THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards Development Platforms

Models, Processes and IT-Tools for Platform-Based Development across the Lifecycle

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Abstract

Product developing companies strive to provide their customers with high quality products, more quickly than their competitors, using as few resources as possible. One way of managing all three aspects at the same time is to reuse old, quality assured designs and knowledge in new products. A common way to do that is to create a platform with designs that are reusable in many different products.

Traditionally, research on platforms has focused on finding ways to provide manufacturing with a low number of parts to be able to increase utilization of expensive production equipment. However, a designer needs more information than just the physical form of a design in order to reuse the design to *cut development lead-time*. The use of platforms based on core technologies and re-configurable systems as platform elements may on the other hand give the needed support. These types of platforms are here referred to as *development platforms*. This thesis elaborates on support for working with development platforms that are integrated across the lifecycle of a product.

The studies in this thesis show that platform approaches in literature today do not cover the need to support holistic platform development across all stages of a lifecycle. As a solution, configurable system elements may be used as a bridge between abstract descriptions of platforms (e.g. technology platforms) and concrete descriptions (e.g. part-based and module-based platforms).

Further, development platforms may be supported by a Product Lifecycle Management (PLM) architecture for engineering-to-order configuration, but it can also serve as a tool to learn about the knowledge gaps that need to be filled to get a product to meet requirements. However, there is a great risk in trying to support design reuse with IT-applications alone. In order to fully support platform-based development, an organization needs to consider *business objectives*, *processes*, *information architecture* and *application architecture*.

Keywords: product development, technology development, platform-based design, product lifecycle management, configurable components.

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Christoffer Levandowski
Gothenburg, September 2012

Appended Publications

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

Paper A

Levandowski, C., Edholm, P., Ekstedt, F., Carlsson, J., Söderberg, R., and Johannesson, H., 2011, "PLM Architecture for Optimization of Geometrical Interfaces in a Product Platform", *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference - ASME IDETC/CIE 2011*, Washington DC, USA.

Paper B

Levandowski, C., Forslund, A., Söderberg, R., and Johannesson, H., 2012 "Platform Strategies from a PLM Perspective - Theory and Practice for the Aerospace Industry", *53rd Structures, Structural Dynamics, and Materials and Co-located Conferences - AIAA/ASME*, Honolulu, HI, USA.

Paper C

Levandowski, C., Bokinge, M., Malmqvist, J., and Johannesson, H., 2012 "PLM as Support for Global Design Reuse - Long Term Benefits and Immediate Drawbacks", 9th International Conference on Product Lifecycle Management - PLM12, Montreal, Canada.

Paper D

Levandowski, C., Corin Stig, D., Bergsjö, D., Forslund, A., Söderberg, R., and Johannesson, H., 2012, "An Integrated Approach to Technology Platform and Product Platform Development," *Accepted to: Concurrent Engineering - Research and Applications.*

Distribution of work

Paper A

Levandowski wrote the paper and created the PLM system architecture and process. Ekstedt created the robustness optimization. All authors contributed in creating the case scenario. Carlson, Söderberg and Johannesson contributed as reviewers.

Paper B

Levandowski did the literature analysis and wrote the paper and also created the PLM system architecture and process. Levandowski and Forslund created the case scenario. Söderberg and Johannesson contributed as reviewers.

Paper C

Levandowski did the analysis and wrote the paper. Levandowski and Bokinge performed the interviews. Malmqvist and Johannesson contributed as reviewers.

Paper D

Levandowski, Bergsjö, Corin Stig and Forslund and wrote the paper. Levandowski created the system architecture. Levandowski, Corin Stig and Bergsjö set up the case, and did the analysis. Levandowski, Bergsjö, Corin Stig, Högman and Forslund contributed to the empirical data. Söderberg and Johannesson contributed as reviewers.

Additional Publications

The following publications are related to the research presented in this thesis although not making a central contribution to the result.

Bengtsson, K., Michaelis, M. T., Levandowski, C., Lennartson, B., and Johannesson, H., 2010, "Towards Sequence Planning Based on Configurable Product and Manufacturing System Platforms," *Proceedings of the 8th International Conference - NordDesign 2010*, Gothenburg, Sweden.

Edholm, P., Levandowski, C., Johannesson, H., and Söderberg, R., 2010, "Applied CC configuration in PDM/CAD environment," *INTECH 2010*, Prague, Czech Republic.

Bokinge, M., Levandowski, C., and Tidstam, A., 2011, "PLM and International Product Development," Entering the Tiger's Cave, D. Bergsjö, ed., *Department of Product and Production Development, Chalmers University of Technology*, Gothenburg, Sweden, pp. 13-18.

Bokinge, M., Levandowski, C., Johannesson, H., and Malmqvist, J., 2012, ”A Method to Identify Risks Associated with a PLM Solution", *The 9th International Conference on Product Lifecycle Management - PLM 12*, Montreal, Canada.

Forslund, A., Söderberg, R., Lööf, J. and Levandowski, C., 2012, ”Robust Lifecycle Optimization of Turbine Components using Simulation Platforms”, The *28th Congress of the International Council of the Aeronautical Sciences - ICAS 2012*, Brisbane, Australia.

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1 Introduction

> *"The world as we have created it is a process of our thinking. It cannot be changed without changing our thinking." - Albert Einstein*

Product development is all around us. The products that we use every day, such as the computers we are using in our work, the car that almost ran you over on your way to work, or the toaster that makes our bread crisp and delightful for breakfast are all results of product development. Often, companies have several thousand employees working with developing new products for the market; a market that is more or less unpredictable. The economic success of most companies depends on how well they are able to identify and interpret the needs of their customers and quickly create products that answer those needs and that can be manufactured at low cost (Ulrich and Eppinger, 2008).

In other words, companies strive to provide their customers with high quality products, faster than their competitors, using as few resources as possible. However, time, quality and cost have traditionally been seen as in conflict. In other terms, if you for example want to achieve high quality, you will most probably end up with a higher cost product that may take longer to develop. Similarly, if you want to achieve a low cost product you would have to compensate by lowering the quality of the product.

One way of managing all three aspects at the same time is to reuse old, quality assured designs in new products. A common way to accomplish that is to create a platform with designs that are reusable in many different products. The combination of different parts or modules creates a variety of products that fulfill a range of customer needs (customization), but still keeps the number of parts at a minimum (commonality).

Using platforms increases quality and reduces risk through the use of already developed and verified designs. It also lowers the cost of production since expensive manufacturing equipment can be used longer. For purchased parts, the volume will also go up, thus allowing for bulk discounