream of activities that either precedes (Eldred & McGrath, 1997b; Cooper, 2006) or runs in parallel with product development (Schulz et al., 2000; McGrath, 2000).
- Technologies need to be integrated in application contexts to bring value (Iansiti, 1998).
- The transfer of technology from technology development to product development is not a straightforward task (Leonard-Barton, 1988; Eldred & McGrath, 1997b; Nobelius, 2004) and the required efforts are often underestimated and mismanaged (Galbraith, 1990; Eldred & McGrath, 1997b).
- A continuous process is generally needed to transfer technology in order to assure sufficient transfer of knowledge and adaptation of the technology and its application environment (Leonard-Barton, 1988; Eldred & McGrath, 1997b). Two factors complicate the adaptation process: the need to combine domain-specific knowledge of technology experts with context-specific knowledge of the application (Iansiti, 1998) and the difficulty of fully testing and evaluating a technology for an application environment that is still at a concept level (Leonard-Barton, 1988; Kihlander & Ritzén, 2011).
- Technologies that are new, or just new to the company, are more difficult to apply and induce higher risk of failure than those for which a company has prior experience (Green et al., 1995).
- The decision of when a technology is ready for transfer to an application project should take into account the risks and costs that remain, which can be

done by assessing Technology Readiness Levels (Mankins, 1995; Nolte, 2008; Olechowski et al., 2015). The timing for transfer should preferably be aligned with the concept selection phase of the receiving product development project (Eldred & McGrath, 1997b).

Technology development does not lend itself to the same level of control and types of processes as product development, and many companies lack support to deal with its inherent challenges. Technological knowledge can be embedded in many different media and has to be adapted to the application contexts into which it is integrated. Consequently, technologies cannot be reused "off-the-shelf" in the same way as components.

Reuse of technology can be seen as a special type of technology integration, where the target application has been preceded by other applications. This means that the company has already developed or otherwise acquired the technology and has potentially valuable experience from prior implementations. It also means that it faces many of the same challenges as regular technology integration, with a few additions. Firstly, there might be a misalignment between the goals that guided the development of the technology in the initial case and the requirements of the new application. An additional technology development effort would then be required to enable the technology and close potential knowledge gaps. Secondly, the transfer of technology is likely to involve a greater temporal distance between the development and application projects than normal if the technology is reused in a later generation product. Thirdly, the transfer might take place over a greater spatial or organizational distance if it is applied to a product managed by a different business unit. These distances place additional requirements on the processes and methods used for preparing flexible technology options and for storing and transferring knowledge, which will be further explored in the following sections.

2.3 Technologies Viewed as Reusable Assets

The notion of investing in reusable assets exists on multiple levels in an organization. On a strategy level, the whole organization can be viewed as a set of intellectual resources, or capabilities, that shall be grown and exploited as effectively as possible to gain competitive advantage and diversify into emerging markets. On an operative level, there is an interest in increasing the operative efficiency by exploiting opportunities for synergy and reuse across product lines and product generations with purposeful methods and tools. Both of these perspectives are important to consider in order to understand how to reuse technological capabilities in practice.

2.3.1 Core capabilities

The late 1980's and early 1990's saw the growth of a new field of management research studying core capabilities of firms (Prahalad & Hamel, 1990; Leonard Barton, 1992; Meyer & Utterback, 1993), which for technology-based companies is often synonymous with their technologies or technological capabilities. It was an extension of the resource-based view of the firm (Wernerfelt, 1984), and encouraged companies to see their capabilities as resources (Kogut & Zander, 1992) that should be actively identified, built and used to gain competitive advantage (Prahalad & Hamel, 1990).

For technology-based companies, capabilities take the form of knowledge assets that can reside in physical assets, skills, managerial systems and values of a firm (Leonard-Barton, 1995) and mainly grow from the development of products and processes. Actions of both managers and employees affect how this growth takes place, and they can nurture it by considering the potential for building knowledge during various types of decision-making (Leonard-Barton, 1995).

According to Prahalad and Hamel (1990), developing core competencies is not solely about investing in research and development. It can also be fostered by regarding competencies as resources to be shared on a corporate rather than on a business unit level, establishing a corporate roadmap of the competencies and technologies to build on for the future, entering strategic alliances, and explicitly identifying competencies to inform and encourage the entire organization to support their development.

In his discussion of organizational capabilities, Grant (1996a) presents the idea that capabilities can be viewed as a hierarchy where the higher levels are achieved by successful integration of the lower level capabilities, as well as of individual knowledge. A challenge for integrating knowledge within the company, he argues, is that the hierarchy of capabilities does not always correspond to the structure of the organization, giving rise to challenges of communication and decision making authority. An example of a hierarchy of knowledge from Grant (1996a) is presented in Figure 5, where the lower-level capabilities ('Specialized' and 'Single-Task') could be identified as technologies.

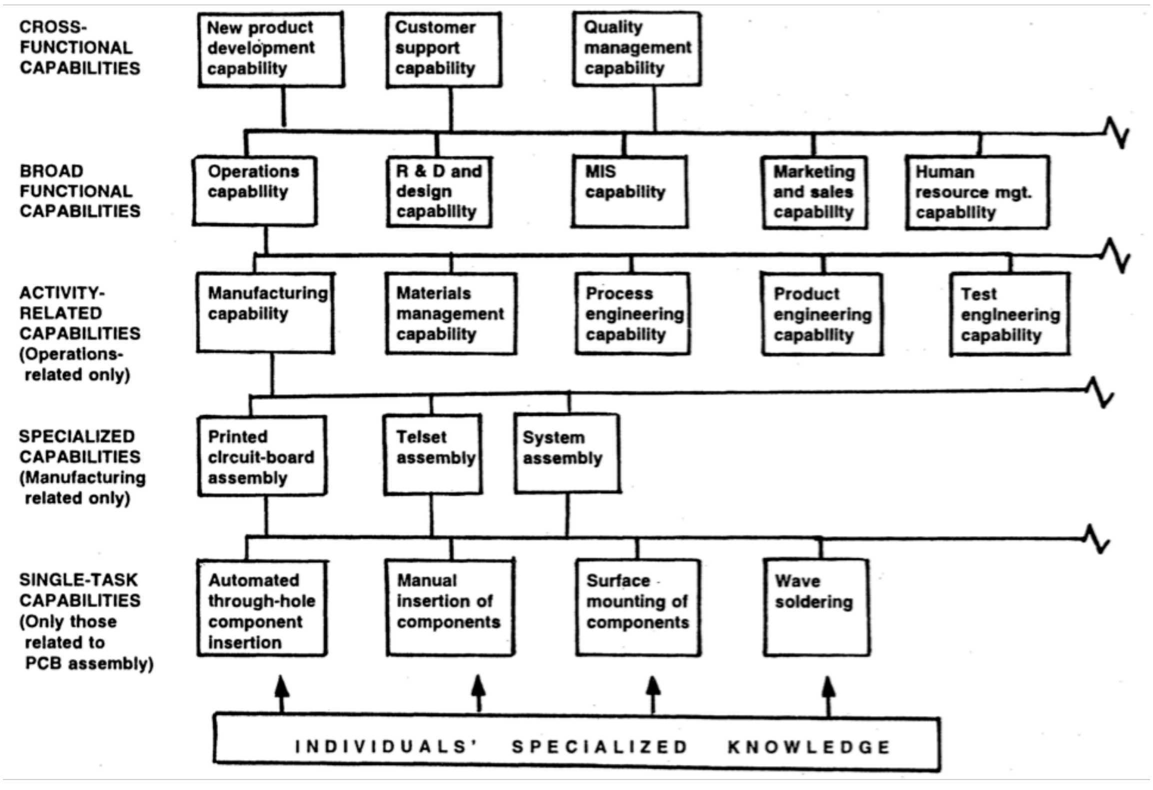

Figure 5. Example of a hierarchy of organizational capabilities (Grant, 1996a).

Leonard-Barton (1995) divides technological capabilities into three groups, depending on their role in contributing value to the firm. 'Core' capabilities are the most strategically important capabilities, which cannot be easily imitated by competitors and are at the heart of the business. 'Enabling' capabilities are necessary for entering a business, e.g. certain manufacturing capabilities, but do not differentiate a company from its competitors. 'Supplemental' capabilities are value-adding to a firm, although they are neither necessary nor unique and can be replicated by competitors.

Companies that over time have developed certain capabilities that make them successful in an industry run the risk of becoming rigid with regard to their competence base. As a company matures, it typically aligns its processes and organization to become as efficient as possible in leveraging its core capabilities, which creates an organizational inertia (Tushman & Smith, 2002). When market conditions no longer favor them, other companies are likely to quickly adopt new capabilities and take market shares. In technology-intensive industries, these changes are typically driven by technological innovation. If an innovation should alter the basis of competition on a market to make previous capabilities more or less obsolete, it is referred to as a 'disruptive innovation', which happened multiple times in the disk drive industry during its first decades (Christensen, 1997). Christensen (1997) showed that possessing the right technological capabilities and resources to pursue a new technological path was not sufficient for companies to survive a technological transition. This organizational inertia to adapt to change has been attributed to various factors, such as being too focused on the current customer base (Christensen, 1997) or using incentive systems that discourage new initiatives (Kaplan & Henderson, 2005).

One of the most widely recognized remedies of such technological 'inertia' and a source of strategic flexibility is to balance the exploration and exploitation of resources against one another, and to balance incremental and radical innovation projects (O'Reilly & Tushman, 2004). Exploration is the process by which companies seek new knowledge and invest in new capabilities, whereas exploitation is the efficiency-focused activities of leveraging existing capabilities and products. The two terms are different in their nature and need to be realized by means of different strategies, structures, processes and cultures (O'Reilly & Tushman, 2004). 'Continuous innovation' and 'ambidexterity' are terms describing the ability of being successful at both operational effectiveness (requiring exploitation) and strategic flexibility (requiring exploration) at once (Boer & Gertsen, 2003).

To conquer the general tendency to prioritize short-term projects, many companies warrant a dedicated budget for exploration and technology development to balance a project portfolio (Cooper, 2006). Based on that premise, the challenge is to allocate those resources most effectively among the ideas and options available. Given the uncertainties of predicting the outcomes of technology development, such strategic investment decisions face two trade-offs (Wernerfelt & Karnani, 1987). The first trade-off concerns the timing to invest in new technologies, thus deciding whether to take a leading role in their development or wait for others to conduct additional testing first. The second trade-off is between investing in either focused or flexible technology options, whereby a focused option may lead to greater success at the cost of higher risks. Wernerfelt and Karnani (1987) argue, in a general case, that strong competition favors early investments, and since large companies can afford to wait and then use their resource advantage to catch up with "first-movers", small companies need to make more focused investments than do large companies.

Decisions under uncertainty are also discussed by Levinthal and March (1993) who focus on how to optimize 'knowledge inventories', defined as collections of information and experience of "products, technologies, markets, and social and political contexts" (p.103). The challenges inherent in optimizing such inventories, they argue, concern the uncertainties of what may be needed in the future; in advance you cannot know precisely what you will need and when you know what you need, it is often too late to acquire that knowledge.

2.3.2 Platform development

One of the most prominent approaches to enable development *for* reuse and development *with* reuse is product platforms. The classic product platform approach is to develop the architecture or components upfront in preparation for the development of a set of derivative product variants later on (Wheelwright & Clark, 1992). In this way, the technical variation between the developed products can be reduced, while at the same time maintaining or increasing their functional diversity (Jiao et al., 2007). Platform strategies have received a lot of attention because of their potential to generate leverage of internal assets and meet a wider range of market needs. Other advantages of platform strategies reported in literature include: increased development efficiency (Robertson & Ulrich, 1998; Simpson et al., 2006), improved ability to update products (Simpson et al., 2006), promotion of learning about complex products (Rothwell & Gardiner, 1990) and improved design quality (Sawhney, 1998).

Leverage of the product platform often comes from developing product families. Sanderson and Uzumeri (1995) showed how the company Sony successfully used a product family strategy for their portable audio player Walkman to deliver a wide variety of products that appealed to different market segments. Their success was attributed partly to the use of a modular product architecture with common core modules and a flexible manufacturing system. Some scholars limit the scope of the platform approach to physical components, while others also include intangible assets such as underlying technology and knowledge (Simpson et al., 2006). Meyer and Lehnerd (1997) define a product family as a set of products that share common technologies and address similar market applications, which relates to more elements than those of the product structure.

When Meyer and Lehnerd (1997) model a generic platform strategy (Figure 6), they incorporate technologies in a foundational layer together with three other generic capabilities upon which product platforms are built: Customer Insights, Manufacturing Processes and Organizational Capabilities.

A research group led by Hans Johannesson has studied how product platforms can be modeled to capture both physical and intangible assets (e.g. Michaelis, 2013; Levandowski, 2014; Johannesson, 2014). Their approach uses a specific modeling language that treats components as configurable objects with information attached to them, including, e.g., geometry, relations to other objects and rationale for their design. Appended Papers C and D describe the approach further and also make contributions to how it can handle technological knowledge.

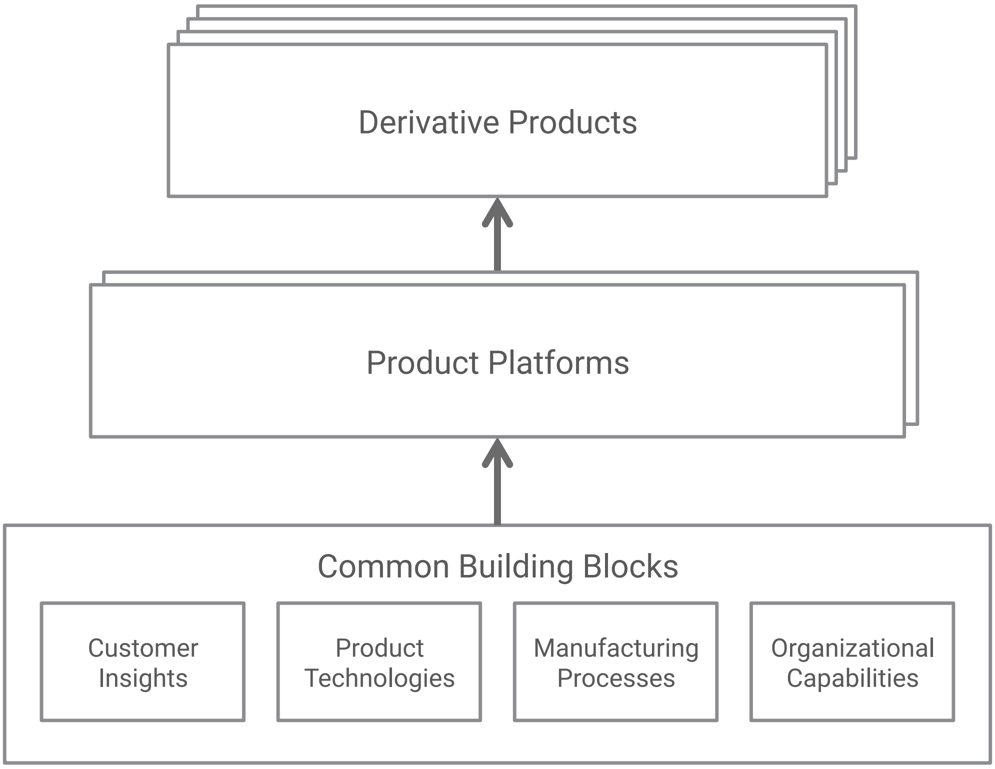

Figure 6. Technologies are leveraged in platforms, which are then further leveraged in products. Adapted and redrawn from Meyer and Lehnerd (1997).

Some authors define a ‘technology platform’ as a distinct approach, e.g. McGrath (2000): “a set of initiatives organized around a macro-level functionality that helps to manage and optimize technology investments across multiple product platforms”. According to this definition, technology platforms represent the core competencies for technology-based companies, which do not lend themselves to the building block modules and interface structure of product platforms. Unlike product platforms, they also capture both physical and non-physical elements, where the company 3M is a clear example with a technology platform based on elements such as adhesives, abrasives, and vapor processing (Shapiro, 2006).

Based on a previous study at the case company used in this thesis, Berglund et al. (2008) propose a platform strategy that includes both a product platform and a technology platform (Figure 7). The authors emphasize the difference between technologies in their general form that belong to the technology platform, e.g. “Laser Welding”, and their applications to specific problems in the product platform, e.g. “Laser welding of titanium fins for a fan hub frame” (p.7). The technology platform would supply development projects with general technology information and then be fed with the new experiences and application-specific knowledge developed in those projects. In order for a technology platform to be effective, they argue, companies need to: identify technological abilities, have a process to finance, conceive, prioritize, develop and implement them, and buy into the idea of platform development on an organizational level. For the case company, many of these factors were considered to be in place, except for a process to formally document technology implementations.

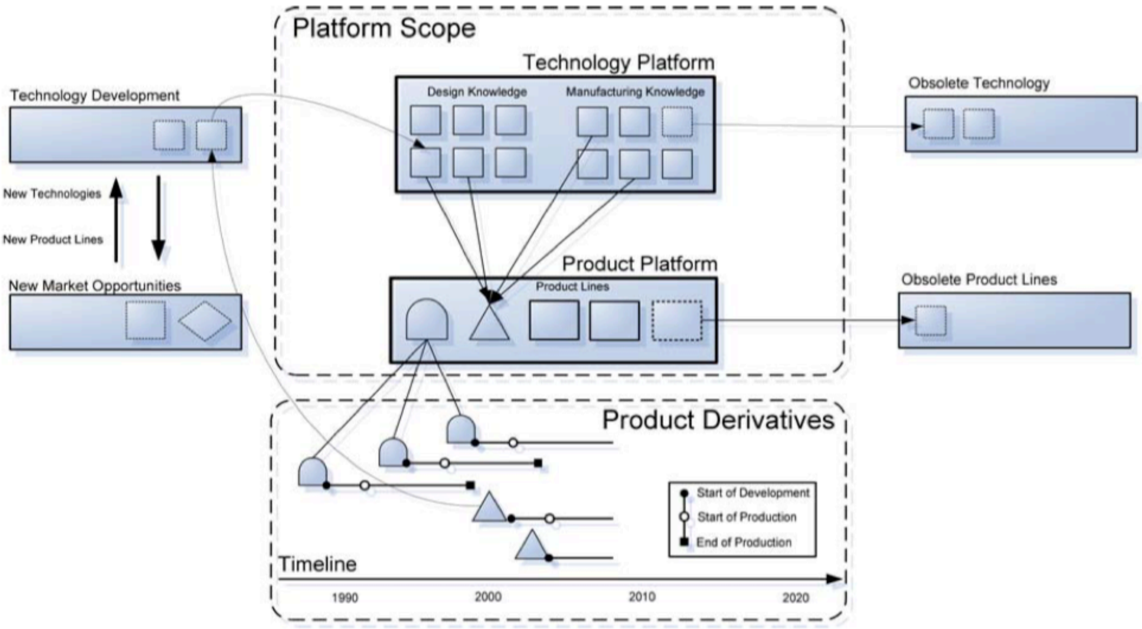

Figure 7. Platform approach previously developed for the case company studied in this thesis, including both a Technology Platform and a Product Platform (Berglund et al., 2008).

Kim and Kogut (1996) use the term 'platform technology' and 'technological platform' to indicate a technology that has a wide range of potential applications, and which offers continued returns to the company when it is explored further and applied to new products. They studied start-up firms in the semiconductor industry and argued that in hypercompetitive markets, technological platforms offer an important advantage in terms of providing options for the diversification into new markets. The link between diversification and the possession of technological know-how, or platforms, is further explored by Nasiriyar and her colleagues (Jolly & Nasiriyar, 2007; Nasiriyar, 2009; Nasiriyar et al., 2010) who use patent data to show that companies are more likely to diversify into markets that share the same technological base, and that a broad technology portfolio increases the likelihood of entering new markets, arguably because of synergies and complementarity among technologies (Nasiriyar et al., 2010).

This thesis views a technology platform as an operational strategy for technology development and management, analogous to the concept of product platforms. Similar to the concept of core capabilities, the technology platform approach is rooted in the principles of the resource-based view of the firm (Wernerfelt, 1984), path dependency of technological competences (Teece et al., 1997) and the need for managerial capabilities to coordinate and deploy technologies in new products (Kogut & Zander, 1992)

2.3.3 Engineering reuse

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

Inspired by reuse methodologies from software development, Duffy et al. (1995) have developed a model for improving the effectiveness of reuse in the context of engineering design. With a formal—instead of ad hoc—approach, they argue that the understanding of the reuse process would be improved, allowing engineers and companies to increasingly leverage their knowledge. The model divides reuse into the processes: ‘design by reuse’, ‘domain exploration’ and ‘design for reuse’ (Figure 8).

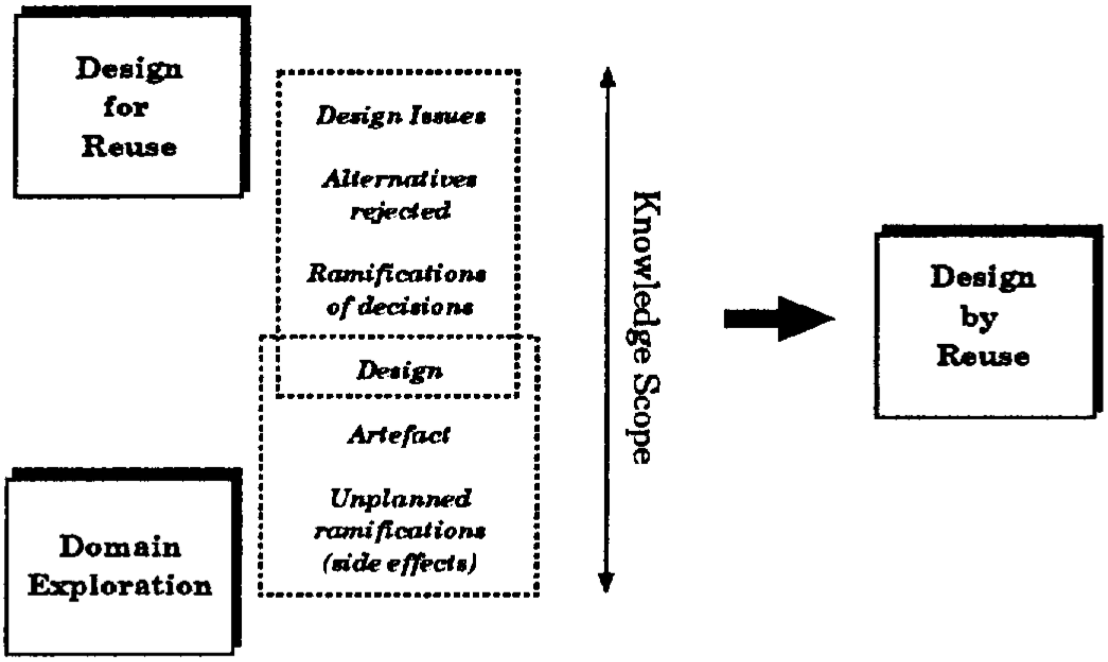

Figure 8. Categorization of reuse processes (Duffy et al., 1995).

‘Design by reuse’ is 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 (Duffy et al., 1995). There are different levels of abstraction for such knowledge, ranging from physical artifacts to abstract concepts. The reuse of abstract level knowledge, as opposed to details of a design, requires additional knowledge relating to its history and rationale in order to revisit prior design decisions and support reapplication in a new context. The two remaining processes support the creation of reusable knowledge. ‘Domain exploration’ is the process of generating an understanding of the field of design where relevant knowledge can be found for handling design problems. ‘Design for reuse’ treats the capture of reusable knowledge during a design process. The purpose is to identify the knowledge that is suitable for reuse and then record it in a way that can be effectively revisited and reused. Consequently, documents containing such knowledge should be stored in a library that is well organized to make them easy to find, as opposed to being stored in unorganized ‘bins’ (Duffy et al., 1995). The topic of how to store knowledge in libraries is covered more in detail in Chapter 2.4.4.

A comprehensive description of a process for the reuse of technologies, systems and software can be found in Davis (1994), which focuses on how to transform a business “from one-of-a-kind system developments to a reuse-driven approach”. It starts with an assessment of a company’s potential for adapting a reuse strategy, including assessment of market and product characteristics, as well as their capabilities in terms of e.g. the availability of reusable assets and organizational commitment to the reuse strategy.

Davis (1994) lists six components of a reuse strategy, of which the third and fifth are of particular relevance to this research:

- Deciding which products to develop with reuse and which to develop for reuse.
- How the business model should be adapted and how to finance the creation of reusable assets.
- What processes, methods and tools that are needed to manage and utilize reusable assets.
- How organizational structure, roles and responsibilities are affected.
- What tools, such as libraries of reusable assets, will be used to support the reuse process.
- How to plan for the transition into reuse-based development.

A number of key issues for successfully implementing a reuse strategy are highlighted, including the risk that reusable assets are not available when needed, avoiding resistance from individuals whose work practices are affected by the change, and the importance of getting management support for the strategy (Davis, 1994).

From the engineering reuse literature, there are also examples where the reuse of technological assets is in focus. Antelme et al. (2000) present a framework for engineering reuse in which reusable assets are listed as physical artifacts, processes, core competences and capabilities. They argue that all of these reusable assets are included in broad definitions of 'technology', and continue to define engineering reuse as technology reuse. The authors divide technologies into either capabilities or products, with the latter defined as assets that can be offered to customers. This definition differs from the definition used in this thesis that treats embodied technological knowledge, corresponding to the 'product' dimension in Antelme et al. (2000), as a separate type of reusable asset.

The framework by Antelme et al. (2000) includes a scheme for categorizing technologies along five dimensions to support the identification of assets that may be reused: layering, structure, abstraction, familiarity and tacitness. In short, layering and structure deal with where technologies belong in a hierarchy of other systems, abstraction measures if resources are reusable on a high abstraction level or close to application, familiarity asks if the asset is well understood and tacitness measures if there is codified content available to support reuse. Their framework also includes a diagram of the data flow between three processes of engineering reuse: Technology Creation, Technology Specification Management and Technology Utilization (Figure 9). The processes for technology creation and utilization roughly correspond to 'design for reuse' and 'design with reuse', respectively, in Duffy et al. (1995). Technology Specification Management is concerned with the storage of information and classification of technologies, as well as the decisions to implement and develop certain technological assets.

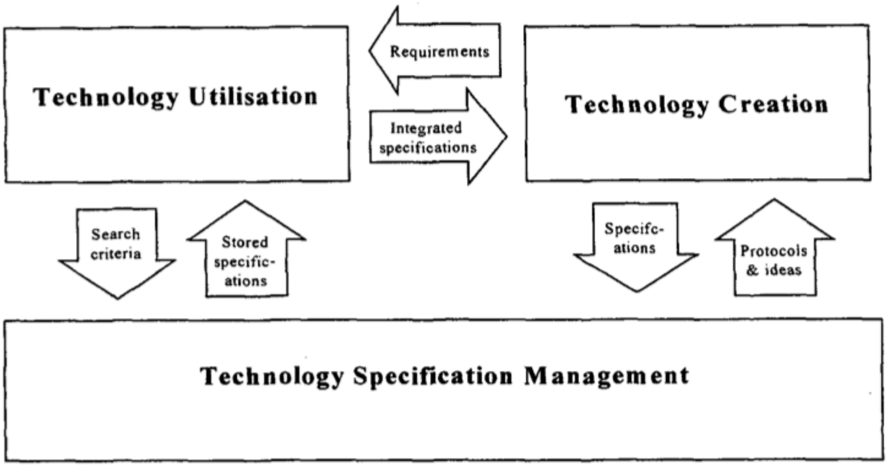

Figure 9. Data flow between engineering reuse processes (Antelme et al., 2000)

With the intention of making the concept of engineering reuse more practically applicable, Hunt et al. (2001) build upon the framework developed by Antelme et al. (2000) by suggesting a process that firms can follow for creating a strategy for reuse and a plan for its implementation (Figure 10). This process starts with the identification of a need for reuse from a business perspective, which is important for backing decisions about resource allocation to reusability efforts. Next, the process prescribes an identification of available assets and analysis of options for reusing them, followed by a phase during which detailed plans are made for implementing the most viable options. Although the process gives an impression of being unidirectional, continuous and focused on planning for the utilization of existing assets, it implies the existence of other processes for further developing the assets that are identified as being promising candidates for reuse. Using a couple of hypothetical cases, Hunt et al. (2001) present examples of possible results from employing this process, including decisions to set up a knowledge library and design products based on reusable modules.

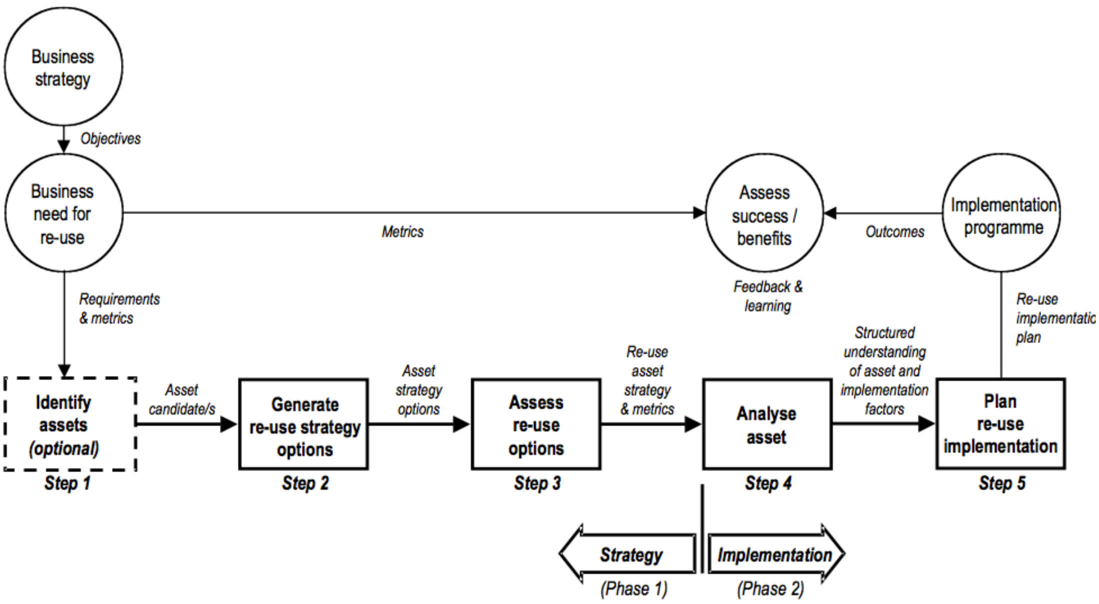

Figure 10. Process for creating and implementing a reuse strategy (Hunt et al., 2001).

2.3.4 Summary

The reviewed literature on how to treat technologies as reusable assets can be summarized as follows:

- Literature on reuse of technological assets covers both the strategic level (e.g. Prahalad & Hamel, 1990; Grant, 1996a; McGrath, 2000) and the engineering management level (e.g. Duffy et al., 1995; Meyer & Lehnerd, 1997), although the distinction is not always clear. They are in agreement that a formal, instead of ad-hoc, approach to reuse of capabilities can provide greater leverage on investments in development (e.g. Prahalad & Hamel, 1990; Duffy et al., 1995).
- On a strategic level, technological capabilities can be seen as resources that can provide companies with competitive advantage if they actively identify, build and use them (Prahalad & Hamel, 1990; Kogut & Zander, 1992; Levinthal & March, 1993; Leonard-Barton, 1995).
- Activities that are in focus on a strategic level to support technology reuse include: investment in R&D, creation of roadmaps for planning acquisition and integration of future technologies, participation in strategic alliances, sharing competencies on a corporate instead of a business unit level, and explicitly identifying competencies to encourage employees to support their development and use (Prahalad & Hamel, 1990).
- On an engineering management level, companies are advised to adopt approaches and methods that prepare technologies for multiple applications upfront and then support the reuse of previously developed technological knowledge (Davis, 1994; Duffy et al., 1995; Hunt et al., 2001).
- Activities on an engineering management level that are credited with supporting both design reuse in general and reuse of technologies specifically include: deciding when to invest in developing reusable assets, identification of what knowledge assets a company has that can be reused, classification of assets, creating organized libraries of reusable knowledge, and assessment of what options exist for reusing assets and their feasibility (Davis, 1994; Duffy et al., 1995; Antelme et al., 2000; Hunt et al., 2001).
- Technology platforms have been proposed as an approach that builds upon the idea of product platforms to systematically manage technological capabilities and support their development and reuse across applications (Kim & Kogut, 1996; Meyer & Lehnerd, 1997; McGrath, 2000; Shapiro, 2006; Jolly & Nasiriyar, 2007; Berglund et al., 2008; Schuh et al., 2015).
- As opposed to product designs and product platforms, technologies include both physical and non-physical elements (Shapiro, 2006) and cannot be described with the same building block and interface structures (McGrath, 2000). They also represent a more abstract level of knowledge than designs, which requires more extensive descriptions of rationale and history in order to support reapplication in new contexts (Duffy et al., 1995).

The literature provides many examples of reuse strategies that promote identification of reusable assets and processes for how to leverage them across applications. Such strategies have been credited with the potential to make development more effective and enable companies to exploit new market opportunities. However, few examples have been reported of companies that have explicitly employed technology platforms, where technological capabilities are managed and deployed systematically as reusable assets with necessary support. Insights into what might be suitable activities can be found within the engineering management literature, but it does not provide answers to how technological capabilities and their knowledge characteristics specifically can be managed and reused between applications to leverage the synergetic effects. As seen in the previous section, the application of technology is complicated even when performed directly after it has been developed for a designated application. Thus, there seems to be a gap between the intent of leveraging synergies between technology implementations and the micro-level challenges faced by engineers to effectively transfer and reapply technological knowledge.

2.4 Knowledge Management

By definition, technologies constitute sets of knowledge, and there is a host of research on how to manage knowledge that is applicable to the study of technology reuse. This section presents theory on how knowledge can be characterized and classified, as well as how companies can work to manage and make use of it effectively.

2.4.1 Defining knowledge

Even if many great thinkers throughout history have defined knowledge, no clear consensus has emerged on what it encompasses (Grant, 1996b). However, a distinction is usually made between data, information and knowledge. Data represents facts that are not explained with context and rationale, and it is usually found as entries in a structured record (Davenport & Prusak, 1998). Information is data combined with meaning (Zack, 1999), often found in the form of e.g. a document that conveys a message to receivers that changes how they perceive something (Davenport & Prusak, 1998). Knowledge lacks a clear definition, but for the purpose of this thesis it is enough to note that knowledge comes in many forms and is tightly connected with the people who are knowledgeable, as well as their experiences, values and insights (Davenport & Prusak, 1998) that make information meaningful (Zack, 1999). Although this thesis could actively use the distinction between these terms, for simplification the term knowledge is used to encompass a mix of data, information and knowledge. For example, a document with information could be perceived as knowledge in a pre-state, since the application of transferred information and data commonly requires a transformation to knowledge at the receiver.

There are many ways of categorizing knowledge that are useful for bringing clarity and for choosing correct mechanisms for managing different types of knowledge elements. Perhaps the most common distinction is that between tacit and explicit knowledge, which is a classification of the extent to which a knowledge element can be expressed, codified and stored (Nonaka, 1994). There is disagreement on the relative importance of these two types (Markus, 2001), but different strategies are needed to support their reuse (Yeung & Holden, 2000; Ćatić, 2011). While explicit knowledge can be codified and transferred using documents and databases, tacit knowledge transfer relies to a great extent on direct communication between individuals or 'learning-by-doing' (Nonaka, 1994).

Knowledge that helps a reuser to make direct progress on a task or project has been referred to as 'actionable knowledge', which can be categorized into five different components: (1) solutions, (2) referrals, (3) problem reformulation, (4) validation, and (5) legitimation (Cross & Sproull, 2004). 'Solutions' include know-what and know-how that directly answer the questions from knowledge seekers. 'Referrals' is knowledge about where to direct a knowledge seeker with pointers to relevant documents or people. 'Problem reformulation' is knowledge provided as a back and forth discussion to help a knowledge seeker to redefine their problems and elaborate on the factors that need to be addressed to solve them. 'Validation' and 'legitimation' are similar, where the former refers to an expert giving feedback on the correctness of a proposed solution and the latter is about getting an expert's support for convincing other stakeholders to trust the solution or information at hand.

Knowledge is also commonly categorized as either declarative (know-what) that describes the state of something, procedural (know-how) that describes a process, how to do something (Kogut & Zander, 1992) or causal (know-why) that describes why something occurs or occurred (Zack, 1999). Declarative knowledge has been linked to explicit knowledge and is arguably easier to transfer to others and codify in documents (Grant, 1996b; Brown & Duguid, 1998). While procedural knowledge can be codified as process-steps and practices, it also has elements of tacit knowledge that are acquired only by extensive experience and learning-by-doing (Garud, 1997).

2.4.2 Knowledge reusers

Collecting and storing knowledge does not create value in itself. Instead the value is realized when the knowledge is retrieved and applied to support a new decision or activity. Hence, the knowledge needed by reusers and the way they would prefer to access it are critical requirements when designing an effective knowledge management system.

Markus (2001) divides knowledge reusers into four different types based on the distance between the source and the recipient of knowledge. She argues that these types have different needs when it comes to reusing codified knowledge and will be subjected to different kinds of problems when trying to do so. Shared Work Producers need to keep track of progress for ongoing work, access the rationale for previous decisions and learn how to improve their ways of working. Shared Work Practitioners, on the other hand, are mainly looking to learn from others how to manage a new and challenging situation and get inspiration for coming up with new solutions. Expert-Seeking Novices typically look to solve an unusual problem that they face or improve their performance in a field where they can learn from an expert. Secondary Knowledge Miners are working to answer new questions that may differ substantially from the work of the knowledge producers. Table II lists these different types of knowledge reusers and recommendations on how to supply them with appropriate knowledge content.

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

Type of Reuser	Description	Recommendations to Improve Reuse
Shared Work Producers	Reusers that have worked together with the knowledge source. These reusers will typically have 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 detailed content that other reusers could misinterpret.
Shared Work Practitioners	People who do similar work as the knowledge source but in a different setting. Since they share the general knowledge in their field of expertise they normally have little difficulty assimilating the reused 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 that they are not themselves knowledgeable within. They may not know that they need advice at all, where to find it or how to interpret what they find for their problem at hand.	- Repackage and decontextualize knowledge, but keep the context to support recontextualization. - Make an effort to make the records understandable to novices. - Provide access to both experts and expertise. - Provide training to increase awareness of the existence of expertise.
Secondary Knowledge Miners	Reusers looking to develop new knowledge from existing records for a purpose that differs from the purpose of the authors of the records. Their main challenges are to locate the right repositories for their purposes and defining precisely what content they search for.	- Store context information as metadata. - Provide training in how the knowledge base is structured. - Provide general training in how to analyze and validate results.

Dixon (2000) identifies five types of knowledge transfer based on their characteristics on the following five factors: (1) whether it was the same or a different team that were going to use the knowledge, (2) if the task required transfer of tacit knowledge, (3) if the task could be considered routine or non-routine, (4) if the task was frequent or infrequent, and (5) if the knowledge would impact large parts of the organization or not. The five knowledge transfer types are summarized below:

- Serial Transfer: The same team applies tacit and explicit knowledge for executing a frequent and non-routine task.
- Near Transfer: A different team applies explicit knowledge for executing a frequent and routine task.
- Far Transfer: A different team applies tacit knowledge for executing a frequent and non-routine task.

- Strategic Transfer: A different team applies tacit and explicit knowledge to an infrequent, non-routine task that impacts large parts of the organization.
- Expert Transfer: A different team applies explicit knowledge to execute an infrequent routine task.

2.4.3 Mechanisms for transferring knowledge: codification and personification

There are a number of steps that need to be taken to transfer knowledge from the moment it is created to the moment it comes to use in a new application. This knowledge reuse process is framed with similar layouts by many different scholars and typically encompasses acquisition, refinement and packaging, storage, distribution, and reuse of knowledge (Zack, 1999; Markus, 2001). Knowledge can be routed from its creation to its reuse through either spoken form with what is called a 'personification strategy', or embodied in e.g. documents or software with a 'codification strategy' (Hansen et al., 1999).

For knowledge that is mature and reused frequently with relatively small variation, person-to-person communication between a knowledge provider and a knowledge seeker can be ineffective. Instead, the design task could be more or less automated by creating a software application (Baxter et al., 2007) or writing a manual that then conveys the knowledge to where it is used. However, for solving unstructured complex problems with many unknowns, one relies more on tacit knowledge that codified sources simply cannot convey, since the format lacks richness and does not lend itself to easy capture of rationale. For such problems, direct communication between knowledge providers, e.g. experts, and knowledge seekers is essential (Hansen et al., 1999; Stock & Tatikonda, 2000; McMahon et al., 2004). Also, there is a risk that too much knowledge is collected in digital repositories since it is so easy to do with modern Information Technology (IT) tools, leading to information overload and too high costs for finding and making use of the knowledge (Garud & Kumaraswamy, 2005).

The decision to go with either a personification strategy or a codification strategy is central to a knowledge management strategy, and should be aligned with the characteristics of the knowledge and with the business strategy. According to Zack (1999), determining what to make explicit and what to leave tacit is a fundamental challenge for organizations that affects competitive performance. Hansen et al. (1999) warn that trying to pursue both equally can have severe consequences, and state that the most effective firms they had studied had focused on one of them and used the other in a supporting role. A personification strategy could be supported by an IT system to help find the right person to contact and provide basic knowledge on a topic as input for the discussions. A codification strategy, on the other hand, could benefit from referring to document authors or other experts to support interpretation of the codified knowledge in cases where its application is not straightforward.

Garud and Kumaraswamy (2005, p.28) state that the knowledge system of an organization should include: "(1) an approach to knowledge creation that stresses the role of individuals, (2) a communities of practice approach that emphasizes informal relationships based on shared language and thought-worlds, and (3) a repositories-based approach that emphasizes codification and central storage of organizational knowledge." Similarly, McMahon et al. (2004) discuss five techniques for knowledge management that span across the personification-codification spectrum; (1) Communities of Practice, (2) Company Organization, (3) Computer-supported

Collaborative Work, (4) Information Systems, and (5) Knowledge-Based Engineering. They all have their roles and limitations in the management of knowledge, and the appropriate mix used in a knowledge management strategy will depend on the types of design activities that need to be supported.

2.4.4 Approaches to codification

Codified knowledge can be found in different types of systems, ranging from informal notes on paper to digital repositories of information to knowledge-based engineering tools that automate design tasks. There are also new approaches based on distributed and collaborative authorship, such as user-created articles collected in a "Wiki" platform, a format that became generally known through the rise of the Internet-based encyclopedia "Wikipedia". For engineering applications, Product Data Management systems are commonly used to systematically store information about the product portfolio and keep track of product designs, their revision histories and other supplementary information such as bills-of-material and production specifications.

Collections of knowledge that engineers use can be located in their personal storages, in files shared within a work group or in repositories shared on an organizational level (McMahon et al., 2004). Lowe et al. (2004) found that 'experts' and 'detail designers' had different profiles when it comes to the use and storage of information. While experts tended to use large volumes of text-based information stored in personal storages, detailed designers used limited amounts of information, often geometry-based, and relied more heavily on storages shared at a group or company level. Experts were also much more willing to search for information than were the designers. In a diary study on the information needs and modes of access for engineers working in engineering design projects, Wild (2010) found that most of the times a document is accessed, it is to retrieve data, answer a question or to learn something. Recurring purposes for accessing documents, but not as frequent, were finding a figure or image, fresh up one's own memory, or to support discussion.

Yeung and Holden (2000) argue that IT is important for knowledge reuse because it packages explicit knowledge and makes it possible to distribute in larger scale. In order to do so, IT should support the following enablers:

(1) Discovery: Make knowledge accessible to users who search for it.
(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 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.

Besides choosing relevant content for representing in digital repositories, it is vital to consider two common hurdles to making such repositories effective: the willingness of employees to contribute to them, and the rate at which users access and use them (Watson & Hewett, 2006). These concerns can be addressed by increasing the perceived value of the system to its users, which is mainly related to how updated and trustworthy the information is, and how easily one can find something useful (Watson & Hewett, 2006). In the conclusions from their case study of a company renowned for their knowledge management initiatives, Garud and Kumaraswamy (2005, p.29) propose the following question for future exploration: “How might knowledge be represented to enhance the propensity of employees to reuse codified knowledge from digital repositories?”.

There are two main strategies to find the knowledge one is looking for in digital repositories: search engines with free-text queries or browse through a hierarchical classification scheme, each with its benefits and limitations (McMahon et al., 2004). Searches require that the users identify adequate search terms and scopes in order to receive relevant results in a manageable amount. With browsing through classification schemes, there are risks such as knowledge matching several or no categories, that users do not know the schemes well enough or that there is an impractical amount of layers in the scheme if the collection of knowledge is large.

There are different triggers and processes for creating codified content for future knowledge reuse. Markus (2001) identifies four typical approaches that differ in terms of how much additional effort is made to facilitate the retrieval and adaptation of the knowledge; (1) unintentionally as a by-product of normal work, (2) as output of formal knowledge generation or knowledge transfer methods such as brainstorming, (3) through deliberate recording by means of structured formats such as test reports, and finally, (4) by spearheading initiatives to gather and index old records into reusable knowledge packets. Depending on the needs of knowledge reusers, either of these approaches may be adequate for balancing the required upfront effort and the ease of reusing the documented knowledge for a given case.

In some instances, investments in knowledge sharing may not be worthwhile since the costs associated with creating the IT infrastructure and getting people to use it may exceed the benefits of the knowledge exchange (Levine & Prietula, 2012). Although IT has advanced to a state where retrieval and reuse of knowledge from digital repositories is much easier than it used to be (Garud & Kumaraswamy, 2005), IT in itself is not enough to gain competitive advantage. It needs to also be tuned to the prevailing human and organizational aspects (Real et al., 2006). While many knowledge management initiatives are focused on perfecting information technology solutions, Zack (1999, p.55) contrasts this common perception: “the technology need not be complex or leading edge to provide significant benefits. Its absence, however, would seriously impinge on the efforts of these companies to effectively manage their knowledge assets”.

The records in an information repository face different requirements depending on whether it is oneself or someone else who is expected to read them later on. Markus (2001) distinguishes between records created for oneself, those created for similar others, i.e. other people with similar knowledge profiles, and dissimilar others, i.e. other people who have different roles and backgrounds to the authors. When documenting for oneself, it can suffice with simple notes or data that help remember details that are believed to be useful later and these are commonly created as a by-product of normal work. Hence, there is a bias toward taking notes for short-term purposes rather than long-term, also since it may be difficult to predict what will be useful in the future. When documenting for others, the records need to be shaped and explained in a way that makes sense for someone who is not fully aware of the context in which the knowledge was created, which requires more effort and at the same time carries less intrinsic incentives for the authors. The more dissimilar the reader, the more the records need to be trimmed from specifics that novices in the knowledge domain would not be able to comprehend. Records for dissimilar others also need to be clear about underlying assumptions that experts would take for granted, but that may be overlooked by someone who is new to the field in order to avoid misuse of the knowledge. For this reason, it may be advisable to avoid sharing certain records outside of specialized teams who know how to interpret them.

Knowledge repositories based on Web 2.0 solutions, such as blogs and Wikis, have been proposed as new means of facilitating knowledge sharing, and some have even suggested such repositories can be used for transferring tacit knowledge (Standing & Kiniti, 2011). Yates et al. (2010, p.543) describe Wikis as “sets of dynamically created Web pages with content contributed directly by users in a Web browser”. These repositories build upon the idea that users collaboratively create the content (Majchrzak et al., 2013) and require a culture of sharing and collaboration, as well as ease of use, in order to supply the intended effects (Standing & Kiniti, 2011). It has been reported that some individuals tend to 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).

2.4.5 Summary

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

- The term ‘knowledge’ can mean different things, and many classifications are used to distinguish between different kinds of knowledge. E.g., knowledge can be tacit or explicit (Nonaka, 1994), and declarative, procedural or causal (Zack, 1999).
- Knowledge can be transferred through either codification or personification mechanisms and a system for managing knowledge should support both, e.g. using organized central knowledge repositories and communities of practice (Hansen et al., 1999; Zack, 1999; McMahon et al., 2004; Garud & Kumaraswamy, 2005). Deciding when to use either codification or personification is a fundamental challenge (Zack, 1999). Regardless of which is chosen, to focus on one and use the other in a supporting role appears to be an effective setup (Hansen et al., 1999).
- There is a host of different formats for codified knowledge, ranging from informal notes to highly structured databases. These records can exist in personal storages, be shared within work groups or shared on an organizational level (McMahon et al., 2004). While records are typically created by specific authors, they may also be created collectively by its readers as in the case of Wikis (Standing & Kiniti, 2011).
- With the use of IT, retrieval and reuse of knowledge is much easier than it was in the past (Garud & Kumaraswamy, 2005) since IT makes it possible to package and distribute explicit knowledge on a large scale (Yeung & Holden, 2000). However, in some cases the costs of setting up an IT infrastructure and getting people to use it may exceed its benefits (Levine & Prietula, 2012). On the other hand, a simple IT design can go a long way, since the most severe problems arise when having no IT solution at all (Zack, 1999).

- The two main strategies for allowing users to find the right content in a repository are searching and browsing through a predefined classification scheme (McMahon et al., 2004).
- In order to be effective, IT needs to be in tune with human and organizational aspects (Real et al., 2006) and support a range of functions. It should allow people to discover which knowledge exists, provide content that is filtered and refined to avoid cognitive overload, organize and store content, allow people to find one another, and make it possible to distribute knowledge on an organizational scale (Yeung & Holden, 2000). In order to be perceived as useful, the content needs to be updated, trustworthy and easy to find (Watson & Hewett, 2006). Hence, a critical question for designers of digital repositories is how to represent knowledge in a way that increases the inclination of people to reuse the knowledge (Garud & Kumaraswamy, 2005) and contribute what they know (Watson & Hewett, 2006).
- The design of knowledge reuse support should also account for who the knowledge reusers are. E.g., if reusers are already knowledgeable about a topic of interest, there is less need to decontextualize the knowledge and explain any underlying assumptions (Markus, 2001). It is useful to categorize reusers according to their relation to the creators of the knowledge: those part of the team who produced the knowledge, people working with similar activities elsewhere, novices seeking expert support, or people mining existing records for different purposes (Markus, 2001).
- The flow of knowledge from its creation to its reuse can be seen as a process consisting of the following stages: acquisition or creation, refinement and packaging, storage, distribution, and reuse (Zack, 1999). Knowledge records can be created from activities that differ in the level of effort made to support reuse: unintentionally as a by-product of normal work, as output from formal knowledge creating methods, by deliberately recording on structured formats, or by repackaging existing records into reusable knowledge packages (Markus, 2001).
- Domain experts use more text-based media and personal storage when documenting and retrieving knowledge than do detailed designers, who tend to use graphical media in shared repositories (Lowe et al., 2004).
- Individual motivation is a common issue for successful knowledge reuse since the effort and cost of creating reusable assets are paid by the creators, whereas the benefits are realized by the reusers. The further away the reusers are, the less intrinsic motivation the creators experience for documenting their knowledge (Markus, 2001).

To manage knowledge effectively, the strategy and methods employed need to be attuned to the characteristics of the knowledge and the needs of the knowledge reusers. The abstract and tacit knowledge often embodied in technologies will likely require much direct communication between technology experts and knowledge reusers. However, there are many opportunities for supporting knowledge reuse with codified mechanisms, but how such a system can be designed for technological knowledge in a way that leverages the costs for creating and maintaining it and that makes employees want to use is not clear from the literature.

2.5 Research Questions

Previous research on why and how companies can benefit from the reuse of technological capabilities has mostly focused on firm level issues, proposing generic management strategies for technology-based companies. Other fields of research provide insights into the challenges of applying reuse strategies and knowledge reuse practices on an operational level, but not explicitly for the purpose of, or with consideration to, the unique characteristics of technologies. The research questions (RQs) have been posed to address this research gap and explore how technology platforms can support the reuse of technological knowledge in practice.

The wordings of the research questions have evolved over the course of this research project. Consequently, the current version is partially based on the results of the early studies conducted, since they increased understanding for what research questions are relevant and not already answered in extant literature. However, the research questions have been fairly stable and since early versions, they have included such themes as learning, collecting information and managing technologies as resources.

RQ1: What barriers to efficient reuse of technologies can be identified at the engineering level within companies?

The first research question reflects an exploratory element of the research in which the problem of managing technology reuse is investigated more deeply to understand existing needs for support. There are sound arguments in the literature for working strategically with portfolio techniques and platform development for technologies, but there is a need for additional insight into what constitutes a capability at the engineering level to effectively reuse technologies. Further, it is not clear how the engineering and knowledge management methods can be put into practice for technology development, and what the reasons may be as to why technology reuse is still perceived as a challenge in industry.

RQ2: How can a company organize its technological knowledge to make it more accessible to internal reusers?

The second research question focuses on how to support reuse from the perspective of the reuser, i.e. how to support development that reuses technologies from previous applications. Technologies primarily exist as knowledge in different forms. Reusing technologies is thus dependent on acquiring access to the knowledge about them, which may be difficult to locate and transfer. The limitations in access to technological knowledge were found to be a significant barrier to reuse during the quest for an answer to RQ1, and were, therefore, deemed relevant for further investigations.

RQ3: How can the feasibility of reusing technologies in new applications be assessed in order to predict and prevent potential complications?

It is a fallacy to believe that a technology proven in one application can easily be integrated in another. Technical optimism or ignorance to the differences in context between the two applications may fuel this fallacy, which can potentially lead to development projects that either get delayed, run over budget or fail altogether. A condition for becoming successful in reusing technology is thus to make decisions about reuse that are well informed about the prospects for success and how to mitigate potential challenges in the reuse process. The purpose of RQ3 is to identify factors that need consideration when making these decisions and prescribe ways to support their assessment in practice.

3 RESEARCH APPROACH

The work presented in this thesis has taken place within the Department of Product and Production Development at Chalmers University of Technology. The department has undergone a transition from mainly dealing with Engineering Science, i.e. the study of applied physics such as materials and mechanics, to focusing more on Design Research and solving issues that require the integration of multiple engineering disciplines.

Both of the research projects that this work has been conducted within have focused on developing support for managerial and engineering related challenges, which is reflected in the research questions. This led the research to be conducted within two related but distinct scientific disciplines: 'Design Research' and 'Management Research' (or 'Business Research'), albeit with the primary focus to contribute to the former. Design Research aims to increase understanding of the phenomenon of 'design' and propose methods and tools that can improve the efficiency and effectiveness of design practice (Blessing & Chakrabarti, 2009). It is clearly positioned as an applied science since it strives to not only understand problems, but also to develop solutions to them. Although there is more disagreement within the closely related field of Management Research about the importance of applying knowledge into practice, its aim is also twofold; to improve understanding of organizations and solve problems related to managerial practice (Bryman & Bell, 2007).

The research has been guided by a methodology for Design Research and has used case studies and development of engineering support as the general methods, with semi-structured interviews, observations and document analysis as the primary data collection methods. This chapter starts by presenting theory on how to design the type of research conducted and ensure that it has good quality. After, the applied research approach and the methods that have been used for each study are described in detail. An evaluation of the results from a quality perspective is presented later in the thesis (Chapter 5.2).

3.1 Research Design

The research design has been chosen to reflect that this work has primarily been concerned with contributing to the academic field of Design Research. To explain the strategy behind the research, two methodological frameworks for research design are discussed. These frameworks have worked as inspiration and general guidelines for the research. They have been shaping the general practice of research within our department, which in turn has provided the foundation for the research approach applied.

3.1.1 Interactive Model of Research Design

The Interactive Model of Research Design by Maxwell (2005) includes five components to be addressed when designing qualitative research (Figure 11). Maxwell argues that rather than sequentially planning the components and their logic, an iterative process is needed in order to capture the integrative effects between them. Adjustments may also be needed as research is conducted to improve the fit between research strategy and the environment studied. The arrows between the components stress the importance of linking them to create a coherent whole. The elements forming the upper triangle establish the contribution sought by means of the project. This subgroup of components emphasizes that goals shall be relevant in relation to the existing theory, or ‘conceptual framework’, and that research questions shall point to areas that are interesting for extending current knowledge given these goals. When addressing the bottom triangle of the model, one should choose methods capable of answering the research questions and validate these answers for correctness.

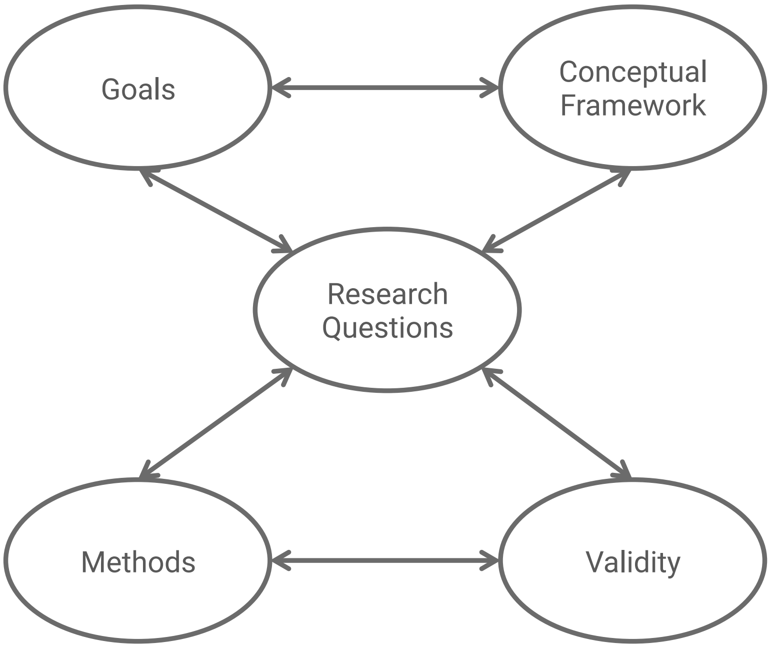

Figure 11. Interactive Model of Research Design (Adapted from Maxwell, 2005).

3.1.2 Design Research Methodology

Blessing and Chakrabarti (2009) propose a specific methodology for conducting research on topics related to ‘design’, i.e. conducting ‘design research’. Here, design is broadly defined as the activities involved in product development, from a perceived need to a finished design. The authors argue that in order to contribute to both practical and academic communities, design research should strive to fulfill two purposes: to understand the object studied and to propose tools, methods, or guidelines useful to practitioners. Hence, there is greater focus than in many other research fields on the creative role of the researcher in designing new ways to deal with the issues studied.

The Design Research Methodology (DRM) is a framework that includes four activities that are explained further below (Figure 12): (1) Research Clarification, (2) Descriptive Study I, (3) Prescriptive Study, and (4) Descriptive Study II. The first activity of DRM is to clarify the ideas and assumptions that initiated the research project and formulate a goal for subsequent activities. The second activity is to find literature or empirical data to understand the object of study, which is often a problem recurrent in industry related to the design process. The third activity is to create tools, processes, methods or guidelines as proposed solutions to the problem studied. This third activity is a prescriptive phase involving a creative step that cannot be derived directly from empirical evidence. However, a systematic design process is proposed by the authors for guiding the development of such support. The fourth and final activity is to test the support in a real or representative environment and describe its effect in terms of actual and intended outcomes. Iterations among the steps are generally required since additional understanding provides feedback that may question earlier assumptions.

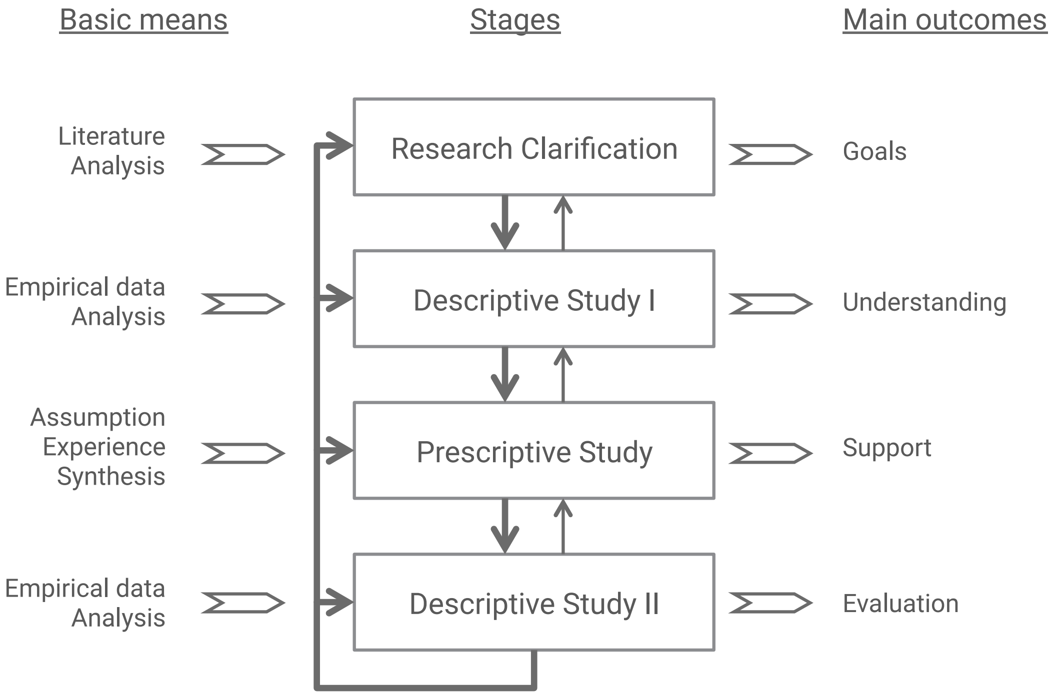

Figure 12. The Design Research Methodology framework (Blessing & Chakrabarti, 2009).

All the stages of the DRM framework are not necessarily performed within a research project, especially not in-depth. Depending on the existence of previous literature and the scope of the project, a stage can be performed by literature review only, comprehensively by the researcher, or as initial work that takes a few steps toward fulfilling the requirements of the stage.

3.2 Quality Criteria

Qualitative research in general and case studies in particular should be analyzed for reliability and validity to address their scientific contribution (Yin, 1994; Blessing & Chakrabarti, 2009). This section presents the theory on how to address reliability and validity in the type of research that has been conducted, while Chapter 5.2 presents the evaluation of the quality of this research.

Reliability as a concept for the verification of research deals with the reproducibility of a result or measurement (Yin, 1994; Blessing & Chakrabarti, 2009). Bryman and Bell (2007) distinguish between three forms of reliability: stability, internal reliability and inter-observer reliability. With stability, measures or tests can be repeated with the same results under equal conditions, provided that the first test does not influence the results of subsequent tests. Discussing case study research, Yin (1994) stresses the importance of documenting the procedure used for conducting the research as a way to improve reliability. Internal reliability means that multiple measures used for the same construct actually measure it. Otherwise, the measures will not correlate and cannot be used to attribute a single score to the variable measured. The last form of reliability, inter-observer reliability, represents the consistency with which multiple observers perceive and categorize a subjective measure, e.g. when analyzing open-ended questions from an interview.

Validity can be interpreted as the quality of the relationship between reality and the descriptions, interpretations and conclusions generated from the research. While full validity cannot be achieved, it is useful to have as a goal (Maxwell, 2005). It is helpful to discriminate between internal validity, i.e. the fit between observations and the theory derived from them, and external validity, which is the ability to generalize findings to settings other than those provided by the data (Bryman & Bell, 2007).

Due to small sample sizes, case studies are inherently weaker for attaining external validity than large-sample cross-case studies (Gerring, 2007). Hence, case studies are typically used for exploration and hypothesis generation rather than for hypothesis testing, something that makes them more sensitive to internal validity threats. Nonetheless, it is imperative that the implication of case studies be analyzed in relation to a larger population in order to integrate them into other studies in the field (Gerring, 2007). Consequently, when conducting an exploratory case study, consideration should be given to what the case represents, in addition to preferably testing the hypotheses generated by using subsequent cross-case studies (Gerring, 2007).

Internal validity mainly concerns claims about causality of identified relationships between measures (Blessing & Chakrabarti, 2009). When comparing observations, e.g. between groups or over time, there may be several potential causes for any differences between them. To support internal validity, it is therefore important to account for alternative explanations when drawing conclusions about causes and effects (Yin, 1994; Blessing & Chakrabarti, 2009).

Maxwell (2005) identifies two types of threats to internal validity that are particularly important in qualitative research: researcher bias and reactivity. The first threat, researcher bias, is a threat to the objectivity of the research and manifests itself through the selection of data by researchers that fit their preconceptions or that catch their attention based on previous knowledge. Although researchers always bring their perspective based on previous knowledge and beliefs, the threat to research validity can be limited by raising an awareness thereof and reflecting on what these preconditions might be and how they might affect the research (Maxwell, 2005). By being transparent on the way interviewees were selected, the number who were interviewed and the roles they occupied in the organization studied, the possibility of evaluating representativeness of the conclusions drawn would improve (Bryman & Bell, 2007). The second threat is reactivity, which concerns the effect that a researcher has on the individuals studied. It is especially relevant in interview studies where the interaction may influence the answers (Maxwell, 2005). Fortunately, there are a couple of ways to limit this influence, e.g. avoiding leading questions (Maxwell, 2005), and letting the interviewees comment on the transcriptions and conclusions (Bryman & Bell, 2007), which is also a remedy to reliability threats (Yin, 1994).

Besides internal and external validity, some authors also distinguish a third type of validity, called construct validity (Yin, 1994; Blessing & Chakrabarti, 2009). It is concerned with whether the characteristics that are measured actually say something about the concepts that the research wants to study. Problems with construct validity arise primarily from inadequate definition of concepts, but also from biased data collection, e.g. if the researcher poses leading questions in interviews or influences the participants of the study in other ways (Blessing & Chakrabarti, 2009).

Maxwell (2005) recommends eight techniques 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,** through e.g. 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 effects of proposed solutions.
5. **Searching for disconfirming evidence** 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. **Quasi-statistics,** whereby quantitative claims can be tested and data made more explicit.
8. **Comparisons**, e.g. using multiple case studies, which provide the opportunity to isolate variables in order to study causality.

3.3 Applied Research Methodology

This section starts by positioning this research in relation to theory on research methodology, after which an overview is presented of the process leading up to the results in this thesis and how they relate to each other. Finally, the methods used in each of the performed studies to answer the research questions are explained in more detail.

3.3.1 Research design

This research has reiterated the components of the upper triangle in the Interactive Model of Research Design (Maxwell, 2005) multiple times to find a common ground for the industrial need—or goal—behind the research proposal and existing literature about technology reuse. Earlier versions of the research questions targeted topics that were both too detailed and too generic, whereas the current version takes a holistic perspective and includes both exploration of the underlying problems in the studied topic (RQ1) and prescription of ways to address them (RQ2 and RQ3).

The studied topic of interest called for deeper understanding of the real-life context of engineers in order to extend the existing literature on technology platforms, and sought to explore what might be important factors that affect technology reuse. This favored the use of qualitative case study research, seeking to generate hypotheses rather than testing existing ones (Yin, 1994; Gerring, 2007). The setup of the research project as a partnership with the case company also gave access to detailed inquiry about the topic in a real setting. This access to data was the main rationale for selecting a single case design, i.e. an opportunity to study a situation otherwise inaccessible to researchers, which Yin (1994) refers to as a 'revelatory case'. GKNA has been described as a company typical of the aero industry (Högman, 2011), which also provides some rationale for regarding the case as 'typical' (Gerring, 2007). However, a more extensive cross-case analysis would have been necessary to infer that the chosen case company is typical in aspects relevant to this study.

Data were collected using semi-structured interviews, document analysis, informal meetings, internal seminars at the case company, and reviews of existent literature. Analyses were often based on the coding of statements in the interview transcripts and identification of patterns, as well as 'thought experiments' using both results from the case studies and from previous research found in the literature. These methods, which are described further below in relation to each study, led to proposed answers to the research questions, i.e. they generated new hypotheses (Gerring, 2007). This, in turn, led to propositions for future research employing methods better suited to test external validity of the findings and evaluate the proposed methods and tools in a 'Descriptive Phase II' of the DRM (Blessing & Chakrabarti, 2009). Hence, this thesis is a step along the way towards answering the generic research questions, opening up for future research that pursues similar goals.

3.3.2 The research process

The ideas behind the research of this thesis came from a well understood empirical setting, i.e. the case company, with clear goals for the intended outcome. However, the understanding was largely based on the experience of researcher Ulf Högman who had been working at the company for many years. Hence, my first step was to identify and describe the situation through additional studies together with him and other colleagues, both for their academic relevance and for improving my own understanding, which corresponded to the first descriptive phase in the DRM framework (Blessing & Chakrabarti, 2009). Two interview studies filled this purpose and used an inductive approach with case studies (Bryman & Bell, 2007) to generate theory on the topic. These are reported on in appended Papers A and B.

Based on the descriptive findings from the first interview study, a prescriptive phase of the research followed where a knowledge repository for technologies was developed as a proposed tool in response to the second research question. Paper B also describes the tool and the feedback provided by the case company during workshops and interviews where the tool was discussed.

Testing the tool further would have required action research, or other forms of validation in interaction with intended users, which was not available to the research group. Instead, the research took a step back to look at other ways of supporting the overall research goal, representing a return to 'Research Clarification' in the DRM (Blessing & Chakrabarti, 2009), which resulted in the pursuit of three different branches of the research area.

One of the branches was to identify other streams of previous research that are applicable to technology reuse, which was conducted as a literature study and supplied content to the Frame of Reference Chapter in this thesis. This study helped frame the problem on a higher level and to position the specific contributions of this thesis in a larger context.

Another branch supported the second research question by relating the work to integrated product platform approaches, which was ongoing research at the department from which this research was a spin-off. Paper C elaborates on how a process for product platform development can integrate technology development, product development and production development, while Paper D explores more deeply how technologies can be modeled in information systems to allow the product concept configurators that are proposed in Paper C to use parameters from technological knowledge.

The third branch was initiated as a response to a problem that was identified in the first interview studies and then seconded by other companies that were contacted during this research. The problem addressed was how to ensure that technologies that the company masters are in fact applicable for reuse in a new application, which also led to the formulation of the third research question. Based on a review of literature and discussions with the case company, Paper E proposes a method for technology reuse assessments that besides its prescriptive elements also makes a preliminary evaluation as a 'Descriptive Study II' (Blessing & Chakrabarti, 2009). This evaluation was continued after the writing of Paper E, but those results have not yet been published.

Table III summarizes the studies conducted within this research, presented in chronological order, including how they map to the stages of design research in the DRM framework (Blessing & Chakrabarti, 2009) and relate to the research questions.

3.3.3 Study 1: Interview study for Paper A

Paper A is based on the first interview study conducted. It examined technology transfer at the case company in order to improve the understanding of current practices and make way for improvements of processes. Data were collected from 22 semi-structured interviews, document analyses, and recurring informal discussions with employees from the Technology and Product Development Departments. This enabled an examination of the highly contingent context in which technology development is performed, leading to difficulties identified by those working on the processes. Much of the interview material was reused from a previous study on technology transfer at the case company that had been performed by Bengtsson and Stetz (2009), covering all types of technologies. Five additional interviews were performed in 2010; since manufacturing methods were regarded as the most difficult technologies to transfer and were common among the technology development projects, these interviews primarily focused on manufacturing technologies. While many of the findings were valid for all types of technologies, this focus on manufacturing technologies may have affected which issues that were regarded by the interviewees as most important and what types of documents that were delivered from the technology development projects. The recordings of all interviews were transcribed and relevant statements extracted and categorized. Technical documents and process descriptions of technology development were also studied in order to supplement interview data and gain deeper insight into development activities.

Table III. Overview of the conducted studies and their relations to the research questions. Entries between parentheses are partly fulfilled or related.

Study	**Purpose**	**DRM phase**	**Data collection methods used**	**Resulting paper**	**Related RQs**
Study 1: Case study	Understand deliverables from technology development	DS-I	Semi-structured interviews, document analysis, informal discussions	Paper A	RQ1, (RQ2)
Study 2: Case study, support development	Learn how information about technologies is stored and retrieved at the case company and test a support tool for organizing technological knowledge	DS-I, PS, (DS-II)	Semi-structured interviews, observations of workshops and meetings, document analysis	Paper B	RQ1, RQ2
Study 3: Literature review	Identify prior research related to technology reuse and create a framework for the studied topic	RC, DS-I	Literature review	(Corin Stig, 2013)	(RQ1), (RQ2), (RQ3)
Study 4: Support development, case study	Develop a methodology for integrating various levels of platform thinking	PS	Discussions with case company during workshops and meetings, document analysis	Paper C	RQ2
Study 5: Support development, literature review	Develop and test a support for assessing technology reuse feasibility	PS, (DS-II)	Literature review, discussions with case company, semi-structured interviews	Paper E	(RQ1) RQ3
Study 6: Support development	Develop an information model for technologies to support the platform methodology in Paper C	PS	Use of a case from literature for illustrative purposes	Paper D	RQ2

3.3.4 Study 2: Interview study and support development for Paper B

The purpose of the second interview study was to learn how information about technologies is stored and retrieved at the case company and test a support tool for organizing technological knowledge. Data were collected from previous observations of meetings, workshops and presentations, as well as from twelve new semi-structured interviews. The interviews lasted for about 90 minutes and focused on technology information, platforms and IT support. The interviewees were chosen from the development organization based on recommendations from the primary contact persons for the research project at the case company, who had good insight into both the research and which employees would be able to supply relevant answers. The interviewees occupied such roles as technology developers, manufacturing method "owners" or managers from either the project or line organization. All interviews were recorded and transcribed and transcriptions were sent to the interviewees for correction. The transcriptions were then analyzed by highlighting relevant sections from which common themes were identified. The transcriptions were then reviewed again to find and classify statements that related to the identified themes.

Before the interviews, a demonstrator for a knowledge inventory of technologies was developed using Wiki software. The design was chosen based on findings from Study 1 and the second author's previous studies at the case company as a hypothesis on how technological knowledge could be organized to increase awareness and access that facilitate reuse. The demonstrator was shown at the end of the twelve interviews to get feedback on its design and potential usefulness.

3.3.5 Study 3: Literature review for Frame of Reference

A literature study was conducted partly as a structured effort to create a framework for technology platforms based on prior research on technology reuse and flexibility, and partly with a snowball strategy of reviewing literature related to technology reuse and their references over an extended period of time. Research covered in the study was found in the areas of technology development, technology transfer, design reuse, and knowledge management. Different practices mentioned in the reviewed literature were collected in a list and then synthesized through various stages of matching, organizing and categorizing in a spreadsheet. The results from Study 3 helped shape the work and the Frame of Reference Chapter. The literature review also resulted in a paper that defines three views of a technology platform: portfolio, catalog and toolbox (Corin Stig, 2013).

3.3.6 Study 4: Support development and case study for Paper C

Paper C proposed an holistic approach to platform development based on the ideas collected and tools developed within our Systems Engineering and PLM Research Group. The theoretical work mainly contributed the integration of the various components of the proposed approach, developed through joint discussions and writing sessions among the authors. The case of configuring an existing product concept at the case company was used to exemplify the approach, which was developed through extended collaboration between the authors and the case company primarily through workshops, meetings and sharing of case specifications in presentation slides.

3.3.7 Study 5: Literature review, support development and initial tests for Paper E

Paper E is based on a review of literature in technology management and knowledge transfer, which presented a host of enablers and challenges for successfully applying technology in different contexts. A couple of papers was found that together summarizes and synthesizes much literature until around the year 2000 in the topic of interest (Stock & Tatikonda, 2000; Cummings & Teng, 2003). These papers were used as a baseline together with the sources they cited. A separate search was then performed to find newer articles that referenced to any of them.

The factors identified from the literature review were then used as possible dimensions for creating an assessment tool. The first prototype of the assessment tool was a “long list” version featuring around 25 dimensions. Some of the dimensions overlapped and many of them were considered too complex to be used by practitioners. The set of dimensions was reworked in two stages, first to eleven dimensions and then further down to the final six dimensions of Technical Readiness and Capability Transfer Readiness.

The tool was developed through multiple iterations where feedback was provided by a technology expert and two technology managers at the case company GKNA during approximately 8-10 meetings. The first complete versions of the assessment were discussed during four interviews with technology experts at GKNA, from which a few adjustments were made to its design.

3.3.8 Study 6: Support development for Paper D

Paper D extends the work in Paper C by further exploring how technologies can be modeled in a product data environment to support integration with product platform development. Literature on technology management and product modeling, as well as the authors’ experience from working with the case company, was used as input to the development work. The results were an information model for technologies and a process for using that information model to support technology integration during platform-based development. A case was reused from a previous publication (Högman, 2011) to illustrate how the information model and the prescribed process could be used to support technology integration in a realistic scenario as a form of logical verification of the ideas.

4 SUMMARY OF APPENDED PAPERS

The five appended papers cover different aspects of how to leverage the potential for internal technology reuse by attempting to answer the three research questions. The same case company was studied from various perspectives, which helped finding coherence among the findings and proposed solutions. This chapter presents the highlights from each appended paper, followed by a summary of the key contributions from each paper in relation to the research questions that they have attempted to answer.

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

Paper A explores the process of transferring technologies from technology development to product development, revealing barriers for both the transfer of technological knowledge and for integrating technologies into products.

Paper B explores ways in which developers and managers access information about technologies and evaluates a hypothetical solution improving access by means of a Wiki-based technology catalog.

Paper C presents an envisioned development approach that integrates technology platforms with product platforms through the use of organized repositories of technological knowledge to supply input to the computer-supported generation and analysis of new product concepts.

Paper D continues the work of Paper C by extending the use case for 'technology-based configurable platforms' to include introduction of new technologies in the platform models. The paper proposes the use of an information model to represent technologies in Product Lifecycle Management (PLM) systems featuring relations to other technologies and components, in addition to information on technology characteristics and performance.

Paper E identifies requirements for the design of an assessment of technology reuse feasibility and then proposes an assessment method that could fulfill these requirements. The proposed method gathers relevant stakeholders in a workshop to jointly fill out a scorecard featuring nine dimensions derived from the literature as factors that influence the success of technology reuse.

4.1 Paper A

Title: *Assessment of Readiness for Internal Technology Transfer* (Corin Stig et al., 2011).

The purpose of Paper A was to explore how technology development results are transferred to product development to gain an insight into the processes that are useful for securing successful technology transfers. As described in Chapter 1.1, the case company develops and produces components and subsystems to the aerospace engine industry. In order to secure technology readiness before committing to integrating them in new products, the company had divided its development process into technology development and product development. The case provided a setting to study the challenges of deploying technologies and transferring knowledge between teams, which was assumed to be applicable to situations of redeployment of technologies as well. The data were collected through interviews, discussions and workshops with managers and developers, as well as by studying documentation of project objectives and development processes.

The company used a Stage-Gate process composed of six gates based on Technology Readiness Levels 1-6. The first stages were often passed already at the outset of their technology development projects, and the gate reviews typically started with TRL 3 or 4. The criteria for passing one of these gates were found in checklists based on an interpretation of the TRLs in Mankins (1995). In the documents studied, the fulfillment of these checklist criteria was one of the main goals when starting a new technology development project, something that was confirmed by the interviewees who perceived these checklists as a reference tool for deciding on deliverables from their projects. In addition, based on the arguments that risk reduction is crucial for success, while cost reduction often is the motive for development in the first place, interviewees believed that creating a robust and cost-efficient technology was the main objective of technology development.

When asked about the transfer process and the challenges inherent therein, the interviewees presented several factors that might pose a risk to successful transfers. These factors contribute to the answer to the first research question about barriers to technology reuse and may be categorized into the following: (1) knowledge transfer, (2) implementation readiness and (3) unclear goals. Concerning knowledge transfer, they emphasized the importance of proving training for the recipients of new technologies in addition to handing them documentation and instructions. Without proper training, there was a considerate risk that they would not be able to apply the technologies as intended but would rather have to deal with future problems emanating from this lack of training. Neither would they be confident in the performance of these technologies, increasing the risk that these new technologies be substituted for more proven ones instead.

Regarding the second risk to successful transfers, the gate assessment checklists used at the company thoroughly tested the degree to which a technology was understood. However, the checklists were not equally precise in testing whether an organization was prepared to start using a certain technology. The interviews revealed that many problems related to long lead times in product development and production were attributable to insufficient preparations in such areas as the education of operators, the purchase of equipment or the planning of production cells. These preparatory steps were not stated as objectives for the technology development projects and could typically not be initiated until there was a commitment for introducing the new technology into a specific project. This led us to the third risk of how to decide on technology development goals. Some technology development projects were designed to deliver results on a specific product, which enabled the transfer to start early by involving the recipients in the project. However, other technologies had been developed toward an anticipated future general need, i.e. no clear target for the delivery of results had been adopted and it had become impractical to prepare the organization for their introduction.

The paper concluded as implications for practice that these problems might likely be supported by solutions from the literature and from extensions of current practices.

One recommendation was to ensure that the transfer process starts well ahead of project completion and that some project members continue serving on the product development team. Another recommendation was to extend the assessment checklist to include more implementation-related criteria in order to ensure that technologies were ready to be introduced on time, as opposed to merely being understood well enough to trust their capability. Another factor affecting the assessment of how prepared an organization was in using a new technology was the difficulty of developing it beyond TRL 6, which is currently performed within the product development projects. A metric for addressing this difficulty of further development would provide a useful complement to TRLs when deciding on technology integration.

4.2 Paper B

Title: *Means for Internal Knowledge Reuse in Pre-Development – The Technology Platform Approach* (Corin Stig & Bergsjö, 2011).

The management at the case company perceived a need to become better at reusing technological knowledge across different products. This paper presents the results of a study to provide deeper understanding of the causes of the perceived need and to test our idea about how information about technologies might be captured and shared within a company.

A 'demonstrator' was developed that used Wiki software to create a web-based catalog of the technologies used within the company. The list of technologies was provided by the company, and a couple of sample pages were created to display the intent and type of content believed to be relevant based on previous experiences and discussions with the company (Figure 13). Twelve interviews were conducted to explore the need for, sources of, and barriers to locating technology information during technology and product development. Towards the end of the interviews, the demonstrator was shown and explained in order to get feedback on the format and its potential, as well as its drawbacks.

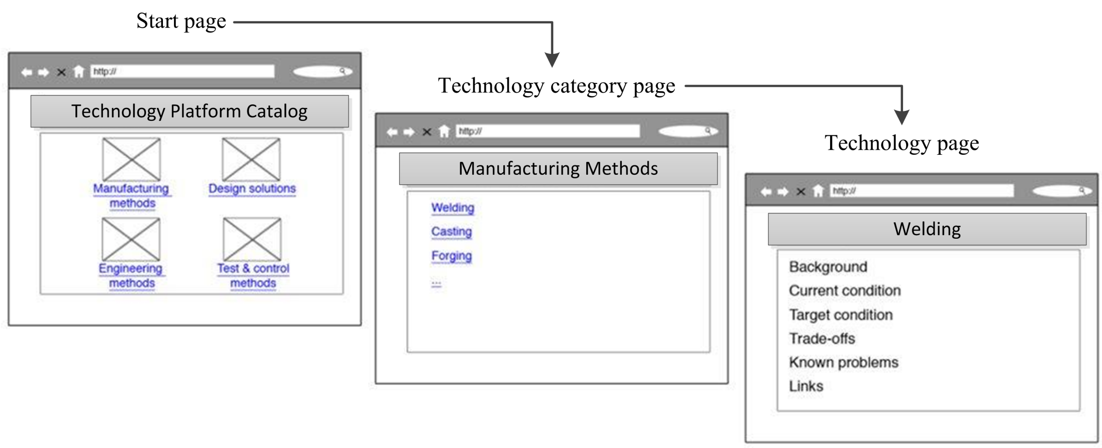

Figure 13. Overview of the Wiki catalog demonstrator.

The type of technology information sought by interviewees depended on their role in the organization. The managers wanted to get an overview of the technology portfolio from different perspectives, to keep track of the progress on current development projects and learn when new technologies would be available for implementation. Developers, on the other hand, were interested in getting detailed information on e.g. design guidelines and cost estimates for applying technologies to products. Technology developers and product planners were mainly interested in following the most recent activities on immature technologies and accessing knowledge about the possibilities and limitations of existing technologies.

The study showed that personal contacts within the organization were the sources of information used the most. The process of looking for new information in databases and reports was restricted by the limitations of internal search engines and strict permission rights to access certain documents. To find information in reports, the interviewees needed to be aware of their existence in order to search for the official names of reports or authors. Asking colleagues or using one's own previous work to gain access to information and knowledge about technologies worked reasonably well, but interviewees also believed that they missed out on useful information and that searches were too time-consuming.

When the demonstrator was shown towards the end of the interviews, the comments confirmed our belief that there was a lack of centralized high-level information about technologies within the company. Although the validity of interviewee support was restrained by a small sample, such a catalog was deemed useful for increasing awareness and understanding, as well as providing a starting point for finding detailed information. A couple of concerns were raised during the demonstrations: (1) how to assure that the information in the Wiki would be correct in a situation where multiple authors could contribute and there would be no review process before publication, (2) the fact that the core knowledge of the company would be collected in an open format might increase the risk that the information would be stolen or spread to competitors.

The conclusion of the study was that the opportunities for technology reuse could be improved by addressing and overcoming barriers to the use of codified knowledge. The following barriers were identified as contributions to the answer to the first research question: the low searchability for reports and other documents, the low level of technology awareness within the company, the lack of a starting point for learning about technologies, the restrictions in access to documentation due to client contracts and risk of theft.

In relation to the second research question, several findings from the case study influence how to organize technological knowledge: (1) the high reliance on personification for knowledge transfer, (2) an expressed need for more time or quicker-to-use tools for recording and refining knowledge, (3) the differences in types of knowledge sought by different stakeholders, (4) a wish for a starting point to access technological knowledge, (5) a wish for a place to publish general information about technologies, (6) a wish for ways to get in contact with others who have faced similar design problems, (7) a need for distinguishing between reviewed or ”proven” information and non-reviewed information, (8) concerns about redundancy of information if stored pertaining to both technologies in general and implementations of technologies in products, (9) a concern that a concentration of key knowledge in a repository could increase the risk that it spreads to competitors, and (10) limited interest in the collaborative nature of the Wiki format where multiple authors can contribute.

The proposed IT catalog was perceived as useful to begin to overcome the barriers and fulfill the expressed needs, and further research was deemed necessary to evaluate the benefits and limitations more closely to see what effects the catalog might have on the design of development processes and the need for other types of documentation.

4.3 Paper C

Title: *An Integrated Approach to Technology Platform and Product Platform Development* (Levandowski et al., 2013).

Paper C presented an approach that provided an extension of the concept of product platforms—which has mainly been focusing on the reuse of physical components in product family development—by also integrating the reuse of product concepts and technologies. These latter assets are also reusable but differ from reusable components in that they are more difficult to model and need to be adapted before implementation, thereby adding new requirements to development processes and knowledge management practices.

The prescribed approach constitutes a compilation of results from previous studies by the authors and was presented both as a generic methodology and as a case applicable to an industrial company. The case was constructed from interviews and workshops conducted at the case company with the results partially validated through discussions with company management.

The approach, involving a 'technology-based configurable platform', consists of two parts: a technology platform and a configurable product platform. As presented in Paper B, the technology platform can be viewed as a collection of knowledge about technologies within the company. This knowledge is organized in a systematic way and is continuously updated based on both new technology development projects and previous applications of the technologies in products and manufacturing. The technology platform uses a Wiki that provides access to technological knowledge to support the development of new product platforms and their derivative products.

In the configurable product platform, technologies have been applied to a product concept without having yet converged into a point-based solution. Instead, a range of possible configurations of parts, as well as a spectrum of acceptable design parameters for the parts included, has been prepared to make sure that multiple ways exist to derive products from the platform. The configurable product platform is modeled according to a specific technique in a Product Lifecycle Management (PLM) architecture that allows these ranges to be defined. These ranges can then be engineered-to-order for different customer requirements, and the creation of derivative products is supported by a software architecture that integrates a number of analysis tools that calculate the most favorable configurations for a given set of requirements. A model of the development process and its support is presented in Figure 14.

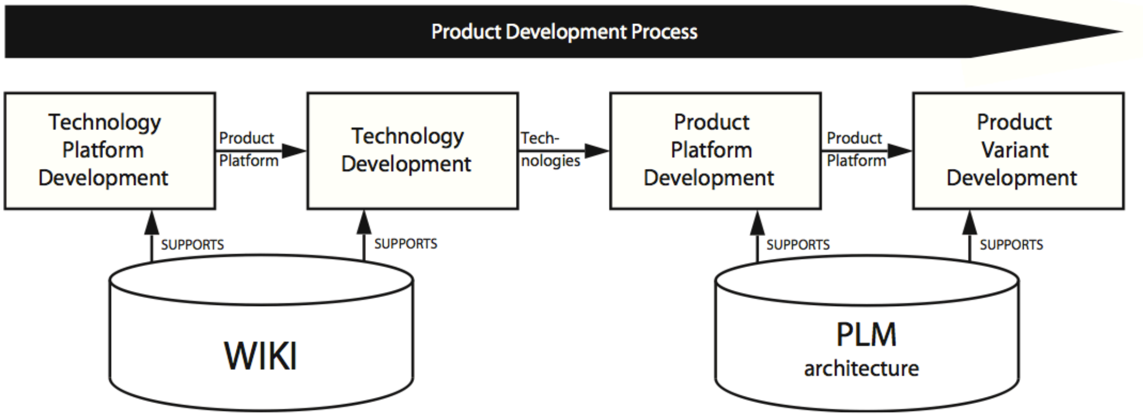

Figure 14. Process and platform support with the proposed approach.

This model is especially applicable to low-volume products with high demands of performance, the situation in which the case company finds itself. This company has a portfolio of similar products, but since the requirements for weight and performance are extremely high, there is little room for the compromises usually needed for creating platform products with predesigned parts. The technology-based configurable platform approach is applied to one of its products and shows how the modeling technique may be used together with analysis tools to quickly generate a number of derivative products, in addition to conducting performance analyses.

The approach has significant implications for how to perform development work and document its results. Besides using the new modeling technique, it pushes companies to front-load their development and prepare for a number of combinations and requirements of the components and technologies used in the product concept. A major part of development focuses on generating knowledge and preparing alternative scenarios rather than creating a single solution, requiring large investments in early phases that may be leveraged at a later stage.

For the right type of products, a well-prepared platform concept can provide a company with the opportunity to quickly find a suitable configuration to meet market demands with little need for redundant design work. The platform approach is also believed to provide an arena for discussing how development may be made more strategic by considering the reuse potential on a higher level in the organization. The technology-side of the platform provides an overview of competencies and facilitates the planning of products, as well as understanding the rationale behind the parameter boundaries in the configuration step.

The case presented about how a product may be quickly configured from a platform using the proposed modeling technique and software support is beyond the scope of this thesis and will therefore not be discussed further.

In response to the second research question, Paper C uses a thought experiment to establish an advanced use case for technology reuse. The platform-based methodology in this use case requires technological knowledge to be retrieved and used by computer tools to generate and analyze feasible design concepts. Two types of knowledge organization are proposed to support such a methodology. Firstly, the ranges of design parameters that technologies allow need to be developed upfront and then codified in an organized and highly structured way that links to the product structure, in this case in a PLM architecture. Secondly, the less structured Wiki format could be used to organize and provide links to the rest of the codified technological knowledge, such as rationale and declarative knowledge that is still in a generic form rather than applied to the product platform.

4.4 Paper D

Title: *Accommodating Emerging Technologies in Existing Product Platforms* (Levandowski et al., 2015).

The research conducted for this paper aimed to explore further how technologies can be modeled in a technology platform to facilitate their introduction in configurable product platforms. The approach of using configurable product platforms is an attempt to minimize the losses in the trade-off between economy of scale and flexibility when designing multiple product variants. When creating a product design that can be easily modified to work for different applications, there is much greater complexity and more requirements that need to be addressed when making changes to its design, such as when introducing a new technology. In the business environment of a supplier in the aerospace industry, new technologies are introduced frequently to optimize product performances and win bids for new contracts. At the same time, the company's products are usually highly integrated instead of modular, which makes it difficult to assess the implications of, and subsequently carry out, required changes to a product platform in order to accommodate new technology.

Paper C defined the type of support needed from a technology platform to facilitate the use of technological knowledge during product platform development, but did not go into details about the format for representing the knowledge. The work presented in Paper D was a continuation of the prescriptive work for Paper C with its roots in the same cases and empirical data collected through interaction with the case company. Paper D proposes an information model to use when representing technologies in a database, such as a PLM system (visualized in Figure 15), that would allow more flexibility in the product platform. Besides the performance limits mentioned in Paper C, the information model also includes technology characteristics and their relations to previous implementations as well as other technologies and components.

Modeling the performance limits of a technology enables automatic configuration of product variants, while the modeling of a technology's relations can facilitate a range of different activities. Firstly, it would be an extension to the widespread modeling of products and their components as a means to keep track of change propagation and new requirements that a technology introduces. Secondly, the use of relations to previous implementations of technologies would simplify the identification of designs, parameters and lessons learned that could be reused. Thirdly, by classifying the specific needs that technologies can solve and the needs that they induce, the model provides a means for engineers to find alternative technologies that could be used or technologies that the new technology can replace.

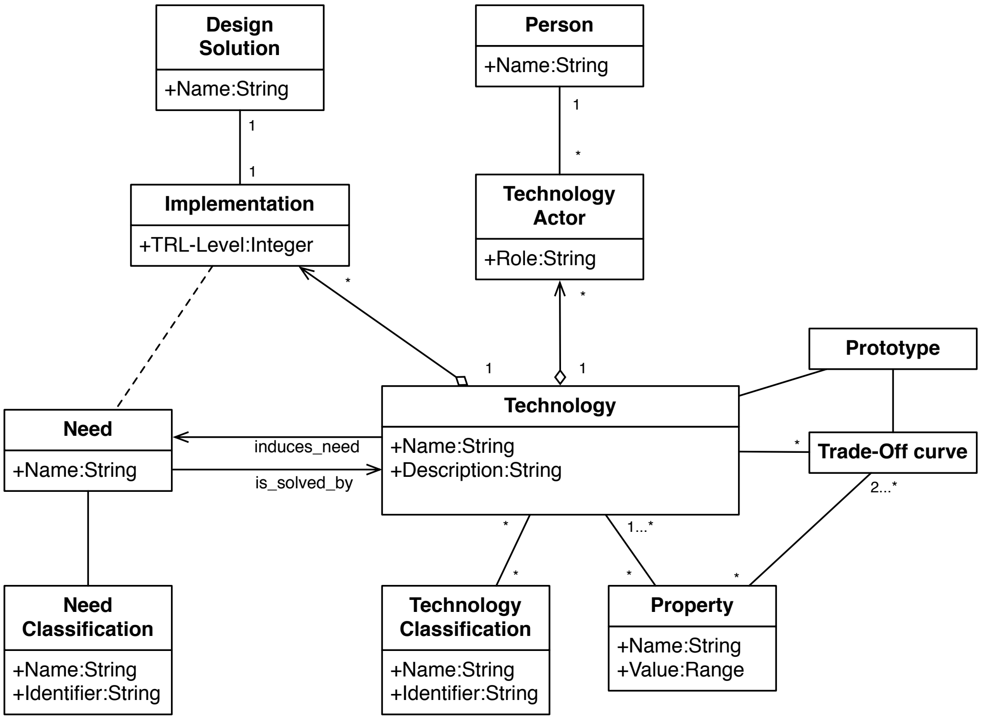

Figure 15. Information model for representing a technology's characteristics and relations.

The process for using the technology representations to support assessment of platform compatibility was described in the paper and applied to a hypothetical case. The case was adopted from Högman (2011) to illustrate how modeling the relationships between technologies can help with assessing the cascading effects from technology integration. Figure 16 visualizes a function-means tree that could be generated by tracing the links from a new technology being introduced to other technologies that are needed to support its introduction.

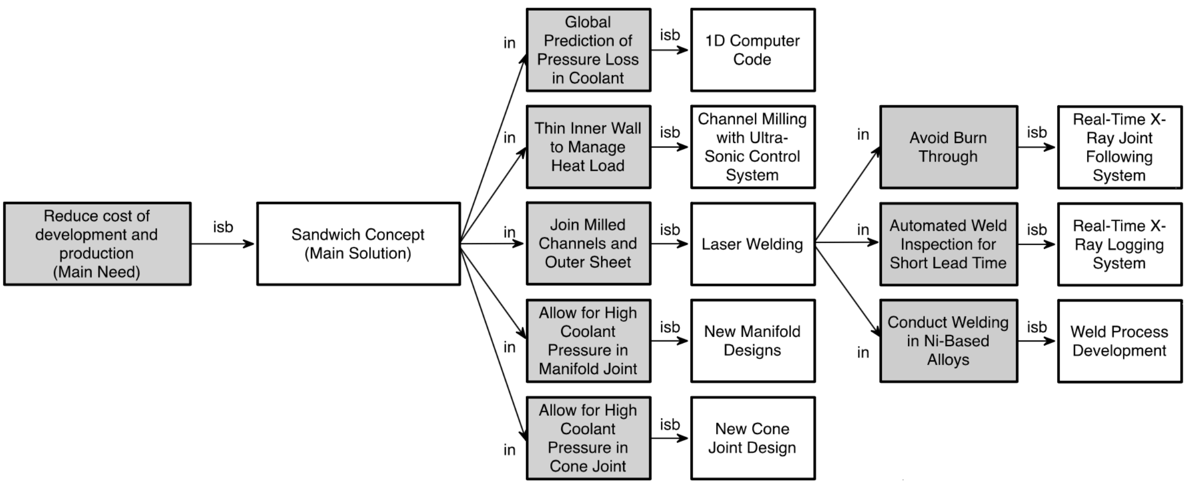

Figure 16 A function-means tree has been generated from the technology "Sandwich Concept" which requires supporting functions that are solved by (isb) a set of technologies, which in turn induces needs (in) for other technologies.

A schematic example of what the Sandwich Concept technology could look like to a user when modeled in the database according to the information model is provided in Figure 17. It features basic information about the technology, as well as links to contact information to key stakeholders, previous implementations, and enabling technologies that are useful or necessary for successfully applying the technology.

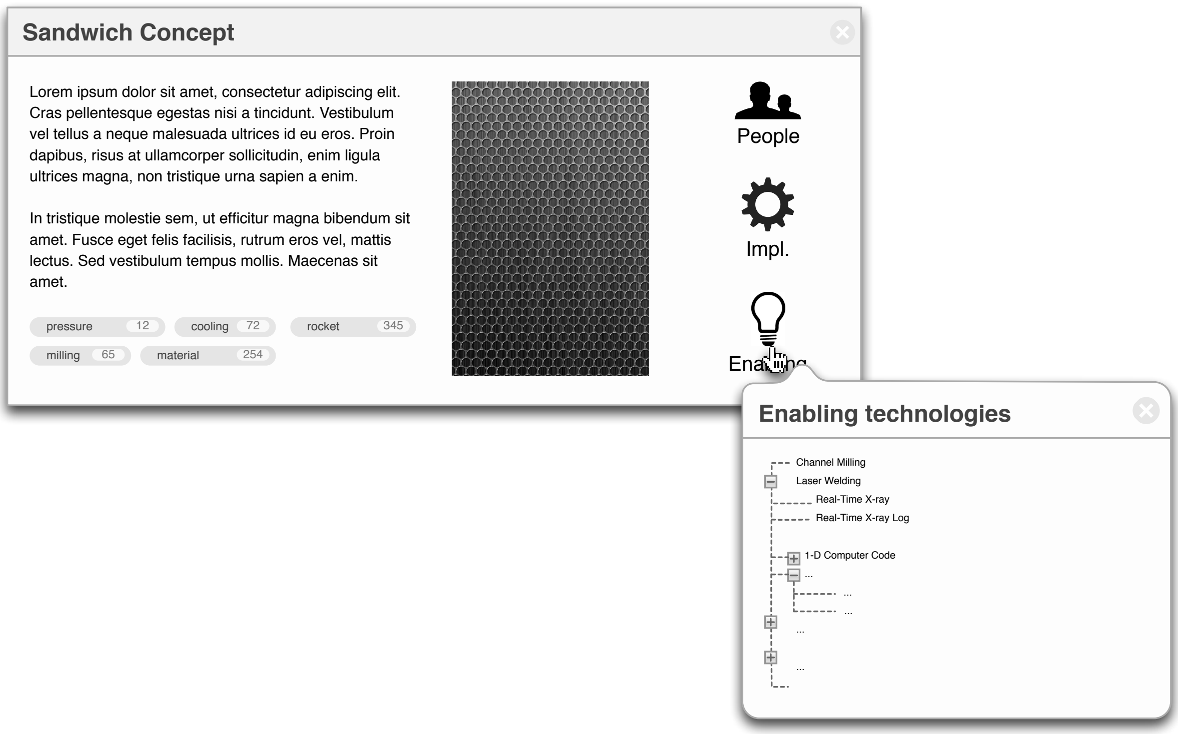

Figure 17. Schematic example of a user interface for viewing technologies modeled in the platform.

Paper D contributes to the answer to the second research question by providing additional insight into the requirements on technology representations when working with a configurable product platform methodology. The thought experiment in Paper C is extended by considering also the consequences of wanting to introduce new technologies into the established product platform models. In order to assess how necessary changes propagate within the product platform, the proposed information model for technologies includes links to other technologies and components to which it has dependencies and that therefore might be affected by the change. Further, it also supports problem-solving during the integration phase by featuring links to records of previous implementations of technologies, as well as links to alternative technologies that meet the same type of needs if a replacement is necessary.

4.5 Paper E

Title: *TERA – An Assessment of Technology Reuse Feasibility* (Corin Stig et al., 2015).

The purpose of Paper E was to clarify the various misconceptions that exist about the feasibility of technology reuse. Many times, a technology that has been successfully applied to a product is regarded as mature, or ‘proven’. The fact that it has only been proven for a specific application and its operative environment is easily overlooked, especially by management but also on the engineering level as a consequence of technical optimism. The effects on business performance from overestimating the capability of a technology can be extensive, as it can lead to delayed product launch, escalating development costs and product failures. Further, as seen in Paper A, the application of technology can also face issues related to the process of transferring knowledge to a receiving unit and lack of preparation for implementation.

By building upon the findings in previous studies within this research and by reviewing existing literature on technology integration, technology transfer and knowledge transfer, Paper E proposed a process mediated by the use of a scorecard to help companies prepare for technology reuse. Five requirements were identified during the discussions with the case company that guided its design: (1) it should involve relevant stakeholders, (2) it should encourage discussion among them, (3) it should ensure comprehensiveness of analysis by including relevant factors, (4) it should help decision makers get an overview of the characteristics of the reuse case, and (5) it should be easy to use.

The developed scorecard featured nine dimensions (see Table IV) to be evaluated by a team of managers and subject matter experts. Three of the dimensions related to the business case for technology reuse, three of them measured technical reuse readiness, and the last three related to the necessary knowledge transfer. Each dimension was also further divided into three or four sub-factors as seen in Figure 18.

The proposed assessment differs from the widely popular TRL assessments (Mankins, 1995) on three main points: (1) it is specifically designed for evaluating an already proven technology, albeit for a new application, (2) it features assessment of factors related to knowledge transfer, and (3) it is intended for earlier stages of planning for technology integration with an easy-to-use format.

The intended results from performing the proposed technology reuse assessment are: (1) to generate a prediction of the main challenges of introducing the technology in its new application, (2) to create a unified view on what the differences are to prior implementations, and (3) to help come up with a list of actions that can facilitate the reuse process.

The first round of feedback from users at the case company indicated that the assessment methodology could provide an organized way of capturing knowledge related to technology reuse that was previously addressed implicitly or ad-hoc when making decisions. Although the scorecard should be regarded as an early version in need of additional refinement and validation, users claimed it was already useful.

Table IV. Dimensions included in the scorecard for the technology reuse assessment.

A. Business Case	
A1. Benefit	What are the benefits sought from this technology reuse initiative?
A2. Cost	What costs and investments would it require?
A3. Relative Strength	What are the strengths of the technology relative to alternative solutions and technologies?
B. Technical Readiness	
B1. Robustness	The confidence and experience in the source's knowledge about the technology and how it will perform under new conditions.
B2. Independence	The ease with which the knowledge and supporting elements for applying the technology can be developed and integrated as an independent module.
B3. Similarity	The similarity between the old and the new contexts of application, e.g. regarding requirements, components and environment.
C. Capability Transfer Readiness	
C1. Learning	The preconditions for the recipient unit for learning the required competence and knowledge elements for applying the technology, related to its learning capacity and the characteristics of the knowledge to be transferred.
C2. Closeness	The closeness of the relationship between the source and recipient unit in terms of prior experience with collaboration, knowledge distance and geographical distance.
C3. Incentives	The incentives for the source and the recipient in actively and loyally participating in the knowledge reuse process throughout its duration.

A page from the scorecard document is shown in Figure 18, where the dimension 'Robustness' is assessed on four influencing factors. Each factor is formulated as a statement to which the assessors set a score from 1-5 depending on how much they agree with the statement for the reuse case at hand, e.g. "The source unit has extensive experience from using the technology in previous applications". They then assign a score of their confidence level for the factor score to indicate whether they were certain about their response or made a qualified guess. The bottom of the page features a table where necessary actions identified during the workshop can be recorded and assigned to someone.

B1. Robustness (Technical Readiness)

Influencing Factors	Assessment	Score (1-5)	Confidence (1-5)
B1.1. The source unit has extensive experience from using the technology in previous applications.			
B1.2. The performance of the technology is robust also when conditions change in the context for application.			
B1.3. It can be well predicted how the technology affects the operation and requirements of a new product and its manufacturing.			
B1.4. It can be well predicted how a new context of application affects the technology and its operation.			

Recommended Actions:

ID	Action	Responsible	Due Date	Time/Cost Estimate
AB1.1				
AB1.2				
AB1.3				
AB1.n				

Figure 18. A page from the TERA scorecard template, showing how to assess the dimension 'Robustness'.

The third research question asked how feasibility of technology reuse could be assessed, which is answered in Paper E with: five requirements on such support, nine dimensions to be assessed, and a method for the assessment. The method specified how to conduct the assessment, whom to involve when doing so, and featured a scorecard as a mediating tool that inquires about the nine dimensions of reuse feasibility. Although the method only underwent preliminary evaluation together with the case company, the feedback was very affirmative about the need for using an assessment and the relevance of the included dimensions. The design of the tool thus seems to fulfill the first three requirements to involve stakeholders, encourage discussion and ensure assessment of a breadth of relevant factors. However, the requirements to provide an overview of the results and be easy to use have yet to be fully evaluated, and there were indications that ease of use in particular could become a challenge. While the fact that the method and scorecard were new to the evaluators provided an inherent difficulty to the perceived ease of use, the definitions of the included factors and the support how to interpret different scores for each factor appeared to be in need of further refinement.

4.6 Summary of Results

Considering the exploratory nature of the research questions and the absence of a one-to-one mapping between papers and questions, the answers provided to them by this thesis will be presented in the next chapter following a discussion of the results in relation to existing theory. To prepare for the discussion, Table V summarizes the key contributions from each paper to the answers of the three research questions respectively.

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

Item #	Result	Descriptive/ prescriptive	Paper
RQ1: What barriers to efficient reuse of technologies can be identified at the engineering level within companies?			
R1.1	Lack of training for recipients of technology transfer.	Descriptive	A
R1.2	Insufficient preparation of implementation related activities.	Descriptive	A
R1.3	Unclear goals of technology development.	Descriptive	A
R1.4	Poor searchability for reports and other documents.	Descriptive	B
R1.5	Low level of awareness about existing technologies and technological knowledge within the company.	Descriptive	B
R1.6	Restriction in access rights to documentation due to client contracts and risk of theft.	Descriptive	B
RQ2: How can a company organize its technological knowledge to make it more accessible to internal reusers?			
R2.1	The case company relied to a great extent on personification for transfer of technological knowledge.	Descriptive	B
R2.2	The case company experienced a need for more time or quicker-to-use tools for recording and refining knowledge.	Descriptive	B
R2.3	Different types of stakeholders at the case company needed to acquire different types of knowledge about technologies.	Descriptive	B
R2.4	The case company had a wish for a starting point to access technological knowledge.	Descriptive	B
R2.5	The case company had a wish for a place to publish general information about technologies.	Descriptive	B
R2.6	The case company had a wish to allow employees facing similar design problems to get in contact with each other.	Descriptive	B
R2.7	The case company experienced a need to distinguish between reviewed and non-reviewed information.	Descriptive	B
R2.8	The case company was concerned about the risk of redundancy of information if records about technologies in general and their implementations in products were kept in different places.	Descriptive	B

(Table V continued)

Item #	Result	Descriptive/ prescriptive	Paper
R2.9	The case company was concerned that a repository with key technological knowledge could increase the risk that sensitive information spread to competitors.	Descriptive	B
R2.10	The case company showed limited interest in using the feature of Wikis to allow collaborative authorship.	Descriptive	B
R2.11	Proposal to use a searchable Wiki-based catalog for presenting basic technology information in an organized way and provide links to experts and reviewed information in official reports.	Prescriptive	B
R2.12	Development of a use case for reusing technological knowledge to support development of product platforms and generation of product concepts.	Prescriptive	C
R2.13	Proposal to codify the ranges of design parameters allowed by technologies in a PLM system to support configurable product platforms.	Prescriptive	C
R2.14	Extension of the use case for technology-based configurable platforms with a process description for how to assess the effects from integration of new technologies in the platform.	Prescriptive	D
R2.15	Proposal to extend the information model implied in R2.13 for representing technologies in a PLM system to include links to related technologies and previous implementations to support the assessment of effects from integrating new technologies.	Prescriptive	D
RQ3: How can the feasibility of reusing technologies in new applications be assessed in order to predict and prevent potential complications?			
R3.1	An assessment of technology reusability should involve relevant stakeholders.	Descriptive	E
R3.2	An assessment of technology reusability should include a comprehensive set of relevant factors.	Descriptive	E
R3.3	An assessment of technology reusability should encourage discussion among participating stakeholders.	Descriptive	E
R3.4	An assessment of reusability should help decision makers get an overview of the characteristics of the reuse case.	Descriptive	E
R3.5	An assessment of reusability should be easy to use.	Descriptive	E
R3.6	Proposal to address nine dimensions when assessing technology reuse feasibility: Benefit, Cost, Relative Strength, Robustness, Independence, Similarity, Learning, Closeness, and Incentives.	Prescriptive	E
R3.7	Proposal of a method for technology reuse assessment where experts and managers participate in a workshop to discuss and score the identified dimensions in a scorecard, as well as decide on any necessary actions.	Prescriptive	E

Figure 19 visualizes how the results in Table V relate to the schematic illustration of the studied context that was presented in the introduction to the Frame of Reference Chapter.

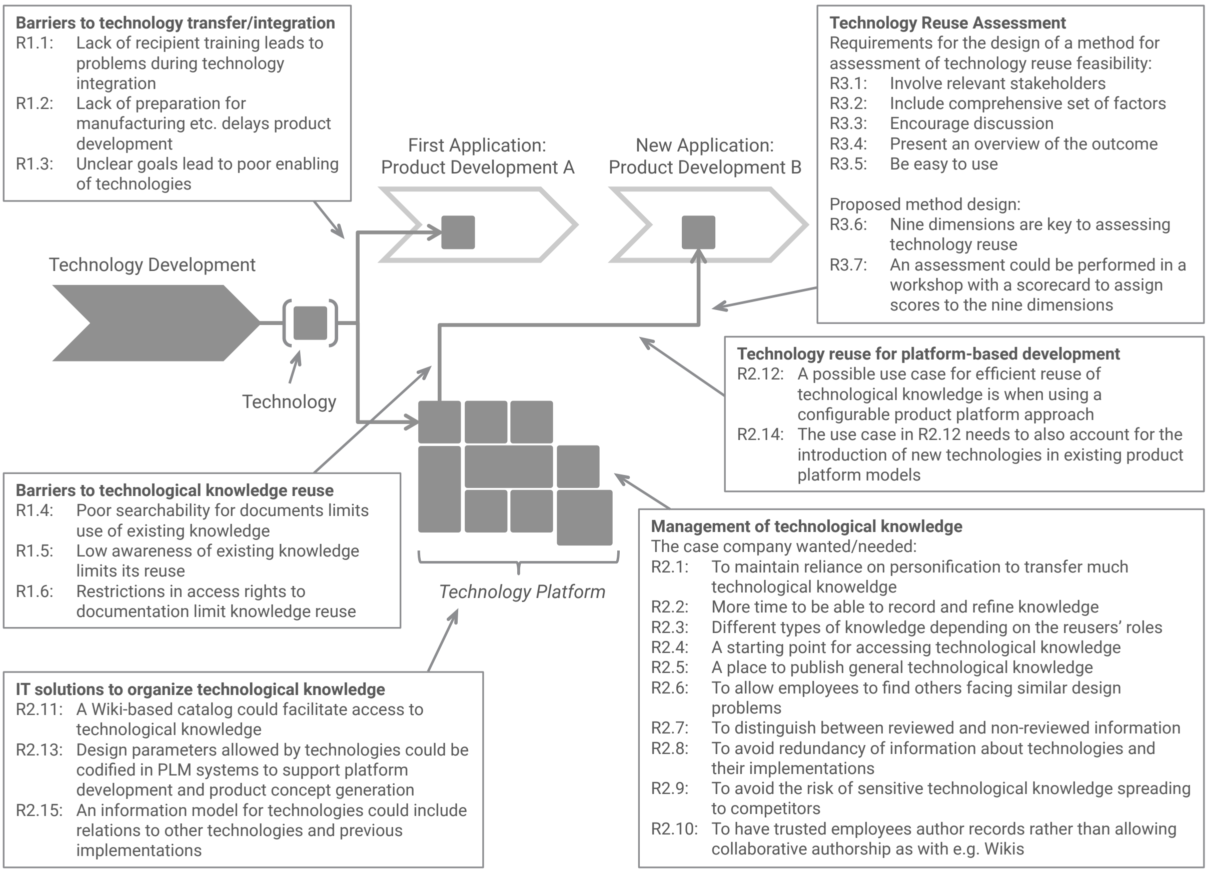

Figure 19. Mapping of results from the appended papers to the schematic illustration of the studied context.

5 DISCUSSION

This chapter elaborates on the results reported in this research by first discussing the findings in relation to the research questions and existing theory, then reflecting upon the selection of research methods and their effects on the validity of the findings and conclusions, and finally presenting the claims for contributions to theory and practice from the research.

5.1 Answering the Research Questions

RQ1: What barriers to efficient reuse of technologies can be identified at the engineering level within companies?

The interview studies for Papers A and B provided insight into which barriers to technology reuse that could be found within the case company. Besides the collected empirical data, there is much to learn about barriers to technology reuse from collecting and synthesizing the findings from previous research in related fields. The empirical findings from this research aligns well with existing literature on e.g. the challenges of transferring knowledge and managing technologies, such as the need for enabling technologies before they are introduced in products (Eldred & McGrath, 1997a), the problem of reusing knowledge documented in specific contexts (Levinthal & March, 1993) and lack of time for exploration (Cooper, 2006) and codification (Alavi & Leidner, 2001) of new knowledge. A detailed discussion about barriers to technology reuse is presented below based on the empirical findings and the reviewed literature.

Investing in reusable capabilities

A precondition for efficient technology reuse is that reusable technological knowledge has been acquired in the first place. When technological knowledge resides in a company, it can be seen as an inventory that management can work to optimize in order to meet the uncertain needs of the future (Levinthal & March, 1993). Contrasting this to the urgent needs of an application development project and the limitations in cognitive capability to trade between future and current rewards, it is not surprising if companies underinvest in preparation for reuse.

Besides the acquisition of reusable knowledge, there is a need for making it available at a later stage, either by storing it in the memory of individuals or in codified sources such as reports, guidelines and processes. Several interviewees in the study for Paper B mentioned that being under time pressure and lacking an internal funding source have hindered them from writing up lessons learned and making them available to colleagues, which is a barrier also found in the literature (Alavi & Leidner, 2001). Even if managers who are able to identify opportunities for commonality across the organization find it worthwhile to invest in documentation for future reuse (Davis, 1994; Hunt et al., 2001), it is also a matter of providing incentives for the authoring of such documentation. The further away a potential reuser resides, the less intrinsic motivation is experienced by the authors–who may not even value documentation for their own future use (Markus, 2001).

The issue of developing technologies with unclear goals was observed in both the empirical studies and in the literature. To have a separate technology stream from which products can be selected as proposed by Clausing (1994) implies a process where the goals of technology development are not as tightly linked to product applications. Contrary to the proposal by Clausing (1994), the separation of technology development and product development at the case company was not a case of a deliberate, systematic process of letting technologies mature independently of products to allow flexibility, but rather a separation in time and organization in a way similar to that discussed by Eldred and McGrath (1997b) to reduce risk. The problem at the case company reported in Paper A where technologies were considered too generic for application was likely the result of confusion about the objectives in those particular cases, and a misalignment between the expectations of the technology development team and product developers as discussed by Leonard-Barton (1988). According to the TRL scale (Mankins, 1995), a target application is needed to progress beyond levels 3-4 to prove the technology in a representative environment, which indicates that the independent 'technology stream' may thus be best suited for early phases of technology development. The implication for the case company is that their ambition to develop technologies as generic capabilities with a platform approach appears to have most potential if combined with good predictions of future product applications.

Finding and recontextualizing knowledge

Technological knowledge is generated inside various departments and is possessed by experts that are not always easy to locate, especially for new employees as found in the study for Paper B. Without awareness about the existence of such knowledge within the company, there is a risk that it may be overlooked, especially knowledge that is cross-departmental or was developed a long time ago.

At the case company, the most used way of accessing technological knowledge was through personal contacts, which is also found in literature to be a common preference (Cross & Sproull, 2004). Most of the workforce had been with the company for many years and typically knew where to turn to find knowledgeable colleagues, but for new employees it was not that easy. The size of the company, around 1300 employees at the studied site, in combination with the specialization inherent in technological knowledge suggests that the effort of tying together relevant competences in networks would not be all too challenging. As an example, an interviewee stated that it would be possible to identify and gather all relevant stakeholders in a seminar for sharing important news about a particular technology. In comparison, consulting firms with tens of thousands of employees with broad competences have much greater needs for actively establishing links that support person-based knowledge sharing (Hansen et al., 1999). However, even at the case company the interviewees perceived a need for a better overview of whom to consult as sources of knowledge, so support for finding the right people within the company seems to be needed even in this setting.

Documents were deemed difficult to both locate and comprehend, many times stored with access control so that even their authors could not access them without requesting permission. Another reason mentioned for the difficulty of accessing knowledge was that it was organized according to the projects and products where the technologies were developed and applied. Hence, to pan for reusable knowledge, much context-specific text needed to be consulted and it required the reuser to identify projects and products in which the technology had been used. This might work for the people involved in the creation of the knowledge, i.e. the 'shared work producers' (Markus, 2001), but for similar others who are 'shared work practitioners' working with similar design tasks, it would be preferable to find knowledge in a format that is organized, repackaged and decontextualized (Markus, 2001). This would require dedicated efforts by a moderating role between the creation and application of records, which was only done to a limited extent at the case company, primarily in the creation of design guidelines. Instead, with limited time and incentives for creating reusable assets, the company mostly relied on returning to by-products from normal work (Markus, 2001) to reuse technological knowledge.

Organizational culture was not explicitly studied as a dimension in the empirical part of this research, but it is clear from literature that it plays an important role in knowledge transfer. It has been stated as one of the most important factors for successfully transferring knowledge (Davenport & Prusak, 1998) and for succeeding with introducing knowledge repositories, especially for collaborative repositories such as Wikis (Standing & Kiniti, 2011). Based on our interviews and discussions, the case company seems to find itself in an early stage of the transformation into a culture of knowledge sharing. The general impression from the conducted interviews was that there were no signs of active resistance such as hoarding or unwillingness of sharing knowledge when asked for it, but there were barriers from low transparency of who could have use for ones knowledge as well as lack of incentives, internal and external, for making an effort to make it readily accessible. This presents a challenge for the adoption of new methods for knowledge capture and sharing, since the mindset of prioritizing future reuse needs to be infused along with the methods.

Another barrier inherent in the reuse of technological knowledge has to do with the generic-applied dimension of knowledge. In late phases of development of a technology, there is a need for adapting it to the specific requirements of the application intended. The knowledge generated during this phase is less generic and reusable in other contexts, which may be difficult to discern when reviewing documentation for reusable elements of previous work conducted.

Technology integration

The research for Paper A supports the findings in previous research that merely artifacts and documentation are not sufficient for the efficient application of a technology (Leonard-Barton, 1988; Eldred & McGrath, 1997a). There is also a need for the support of developers and experts who have been using the technology in order to build trust and contribute their tacit knowledge. As the reuse of technologies involves application in new contexts, there is also a need for predicting and preparing for the challenges of adapting the technology and making it work in the new system, including preparations for manufacturing. This was not equally clear from the reviewed literature and constitutes a more novel contribution to the study of internal technology transfer, which is further discussed in relation to the third research question. The commonly used TRL metric for assessing readiness of a technology (Mankins, 1995) focuses on feasibility rather than level of preparation for starting production. Lead times in e.g. acquisition of equipment and training of operators are also risks that can push the deadlines of application projects, even if these risks are more predictable than the technical risks of immature technologies.

Summary of answer to RQ1

The answer to the first research question provided by this thesis is multifaceted, as seen in the discussion above. Table VI provides an overview of the elements of the answer and where they stem from.

Table VI. Summary of the answers provided by this thesis to the first research question: What barriers to efficient reuse of technologies can be identified at the engineering level within companies?

Item #	Answer	Source
A1.1	Companies tend to underinvestment in preparations for reuse in general.	(e.g. Davis, 1994; Hunt et al., 2001)
A1.2	Technology development performed with unclear goals restricts the possibilities to enable technologies for their applications.	Paper A, (Leonard-Barton, 1988; Eldred & McGrath, 1997b)
A1.3	Low awareness of technological knowledge existing at the company.	Paper B
A1.4	Lack of a starting point for finding general knowledge related to a specific technology.	Paper B
A1.5	Technological knowledge has an extensive tacit component, which makes access to knowledgeable persons essential to ensure successful technology reuse.	Paper A
A1.6	High reliance on personal networks to find existing knowledge.	Paper B
A1.7	Difficulty of locating documents about previous implementations of technologies.	Paper B
A1.8	Restrictions in access permission for existing documentation.	Paper B
A1.9	Low incentives for preparing documentation for anticipated future needs of others than oneself.	(Markus, 2001)
A1.10	Lack of time for recording and refining knowledge more than as by-products of normal work.	Paper B, (Alavi & Leidner, 2001)
A1.11	Difficult and time-consuming to read and recontextualize knowledge documented as by-products of normal work.	(Markus, 2001)
A1.12	Difficulty of distinguishing between applied and generic knowledge about technologies.	(Herschbach, 1995; Iansiti, 1998; Berglund et al., 2008)
A1.13	Preparations for the start of production risk being overlooked when enabling technologies for applications.	Paper A
A1.14	Technologies that are considered for reuse might be mistaken for having high 'readiness', although they have not yet been tested for the new application context.	Paper E

RQ2: How can a company organize its technological knowledge to make it more accessible to internal reusers?

Neither the case company nor the other companies that have been contacted in this research had introduced formal knowledge strategies featuring technologies as foundational elements or reusable building blocks. The main case company had decided to do so, which also led to the formation of this research project, but had not decided how to realize the strategy. The current knowledge sharing at the case company could be characterized as having primarily a personalization strategy, supported by a decentralized IT infrastructure for codified knowledge with partly ad-hoc content–a central repository of design practices under development being a notable exception.

At the case company, there were examples of functional teams or interest groups that centered around a technological capability, and also experts appointed as 'method owners' for technologies, especially those involving an engineering or manufacturing method. To find technological knowledge, knowledge seekers could identify this functional unit or group of employees who would hopefully be able to answer any questions or refer to other sources for the answer. However, directories of existing groups were nonexistent or inaccessible. The groups often stored codified knowledge in reports, specifications and manuals in shared folders on their intranet. The content of these folders differed between groups, but there was some standardization stemming from the requirements on certain documentation specified in the technology development process. Hence, for technologies that had been developed in dedicated projects recently, these documents could be found.

The use of centralized knowledge repositories is commonly stressed in the literature as being a critical component for supporting reuse, and it was wished for by the interviewees at the case company. However, from technology transfer literature and from the findings in Paper A, it is clear that much knowledge related to technologies is tacit and thus difficult to transfer in codified form. Further, experts tend to use more local storage for documents than do designers (Lowe et al., 2004), and notes that are not widely accessible can be allowed to include more details and contextual knowledge (Markus, 2001). So, while the discussion on how to organize knowledge focuses primarily on what can be done from a central viewpoint, it should also be noted that uncodified sources and decentralized storage might be particularly important for the reuse of technological knowledge. In the design of methods and tools proposed in this thesis, this realization has often been addressed by emphasizing the provision of contact information to experts and links to detailed records.

Repository for technological knowledge

A first step toward increasing the usefulness of technological knowledge residing in a company is to make it visible to the employees to make sure that they are aware of its existence and can find it (Yeung & Holden, 2000). A knowledge repository that allows users to find knowledge related to specific technologies would greatly facilitate location of such knowledge within a company, such as the one studied in this research. Considering the current situation at the case company reported in Paper B where engineers lack a natural point of access to codified technological knowledge, an IT tool would likely not need to be particularly advanced to realize most of the sought benefits, as suggested by Zack (1999).

Two design decisions for knowledge repositories are whether they should rely on search or browsing to locate knowledge (McMahon et al., 2004), and whether the content could be supplied from by-products of other work or by creating specific records that are intended to support knowledge reusers (Markus, 2001). As technologies are composed of sets of related knowledge needed for their application, they constitute natural nodes from which knowledge records can be linked in a hierarchical system that users can browse through. It became clear during the interviews that technologies differ in where, when, and how they are applied, as well as who applies them, so the specifics of what knowledge to include in a repository is difficult to specify with general recommendations. In some instances, knowledge might be accessed frequently with little variation in how it is applied, which would make it natural to spend some time on improving reusability with general guidelines or similar. In others, it may be impractical to decontextualize and generalize results into guidelines, and instead references to by-product records from earlier implementations could be used to support knowledge reuse. However, a good starting point on a general level would be to explain brief information to users of the knowledge repository that would help answer simple questions that a broad audience of novices might have. Then to facilitate access to more detailed knowledge, the information should include hyperlinks (Yeung & Holden, 2000), or referrals (Cross & Sproull, 2004), to more extensive records and experts who may be consulted.

A Wiki-based solution was developed as a demonstrator of a centralized knowledge repository about technologies, which is presented in Paper B. The Wiki features a catalog of technologies that are accessed by browsing through a categorization scheme of technologies based on their type (starting with the categories: Design Solution, Manufacturing Method, Engineering Method and Test and Control Method). Each technology had a page to be moderated by an appointed technology expert and provided a brief description of the technology, the status of development, contact information to relevant experts and links to detailed reports and other codified knowledge.

The Wiki that was presented to the case company received highly positive feedback and got its intended users enthusiastic about its potential to meet their needs for improved access to technological knowledge. However, it also raised some concerns about the Wiki format as the placeholder for knowledge. The feedback on the Wiki-based technology catalog rephrased a number of considerations also found in the literature for knowledge repositories in general, e.g. the issue of additional workload for their creation (Markus, 2001), as well as the importance of keeping information up-to-date and making it trustworthy (Watson & Hewett, 2006). Concerns were also raised regarding the risk of sensitive knowledge spreading to competitors, which was not found in the reviewed literature. Neither was the concern for redundancy between repositories for technology and product information, which is inherent in the generic nature of technological competencies and the specific nature of technologies configured to applications. Besides the opportunity to get feedback on their internal publications, the collaborative nature of the Wiki format did not seem to be a significant feature to the intended users, which would favor the use of a standard intranet solution with a similar interface for readers. In the industry, trustworthiness is a key factor for knowledge to be useful, and with multiple collaborators on the content it would be difficult to know whether it was tested and certified for use. Further, the idea that people would contribute high quality content on their own initiative is wishful thinking since such contributions to support others have low priority and incentives compared to the more urgent tasks of normal development (Markus, 2001).

Representing technologies with an information model

Another branch of this research explored how reuse of technological knowledge can support a technology-based configurable product platform approach. The approach is presented in Papers C and D, which highlighted the need for new processes and practices to leverage a comprehensive reuse strategy that spans technologies, products and production. This represents a more visionary solution that could be suitable in the industry where the case company operates. The high performance requirements and long development cycles mean that a traditional product platform approach becomes impractical since it assumes that products can be configured-to-order. The development of an aircraft engine component is more of an engineer-to-order activity since the integrated nature of the designs result in highly complex interactions that cannot be fully tested or foreseen in the product platform design. However, in order to reduce development time and provide better predictions on what capability they can deliver, it is attractive to move closer toward a configure-to-order process.

The proposed approach focused on early phases of development and suggested new types of development projects to prepare technologies and product concepts for a range of different applications as opposed to traditional approaches that develop point-based solutions. In the new development context, where new product configurations are generated rapidly with support from tools for automated design and simulation, the viable design parameters for which included technologies have been previously prepared and tested would need to be codified as constraints and modeled in new ways. The variants generated by the configurator would then be compliant with the capabilities of the included technologies. This would mainly require declarative knowledge about the performance data and necessary parameters of the design space that the technologies can support, as well as any possible dependencies on other technologies for those that are of a 'network' or 'complex' type in the terminology by Drejer and Riis (1999).

The use of a pre-developed platform as the basis for new concepts might be a threat to innovation if it only allows configurations within a proven design space, which is particularly critical in an industry where offering new technology is key to winning bids. There could be situations where a design concept is still worth pursuing even though it requires more from a technology than it has been previously tested for. The costs of extending the technology capability, or replacing it with another technology, might generate enough increase in product performance or savings in manufacturing costs to motivate the increase in development cost. To enable such analysis upfront, it would be useful to extend the proposed information model from Paper D to help predict the challenges of extending a technology's capability to parameter ranges outside the current performance and include that in the configurator. Likewise, new technologies that are not yet mature could be included as potential options to be considered if there is enough to gain from allowing new configurations that would require extension of the product platform.

There are major challenges to successfully introduce the technology-based configurable product platform approach. From a technology reuse perspective, it would be necessary to create and maintain models of technology capability on important measurable parameters and at the same time build into the models an awareness of more complex interactions and dependencies that may threaten the feasibility of concepts generated by the configurator. It is likely that the assessments of configured concepts still need to rely to a great extent on manual work in order to address tacit elements of knowledge and avoid excessive workload for preparing the platform with coding all explicit knowledge into configuration rules. However, some parameters would probably have a clear logic that can be coded into the models and others could be programmed to trigger focused manual analyses of potential issues. For instance, if a specific manufacturing technology is introduced in the configured concept to meet tolerance requirements, that might trigger the need to also introduce an additional inspection technology, which in turn needs to be attuned to the rest of the product and manufacturing system. Some of these dependences could probably be modeled and managed by the configuration logic, while others would require an expert judgment.

Technology Communication Plans

The work on how to systematically design and populate a repository of technological knowledge was continued at a later stage of the research, which has not been published yet. Despite not being part of the main results of this thesis, it is reported on here since it is indicative of what I find most significant in the findings from the included studies and of what might be missing from the provided answers to the research question so far.

The work builds upon the idea that each technology would have one or more appointed experts taking the roles as 'knowledge owners', who decide on the best strategy to empower other employees with the knowledge in their domain. The goal would be to achieve the best possible leverage on any time and money spent on preparing and sharing knowledge for reuse, which is especially important when the resources and intrinsic motivators are scarce, as they tend to be for that type of activity. In relation to existing literature, this practice would fit into several of the reuse frameworks from engineering management research. It can be seen as a refinement of the classification phase in the process for improving reuse of technological assets proposed by Antelme et al. (2000), and as a method related to both the 'design for reuse' process in Duffy et al. (1995) and the decision on what products to develop for reuse in the proposed reuse strategy by Davis (1994).

An early version of a method has been developed for supporting this development of individual 'Technology Communication Plans'. It asks technology experts to identify potential knowledge reusers, how many they are and what type of knowledge they might need. Guidelines are then supplied to the experts for helping them decide how to satisfy these needs effectively. For instance, depending on the type of knowledge, different mechanisms for transfer such as manuals, newsletters or face-to-face consultation with experts could be suitable. Further, if there are many potential reusers and the knowledge is primarily explicit, it could be worthwhile to make an investment in making it easy to recontextualize and apply knowledge in a guideline or even create an expert system to execute tasks automatically. If the knowledge is needed infrequently, then by-products from normal work or modes of getting in contact with experts to pose a question might be sufficient.

There are three main reasons for suggesting individual plans for how to make knowledge about technologies accessible. Firstly, it is desirable to introduce a general strategy that is applied for all technologies to ensure optimization of the whole inventory of technological knowledge. Secondly, each technology is unique and has specific elements of knowledge that are critical or useful to ensure that reusers address, which are best identified by the experts themselves. Thirdly, knowledge management initiatives often fail because of a lack of motivation or lack of resources, which means that there needs to be a clear purpose to every activity and they need to be chosen wisely to achieve their purposes with minimum effort. In order to make smart choices on how to share knowledge, the technical experts need to have the skills for doing so, which could be ensured with support from guidelines as proposed above, or with training or direct support from a knowledge management expert.

A new challenge became apparent during this late phase of the work, which can also be found in the literature (McMahon et al., 2004; Garud & Kumaraswamy, 2005). Although many of the case company's technologies could be identified as distinguishable sets of knowledge, possible to name and with dedicated experts linked to them, much activity in the technology development department was difficult to link to reusable elements. To decide on a breakdown structure for technological capabilities would thus be more difficult than initially anticipated, especially if the resources for each element should be maintained by an appointed 'knowledge owner'. A risk is then that important knowledge that does not fit with the classification scheme is left out of the repository and remains difficult to find. On the other hand, there are potentially important benefits to be gained on a strategic level from attempting to create a classification that works, even if it needs to be made with certain compromises. If there is an awareness among employees of the existing capabilities and the classification scheme, employees may also think more about how their work relates to them and how it could be reused in the future, as suggested by Prahalad and Hamel (1990).

Summary of answer to RQ2

There is a host of different considerations that need to be taken into account when deciding on a way to represent technological knowledge in an organized way to support its reuse. Table VII presents a summary of the key considerations and proposed solutions provided by this thesis to the second research question.

Table VII. Summary of the answer provided by this thesis to the second research question: How can a company organize its technological knowledge to make it more accessible to internal reusers?

Item #	Answer	Source
General recommendations for organizing technological knowledge		
A2.1	Detailed codified technological knowledge typically resides in reports, specifications and manuals.	Paper B
A2.2	Besides storing records of technological knowledge in archives, detailed content with context descriptions should be available and shared within domain expert groups.	Paper B, (Markus, 2001; Lowe et al., 2004)
A2.3	Basic general knowledge about technologies should be made available to a broader audience within companies to raise awareness of its existence and provide a natural starting point for accessing more detailed reports.	Paper B, (Prahalad & Hamel, 1990; Yeung & Holden, 2000)

(Table VII continued)

Item #	Answer	Source
A2.4	Access to tacit knowledge is important to allow teams that integrate technologies in applications to trust the technologies and be able to cope with unexpected issues.	Papers A and B
A2.5	Technologies could potentially be classified and organized in a hierarchical system, but not without effort and compromises during the design of the classification scheme.	Paper B, (Herschbach, 1995; Granstrand, 1998)
A2.6	Intrinsic motivation is usually insufficient for triggering the additional workload necessary for creating decontextualized and refined knowledge records that facilitate reuse.	Paper B, (Markus, 2001)
A2.7	The decision of how much effort is worthwhile for preparing records for reuse is contingent on the technology and knowledge at hand. In some situations, by-products from normal work are enough, while in others there is reason to create e.g. manuals or software applications that support reuse.	[Hypothesis derived from the discussion]
A2.8	A digital 'technology catalog' could be a viable solution for increasing the general access to reusable technological knowledge at a company. It would allow users to browse through a hierarchy of technologies used at the company, read brief information about their capabilities, and find links to detailed records and individual experts.	Papers B and C
A2.9	Wikis could potentially be used as IT systems for 'technology catalogs', but should then make clear to the users what information is approved by the organization and not, have moderators who frequently review the information for correctness, and be combined with incentive structures that ensure enough contributions to build a critical amount of content to make them useful.	Paper B
Organizing technological knowledge to support technology-based configurable platforms		
A2.10	A company that develops integrated products with high performance requirements in a engineer-to-order environment could benefit from modeling technology capabilities in a PLM system in order to support product platform configurators to automatically generate and analyze multiple product concepts that fall within the design space allowed by the included technologies.	Paper C
A2.11	Extension of the technology information model proposed in A2.10 to include relations to other technologies and previous implementations would facilitate assessments of the impacts from introducing new technologies to product platform models.	Paper D
A2.12	In order to avoid disqualification of innovative product concepts, product platform configurators could allow the generation of some product concepts that build upon immature technologies, or that require extension of the capabilities of existing technologies, as long as these are flagged accordingly to distinguish them from proven concepts.	[Hypothesis derived from the discussion]

(Table VII continued)

Item #	Answer	Source
A2.13	Challenges to the representation of technological knowledge in a way that supports technology-based configurable platforms include: modeling technology capabilities as explicit constraints on the design space, keeping technology constraints updated, modeling complex dependencies between technologies, and ensuring that necessary tacit elements of technological knowledge are also consulted in the creation and analysis of product concepts derived from the platform models.	[Hypothesis derived from the discussion]

RQ3: How can the feasibility of reusing technologies in new applications be assessed in order to predict and prevent potential complications?

Inherent in the notion of technology reuse, as the term is used in this thesis, is a need to recontextualize the technology to its new application. Otherwise it would also be possible to categorize it as component or process reuse, which could be supported in ways that are outside the scope of this research. Technology Readiness Levels (TRLs) (Mankins, 1995) have become widely used to support the assessment of how far along the verification of a technology is for a designated application environment. However, their design works best for measuring progress rather than a current status of readiness. Speaking of technologies as mature and having high TRLs in general is a fallacy that disguises the contingencies from the environment in which the technology has been proven. This was raised as an important issue during discussions with the case company, and other companies seconded the issue during informal conversations. In the literature, no support was found for helping engineers to make an holistic assessment of whether a technology would be suitable for reuse in a new application, so it appeared to be a research gap suitable to address in this research. This led to the formulation of the third research question about how to assess the feasibility of taking a technology previously proven in one context and applying it in a new context, which was addressed in Paper E.

There were only a limited number of cases of technology reuse that could have been studied at the case company, and problems arisen from these, if remembered by the employees, would likely only have represented a fraction of the possible issues that technology reuse cases could face. Therefore, it was decided to look for candidate factors for an assessment in prior research on related topics. A literature review revealed a host of previous research on issues relating to the integration of technologies into product systems and transfer of technologies to new contexts (e.g. Leonard-Barton, 1988; Szulanski, 1996; Iansiti, 1998; Cummings & Teng, 2003; Magnusson & Johansson, 2008). These identified issues can have strong effects on technology integration success, but have not been presented in relation to technology reuse specifically or in a format that is accessible to decision makers and that would let these research findings have an impact on practice. The first challenge of this research was thus to compile relevant findings already existent in the literature and synthesize it to a format that would be perceived by practitioners as easy enough to be useful and understandable.

Through meetings with the case company, five general requirements for the assessment methodology were derived: (1) it should involve relevant stakeholders, (2) it should attempt to include a comprehensive set of key factors that affect technology reuse, (3) it should spur discussion among the participating assessors, (4) it should help decision makers to overview and understand the outcome of the assessment, and (5) it should be easy to use.

The result, which is presented in Paper E, was the creation of a method called TERA–TEchnology Reuse Assessment–intended as decision support when companies first consider a case of technology reuse. TERA asks stakeholders of the technology reuse case, i.e. technology experts and managers, to attend a workshop where they jointly fill out a scorecard of factors relevant to technology reuse. The extended distances in time, team and application context when reusing technology as compared to normal technology integration and transfer led the scorecard to focus on three factors relating to technology integration (Robustness, Independence, Similarity) and three factors relating to knowledge transfer (Learning, Closeness and Incentives). The inclusion of both technology adaptation and knowledge transfer related factors constitutes one of the key propositions of the assessment. These six factors were further decomposed into three to four subfactors each to increase the resolution of the assessment and spur more discussion about each factor from multiple viewpoints. Arguably, this increases the chances that relevant information is identified during the discussions and brought to the attention of the group of assessors. Three factors for addressing the business case for reusing the technology were also included (Benefit, Cost and Relative Strength), but mostly to ensure the assessors had a reference point for the importance of the reuse case when subjectively assessing the magnitude of potential challenges.

Including research performed after the publication of Paper E, two case companies have been involved in the verification and refinement of the scorecard – the main case company for this research from the aerospace industry and the other a large international company from the automotive industry. Although the findings from previous research had been carefully synthesized and simplified to be understandable, the most common response the test subjects was that further simplification and more explanations were necessary to make it useful. At the same time, the test subjects asked for a format that was quicker and easier to use than the Word template presented in Paper E. While the purpose of the scorecard was credited as very important and a solution to an issue that is easily overlooked, the time available for formal methods like this was perceived by the companies to be limited. Consensus from the ten people or so that participated in workshops and interviews was that 2-6 hours was a reasonable time for the completion of an assessment of this kind. In a test of the tool, which is not yet published, the scorecard was close to completed at the end of a 2h session where four participants assessed the planned reuse of a technology.

When starting to test and discuss the design of the scorecard with the two case companies, I was expecting them to perceive it as too limited in scope after having been simplified from the host of details laid out in previous research about potential reuse issues. Instead, the concerns were that it was too extensive and advanced. A new iteration of the design of the scorecard was made to make it resemble the existing formats used at one of the case companies for similar types of assessments. Instead of five pages in a Word document, the main body of the assessment was fitted into one sheet in Excel where more explanations were added for the different scores (1-5) and how to interpret them as comments to the spreadsheet cells (Figure 20).

TERA SCORECARD

Instructions:
Fill out the scorecard to the best of your knowledge, it's not an exact science and the intention is to characterize the technology reuse case to improve the plans for the transfer.
Provide a short comment on why each factor was given a certain score.
If the score is 3 or lower, at least one action item shall be provided on how to assure that the factor is addressed further on and doesn't lead to unexpected problems.

Score	Interpretation
5	This factor is under control and very unlikely to cause any problems to technology reuse.
4	This factor will likely not present any issues to technology reuse but may be controlled for if deemed important.
3	This factor presents a risk for technology reuse and should be addressed or monitored with special attention when making plans.
2	This factor brings great uncertainty to technology reuse and activities for mitigating and controlling for risks must be integrated in the plans for the project.
1	This factor could possibly threaten the whole feasibility of teechnology reuse and the project can proceed only after a detailed investigation has been conducted and risks have been addressed.
0	This factor makes the technology reuse a no-go.

TECHNICAL ASSESSMENT

	INFLUENCING FACTOR	SCORE 0-5	COMMENT ON SCORE	ACTIONS NEEDED	RESPONSIBLE	DUE DATE	ACTION DONE?
A. ROBUSTNESS							
A1	Prior Experience from Reusing the Technology						
A2	Robustness of Technology Performance						
A3	Technology Impact on System						
A4	Need for Technology Adaptations						
B. INDEPENDENCE							
B1	Interface to Context Environment						
B2	Dependency on Environment						
B3	Cross-Functionality						
C. SIMILARITY							
C1	Understanding of New Context						
C2	Similarity of New Context						
C3	Reuse of Equipment, Processes and Routines						

Daniel Corin-Stig:
Legend for scoring "Prior Experience from Reusing the Technology":

5: The source unit has extensive experience from applying the technology to new applications multiple times before.

1: The technology has never before been reused in a new application.

0: This factor makes technology reuse impossible or infeasible for this application.

Fill out the section below only if the technology will be applied/integrated by a different unit from prior applications.

TRANSFER ASSESSMENT

	INFLUENCING FACTOR	SCORE	COMMENT ON SCORE	ACTIONS NEEDED	RESPONSIBLE	DUE DATE	ACTION DONE?
D. LEARNING							
D1	Knowledge Transferability						
D2	Knowledge Ambiguity						
D3	Recipients' Prior Knowledge						
D4	Recipients' Learning Culture						
E. CLOSENESS							
E1	Prior Collaboration						
E2	Relationship Between Transferring Parties						
E3	Geographical Proximity						
F. INCENTIVES							
F1	Priority for Recipient						
F2	Priority for Source						
F3	Recipients' Intrinsic Motivation						

Figure 20. New version of the TERA scorecard created after the publication of Paper E.

It seems there is great variety in the types of situations in which technology reuse is decided, and the design of the scorecard is a compromise that can accommodate them in different ways. It facilitates the initial assessment for difficult cases of reuse where there might be a need for extensive development efforts to adapt the technology to the new environment. Those cases should probably also use TRL assessments once the company has committed to reusing the technology in order to track progress in the adaptation process. Perhaps they should even go further to also assess the Integration Readiness Levels (Sauser et al., 2006) between technologies that have shared interfaces or that interact in other ways in order to acknowledge the uncertainties stemming from dependencies between a technology and its environment.

At the other end of the scale, the case company from the automotive industry saw a use for the scorecard also for simpler assessments where they did not expect much need for adaptation of the technology. Instead, they wanted some support for the decisions on reusing components and technologies from one model to another. In this case, the format was seen as extensive enough on its own, and maybe even a simpler version could satisfy the needs of the evaluation. The very existence of a formal methodology for the decision and its scope where both the technical and knowledge transfer dimensions are assessed were perceived as the key benefits.

A limitation in the design of the scorecard is that those who review the results might get a false sense of objectivity, since the measured factors are assigned number based scores based on subjective assessment. Arriving at 'true' scores for each factor should therefore not be seen as the main goal, but rather as a process to stimulate and mediate discussion and communication about technology reuse feasibility among stakeholders. As intended with the design of the scorecard, the participants in the performed test at the automotive company valued the discussions that it stimulated and added comments to all the metrics to provide rationale to their thought process. They also appreciated the option to add a confidence score for each factor in the scorecard, claiming that it allowed them to make more honest qualified guesses without running the risk of being held accountable for bad estimates later on. A low confidence score could also be interpreted as an indication that there is a perceived need for further investigation, and vice versa.

Summary of answer to RQ3

The development of support for assessing technology reuse feasibility is still in an early stage after only one iteration of its design without a full round of testing in real environments. However, the issue has now been acknowledged and a first proposition has been developed to define the general requirements an assessment should fulfill, what dimensions it should address, and how a method for conducting the assessment could be designed. Table VIII summarizes these points as answers to the third research question.

Table VIII. Summary of the answers to the third research question: How can the feasibility of reusing technologies in new applications be assessed in order to predict and prevent potential complications?

Item #	Answer	Source
A3.1	An assessment method for technology reuse feasibility should address potential challenges stemming from the increased distances in time, team and application context as compared to normal technology integration.	Paper E
A3.2	Five general requirements on the assessment method are that it should: (1) involve relevant stakeholders, (2) include a comprehensive set of relevant factors, (3) encourage discussion among participating stakeholders, (4) help decision makers get an overview of the characteristics of the reuse case, and (5) be easy to use.	Paper E
A3.3	Nine key dimensions are relevant for assessing technology reuse feasibility: (1) benefit of using the technology, (2) cost of using the technology, (3) relative strengths as compared to other options to fulfill the same requirements, (4) robustness of technology performance in different applications, (5) independence from other technologies and surrounding environment factors, (6) similarity between the new application context and previous ones, (7) how difficult it is for the recipient team to learn how to apply the technology, (8) closeness between the source and recipient of technological knowledge transfer, and (9) the strength of incentives for the source and recipient to prioritize and support the reuse process.	Paper E

(Table VIII continued)

Item #	Answer	Source
A3.4	A potential method for technology reuse assessment gathers experts and managers in a half-day workshop and lets them discuss and numerically score the identified dimensions on a scorecard and decide on actions necessary to prevent potential complications or close knowledge gaps should the considered case of technology reuse be approved.	Paper E
A3.5	For important and difficult decisions on technology reuse, the proposed method in A3.4 could be used as an initial assessment to set the agenda for necessary actions and make a preliminary evaluation of reuse feasibility. For less complicated decisions, the method could be used as the primary source of information for making the decision.	[Hypothesis derived from discussion]

5.2 Validity of the Results

Research should aspire to bring as truthful results as possible and use an approach and methods that support this goal. It should also be transparent about its limitations and potential threats to the validity of its claims, which are provided in the following discussion on the quality of this research.

5.2.1 General reflections on the research design

Qualitative case studies allow close examination, provide rich information and are thus well suited for generating ideas and theories. This research started with an industrial need and idea notion of how to address this need by using the vague concept of technology platforms. The research called for clarifications and case studies allowing for both deeper insights into industrial contexts and inspiring thoughts approaching solutions for improved technology reuse. An established contact and access to previous empirical data played important roles in the selection of the case company. This choice facilitated practical matters during the research process and provided an understanding of the phenomenon from which the idea of the research originated.

The wide approach taken in this research to address the topic has negatively influenced the possibility to reach far in the validation of results in any of the focus areas. However, it was regarded as necessary to make efforts to define the topic of interest as a cross between technology integration and knowledge management on the one hand, and a cross between strategic and operational on the other. This also means that parts of the contribution to both theory and practice are the frameworks for defining the topic of technology reuse in a way that allows research to reach the practical level where findings meet the needs of industry and create value to society. Continuations of this research would likely be able to leverage these results and be more focused on testing and refining the developed methodologies and tools, which represents the later phases of the DRM process (Blessing & Chakrabarti, 2009).

The open definition used for the term ‘technology’, encompassing many different types of capabilities, is commonly seen in management research. When conducting this type of research, it has been a challenge to balance the wish for finding patterns among observations about studied technologies at the case companies and the wish for remaining general enough to be able to propose methods that can work for all or most of the technologies that a company works with. If the research instead would have focused on only manufacturing technologies, the results could have been more specific and the tools would likely have had a more detailed content. As a case in point, Paper A discusses the Technology Readiness Levels (TRLs) and their assessment, which both at the U.S. Department of Defense and at the case company had been reinterpreted for manufacturing technologies to increase the resolution of factors critical to that subset of technologies. However, the use of the TRL scale has been kept general in most organizations that I have heard of and read about, which I assume is based on the wish to keep processes simple to maintain and avoid overspecifying them to a level where they become impractical to use. For this reason, keeping the scope to a wide definition of technology has seemed adequate in order to meet the goal of creating results that can be implemented in practice.

At the start of the research process, the technology management literature was the main frame of reference and the studied topic was seen as a subset of how to manage technologies to support reusability. Over time, it became more clear how applicable the body of knowledge from the academic field of knowledge management was to address the underlying problem faced by the case company, which led me to perceive the topic more as a special case of knowledge reuse. In my answers to the first and second research questions, it is also clear that much of the results replicate previous findings from knowledge management research. However, there are aspects related to technology integration that make this topic a special case with cause for closer examination. The formulation of the third research question is in itself a result from this research, as it clearly captures the uniqueness that motivates study of technology reuse. Even if they are in an early stage of validation, I believe that the assessment methodology and scorecard that were developed in response to the third research question represent the most promising contributions from my work. I expect its design and content to be refined from its current state, but the most important step has been taken already: to highlight the need for making decisions on technology reuse with a systematic assessment of key factors.

5.2.2 Coverage of relevant literature

In both knowledge management and technology management literature, there is a host of research covering related topics. Many times they use different terms for describing similar phenomena, which means that relevant literature may have been overlooked when conducting the literature reviews. When searching databases for research articles, the terms used have been the ones I have become familiar with, which resulted in an experienced saturation of search results after a number of different queries had been used. However, throughout this research project there have been occasions where new fields of research have been found that provide new perspectives on the studied topic. Thus, there is likely a lot more to be found in previous research to help define the barriers and solutions to effective technology reuse than what has been covered in this research. As no sources have been found so far that integrate all the elements that I have included in the review of literature related to technology reuse, it is reasonable to believe that this research still makes a new contribution to the collection and synthesis of theory related to this topic.

5.2.3 *Single-case method and external validity*

It is important when conducting case study research to reflect upon what the case represents, i.e. what it is 'a case of', in order to support external validity. GKNA has been described as a company typical of the aero industry (Högman, 2011), which lends some support for generalizing the results to that industry. There are factors specific to the aerospace industry that limit the generalizability of the results to other industries, such as the strong policies on security and verification and the continuously evolving technology base. It is, however, reasonable to assume that these issues are shared with several other companies. Additionally, during the course of this research, the findings and ideas have been discussed informally during meetings and workshops with companies in other industries, in seminars for industrial partners of the research and at academic conferences. Many of the companies that also develop and manufacture technologically advanced products recognized the issues relating to technology reuse and showed an interest in the solutions proposed. Hence, there are indications that the results are transferable to a certain extent and could be duplicated in studies at companies in other industries that have characteristics similar to GKNA. If more than one company had been studied, allowing comparisons to support the identification of unique and common features, the possibilities of testing for such external validity would have been greatly improved.

In the answer to the first research question, the specific barriers to reuse identified, such as the way in which reports are stored and indexed in repositories, are based on a single-case method and may not be generalizable to other settings even within the aerospace industry. Various contingencies can affect whether barriers exist in a specific company, and the interviews will likely not reveal the potential barriers to reuse that are *not* experienced by the case company. On the other hand, there was a high level of agreement between the barriers identified from studying the case company and the barriers found in the reviewed literature on technology integration and knowledge reuse. This supports the generalizability of the answer to the first research question and suggests that prior research results are applicable also to technology reuse. However, it should not be inferred from the agreement with the literature that technology reuse can be equaled with knowledge reuse. While most identified barriers matched the general case, the answer given in this research could be an indication of the relative prevalence and importance of barriers when dealing with the specific case of technology reuse. To fully answer the first research question, it would have been necessary to study more cases, both to make sure a comprehensive set of barriers is identified, and to be able to draw conclusions on the relative prevalence and importance of different barriers when dealing with technology reuse specifically.

5.2.4 *Interview method and potential threats to construct validity and reliability*

Many open-ended questions were used during the interviews to ensure that the concepts discussed, such as 'technology', conveyed the same meaning to interviewees and that all relevant and meaningful responses to questions were exhausted. This was important to support construct validity considering the ambiguity of many terms used, and reduce the risk of influencing the interviewees. When analyzing the responses to open-ended questions there is a risk that different observers will make different interpretations, known as inter-observer reliability. This was mitigated in this research by the fact that there were multiple observers at almost all interviews conducted at the case company, typically one person asking questions and the other taking notes, and the analyses did not elicit any major discrepancies between the interpretations of the answers by the various observers.

In the case study for Paper B, the interviewers used a semi-structured approach with both open-ended and closed questions, focusing primarily on knowledge management. An unstructured interview methodology without a theme decided in advance by the interviewers might have revealed other barriers to technology reuse and thus contributed to a broader answer to the first research question. However, literature, previous experience at the case company and logical reasoning indicate that knowledge management is a key element in motivating companies to reuse technologies. Therefore, a deeper investigation of that particular type of barrier was deemed relevant and chosen for these interviews, but it might also have contributed to the prominence of knowledge management among the barriers found.

5.2.5 Internal validity of prescriptive results

There is a strong prescriptive element inherent in the second and third research questions, for which the strongest validity test would be to evaluate an actual implementation in a representative setting. As the Design Research Methodology proposes, development of practical tools should be followed by tests to see that they in fact lead to the intended effects (Blessing & Chakrabarti, 2009). The Wiki-based catalog for sharing and managing generic knowledge about technologies has not been implemented at the case company, partly due to the limitations of Wikis in small-scale implementations as they require a critical mass to become useful. Hence, without a large intervention at a case company, it would be impossible to achieve a representative environment for testing the support tool. Instead, a prototype was developed and shown during interviews to get feedback from intended users on how well it might support their work. Not only did a vast majority of them approve of the concept, but also the enthusiasm in the positive reactions from some respondents led us to believe that a simple repository would be highly useful as a tool for supporting a technology reuse strategy. As a proxy for real implementations, the tools have thus been validated in part through scrutiny and commenting from intended users at GKNA, as well as one other company for the technology reuse assessment from Paper E.

It should be noted that the positive feedback received could be questionable as validation due to the reactivity effect, where the researcher influences the individuals studied (Maxwell, 2005). Respondents are likely to be biased towards pleasing the researcher rather than providing all their criticism, especially if the researcher is also the creator of the tested support. Critique from test persons was nonetheless received during these tests, which suggests that this bias might have been limited, and the critique has been clearly reported on in the results. Much of it focused on details in the format or was requests for additional support, e.g. for interpreting the scales on the technology reuse assessment. Such aspects will likely have to be adjusted to each company anyway upon implementation in order to align with their processes and the criticality of decisions on technology integration. Thus, it should not be a critical threat to the relevance of the proposed methods and tools.

Wishes for both a knowledge repository about technologies and more support in making decisions on technology reuse, especially to probe into the softer aspects of knowledge transfer, were clearly expressed in the interviews. At the time of writing, there is still ongoing collaboration with two companies about the proposed solutions for meeting these needs. The repository is being refined for a pilot test in the main case company and the technology reuse assessment is being refined for additional tests in a different company. Hence, the prescribed tools and the methodologies for their use are partly becoming verified by acceptance from the case companies for their ability to address the associated problems, even if their formats may need further revision.

The most frequently used source of technological knowledge at the case company was contact with colleagues, something that should not be overlooked when discussing the value of introducing new support tools. Instead, such personal contacts may present an opportunity for further improvement or be advised as a general recommendation to other companies. The findings may have influenced the development of support towards a format that complements existing carriers of knowledge at the case company. There are various methods for supporting personification-based sharing of knowledge that could potentially have been given more attention if the research were performed with other case companies, such as exhibitions, cross-functional teams, virtual or real discussion fora, and expert hotlines.

The proposed use of platform thinking for technologies, how it would affect the organization and how it may be integrated into other processes was mainly developed by thought experiments with support in prior research about product platform development, technology platforms and core competencies. The validity of the propositions can be tested only by evaluating them in a representative case and in the absence of such a case, logical verification of the claims can instead be used. It is our belief that the solutions proposed in Paper C to integrate platform thinking in the development processes are plausible and logically sound. However, the extent to which they can be implemented as profitable trade-offs against the, largely unknown, implications of such drastic changes remains to be tested. To provide such validation is not within the scope of this research, and future contributions and evaluations of the platform development approach will, hopefully, be able to discern its value to intended users in competitive technology-intensive industries.

5.2.6 Use of common techniques to strengthen validity

The list below summarizes the extent to which the eight techniques proposed by Maxwell (2005) and described in Chapter 3.2 were used to strengthen research validity:

1. **Long-term involvement** has been a key element in this research, using the same case company in multiple studies and closely following previous research conducted on similar topics in the same setting.
2. **Rich data** has been gathered by interviewing both managers and engineers from different parts within the organization and by using recordings and detailed transcripts of the answers.
3. Transcripts were used for **respondent validation** after the interviews and workshops were held at the case company to discuss findings and proposed solutions.
4. **Intervention** has not been performed, something that would have significantly strengthened the validity of the solutions proposed. Such implementations correspond to the second descriptive stage of the framework of Blessing and Chakrabarti (2009) and are a prominent candidate for future research in terms

of implementing a knowledge repository and assessment methodology for technology reuse feasibility.

5. **Search for disconfirming evidence** has been performed through a broad literature review and a critical analysis of whether the expressed needs of the case company were in fact real needs based on comparison to cases from the literature. Also, the negative feedback from the demonstration of the Wiki and the technology reuse assessment 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 company, and by interviewing them both before and after the demonstrators were illustrated to avoid biased answers. However, a more thorough examination of reports and other documentation would have deepened our understanding of the content of codified technological knowledge. Instead, statements by interviewees have been our primary source for drawing conclusions about the availability and accessibility of information, which may be subjective and not representative of the company as a whole.
7. **Quasi-statistics** have only been used to a limited extent when reporting on findings from interviews by indicating whether an opinion was shared by a few or the majority of the respondents. Asking for numeric ratings to statements and employing larger samples would have increased the validity of findings.
8. **Comparisons** have not been used which is a major limitation of the generalizability of the results from these studies. However, they provide opportunities for testing the external validity in future studies, as well as examining the causal impact of implementing the proposed solutions by comparing the situation before and after such interventions.

5.3 Contributions to Theory

As its title suggests, this thesis makes its primary contribution to the study of technology platforms, which is an extension to the concept of product platforms. It can be seen as an applied research field that builds upon previous research in technology management and engineering design. This thesis has focused on how to represent technological knowledge to support the micro-level activities in the interface between technology platforms and product development where knowledge is reused in new applications. Its main contributions to theory are listed below:

a) Identification of different types of needs for access to, and reuse of, technological knowledge (Papers B, C and D).

b) Relating prior research in technology integration and knowledge management to the field of technology platforms to increase understanding of potential challenges faced when realizing strategies for technology reuse on the engineering level.

c) Reports on practices and challenges for how technological knowledge is transferred, stored and accessed in a case company in the aircraft engine industry working with low-volume products with high-technology content (Papers A and B).

d) Support for existing theory that tacit knowledge transfer is key to successful application of technologies, and that decentralized storage of expert knowledge in by-products from normal work is common (Papers A and B).

e) Demonstration of two possible solutions for representing technological knowledge to support reuse, a digital technology catalog and an information model for technologies (Papers B, C and D). The former attempts to support the current strategy of the case company that primarily relies on personification for providing access to technological knowledge, while the latter is a more visionary approach where codified technological knowledge is in focus and supported by personification when necessary.

f) Recognition of the challenge to assess technology reuse feasibility (Paper E).

g) Identification and synthesis of factors that influence the viability and potential challenges of technology reuse (Paper E).

5.4 Implications for Practice

This research had a clear intent to contribute to practice, and the theoretical elements have been used to guide the creation of implementable engineering supports. It is easy to imagine on a theoretical level that leveraging the synergetic effects of reusing technologies across applications would be a profitable strategy. However, without smart ways of changing the ways engineers work with technologies and technological knowledge, such strategies risk leading to the creation of excessive and useless documentation, as well as naive decisions on technology reuse that fail to account for the difficulties in applying technologies to new application contexts.

For companies that want to implement a general strategy that promotes the creation and repeated exploitation of technological capabilities across applications, this thesis proposes the following recommendations:

a) Classify technologies and appoint experts to them who can moderate and review collections of codified content and be contact persons for reusers who need help with referrals or access to tacit knowledge. During technology integration, there is often a need to also have experts that engage in the process in order to build trust in the technology and be able to cope with unexpected problems.

b) Do not expect people to document and refine records of technological knowledge out of their own interest. Necessary components for ensuring the creation of reusable documentation for technological knowledge include: a formal reuse strategy, requirements on knowledge documentation, a funding source and time for activities supporting reuse, encouragement to think of potential reusers of one's work, as well as formats and repositories for making knowledge available to others.

c) Start small to make sure there is at least a starting point for accessing technological knowledge. By contrast, the absence of a central repository for general technological knowledge leads to low awareness of existing technological capabilities and barriers to finding knowledge that potential reusers may search for. All technologies should be possible to represent with basic information, examples of applications and referrals to experts and more detailed records that describe them, even if such detailed records could require additional access permission.

d) The decisions on how much effort to spend on knowledge codification and refinement would likely have to be made by technology experts themselves in combination with training or consulting on knowledge management expertise. These decisions should address, e.g.: which knowledge could be reused, if it is tacit or explicit, how much knowledge reusers already know and would need to know, whether they know to look for knowledge or if it needs to be pushed to them, how often the knowledge is needed, the importance for reusers to actually reuse existing knowledge, i.e. the potential implications if existing knowledge is overlooked and not reused, and how often the knowledge changes and would need to be updated.

e) Companies that operate as engineer-to-order suppliers and cannot use a modular product architecture to configure products that satisfy customer requirements should consider the possibility to use technology-based configurable platforms. This approach would allow them to quickly generate and analyze a wide range of product concepts within feasible design ranges. This would require that technology constraints and dependencies are modeled in a database, e.g. in a PLM system, to set the boundary conditions for the configurator software.

f) Avoid speaking of technologies as generally mature and ready for application. Technologies must be treated with respect to the applications for which they are considered and the applications for which they have been previously enabled and proven.

g) Install a formal process for assessing technologies before they are reused in new applications to ensure that reuse decisions recognize any predictable challenges related to the enabling of the technology and necessary knowledge transfer.

6 CONCLUSIONS

'Technology platforms' is an approach for companies to systematically leverage their technologies across different applications, but it has previously been studied mainly from the business strategy and management perspectives. This research has attempted to contribute to theory on the approach by studying its implications at the engineering level, with a particular focus on existing challenges for the effective reuse of technological knowledge in new applications. The research also aimed to contribute to practice, which led to the development of methods and tools for organizing and assessing technological knowledge to help engineers find and recontextualize it to new applications.

A company operating as a supplier of technologically advanced components in the aircraft engine industry that faces these challenges was studied as a case throughout the research. The overall approach for the research was guided by a Design Research Methodology, including both descriptive and prescriptive elements, in order to answer three research questions described further below. In the descriptive phases, literature reviews and interviews with engineers and managers at the case company were used as the primary methods for data collection. The development of methods and tools for the prescriptive parts of the research was based on both findings from the empirical studies and existent literature, mostly from the academic fields of technology management and knowledge management.

The first of the three research questions posed in this thesis inquired about the barriers that exist against efficient technology reuse at the engineering level. The answer provided by this research concerned two main elements. The first was the difficulties of locating and deploying knowledge generated by previous development projects, which is a problem that is shared by most organizations and addressed in the knowledge management literature. The second type of barriers related to the nature of technologies: the need for adapting technologies before introduction in new applications. Thus, knowledge management and technology integration are two important areas to address when facing challenges to the reuse of technologies. If a company successfully establishes a culture, processes and an infrastructure for managing knowledge in general, they would be well prepared for reusing technologies. However, to support reuse of technologies specifically, there should also be a way to retrieve knowledge related to a certain technology and support for evaluating and integrating that knowledge in new applications.

The second research question was partly based on the answer to the first question and focused on how to organize knowledge about technologies that exists within a company in order to make it accessible for reuse. The proposed answer is to adapt knowledge repositories specifically to the characteristics of technologies and their development. A couple of recommendations about how they may be designed were presented. A central repository in the form of a 'technology catalog' was first proposed to allow easy access to basic knowledge and links to detailed records and contact information to relevant experts. A prototype based on Wiki software was developed and demonstrated at the case company, which received very positive feedback. However, concerns were raised whether it would gain momentum in terms of use and whether the risks of security and misinformation may be mitigated, which indicated that a static repository with a similar interface for its users might be sufficient.

Another contribution relating to the second research question was how to organize technological knowledge when using a ‘technology-based configurable platform approach’. This approach features several levels of platform thinking to take advantage of different opportunities for reuse, of which the modeling of technologies represents the widest and most generic level. In this context, the technology platform acts as a source of knowledge towards the development of both product platforms and the product concepts derived from them. By modeling technologies in a PLM system with information about their limitations on important design parameters, the software configurators used by the platform approach could automatically generate and analyze multiple product concepts that fall within the design space allowed by the included technologies. This model of development for reuse has been tested in demonstrators and gained appreciation on a theoretical level among our industrial partners of this research, but has yet to be tested in a live business setting.

The third research question focused on how companies can assess potential challenges related to the reuse of technologies in new applications. The problem was framed as a combination of two overall dimensions, technology adaptation and knowledge transfer, which were further divided into a set of influencing factors. From discussions with the case company, a methodology featuring a scorecard that probes these factors was developed for supporting technology reuse assessments. The scorecard was designed to be used by technology experts in a workshop setting as a way to stimulate discussions and provide better identification, communication and treatment of potential issues before decisions are made on technology reuse. The factors addressed in the scorecard were identified by reviewing previous research on technology management and knowledge transfer. Preliminary evaluations of the scorecard and methodology show great promise, and further tests will be necessary to answer a couple of remaining questions: whether the format can be refined to improve ease of use and, more importantly, if it can help predict and prevent potential complications in the technology integration phase. These validations could well be made within the companies themselves as a part of their implementation of the methods, but it would also be of interest to the academic community to monitor and report on such results.

The results presented in this thesis are subject to a number of important limitations. First of all, they rely primarily on a single-case research method, which limits the possibilities to generalize the results to other cases. While the case company has been described as ‘typical’ to its industry, there may well be contingent factors that threaten the external validity of the results. Further, neither of the proposed supports has undergone rigorous evaluation in real settings. Preliminary tests have been made for the Wiki-based technology catalog and the reuse assessment method by asking their intended users to give comments on expected usefulness and what they would like to change in their design. The general feedback was very positive for both, and real implementations would be necessary to validate them further.

7 FUTURE WORK

The work outlined in this thesis is mainly exploratory and has led to propositions on how engineering practices can be improved to support technology reuse. Further validation is needed to determine their effectiveness, which constitutes a viable opportunity for future research. More specifically, the following questions would be interesting to find answers to:

a) *To what extent does an introduction of a technology-centric knowledge repository increase the reuse of technological knowledge?*

   The partial validation in this research has not measured quantitatively the value of introducing knowledge repositories. It is a challenge to measure such effects, but possible starting points could be to ask engineers about their awareness of, and access to, technological knowledge before and after an introduction, which by logical reasoning should be positively correlated with the amount of performed reuse.

b) *How is the perceived usefulness of a repository for technological knowledge contingent on a company's organizational and technology characteristics?*

   There is a cost associated with creating and maintaining a repository of knowledge, which in some organizations can be a good investment while in others would not be worthwhile. For instance, organizations that have the same domain-specific knowledge in multiple units have a greater need for synchronization, which could motivate the use of a shared repository. In contrast, if the technological knowledge were held by only one group that can independently apply it in implementations, a local repository would probably suffice. Cross-case studies could potentially reveal how different organizations perceive the usefulness of the two types of repositories for technological knowledge proposed in this thesis.

c) *What factors should be assessed when evaluating the business case for refining and packaging knowledge about a technology to facilitate reuse?*

   Assuming that it is possible to improve reusability of technological knowledge by spending time on refining its content and format, there is a trade-off between the investment in reusability and the cost of reuse. For instance, calculation of mechanical stress, which could be regarded as a technology, is performed frequently in most product developing companies and is time-consuming to do manually. Therefore, there has been reason to invest in automating the process with computer-aided design tools. A new manufacturing technology on the other hand might be developing rapidly, require tacit knowledge for its application and be performed only on a few products. Hence, efforts to standardize and automate the process of application would probably be waste of time since more time would be spent on updating the manuals than on actually performing the work. Since there are several cognitive biases that prohibit us from making rational decisions when comparing current efforts to uncertain future gains, it could be highly useful to create support for making such decisions. A general practice to make such assessments of how to best support reuse of each technology could also represent a lean and bottom-up approach to ensuring that technological knowledge is efficiently leveraged from the whole technology portfolio. The discussion about 'Technology Communication Plans' in Chapter 5.1 represents an effort to address this area of future work.

d) *To what extent can potential challenges of technology reuse be predicted and prevented by using the TEchnology Reuse Assessment (TERA)?*

   It is reasonable to believe that the probing of different dimensions that have been proven to affect technology integration and knowledge transfer would be helpful. However, the awareness of a problem type may not be enough to predict a problem in a specific case. Comparison of data from a retrospective study on technology reuse related problems at a company with those appearing after the introduction of a technology reuse assessment could potentially show which types of problems, if any, that decrease or come expected rather than unexpected when the assessment is used.

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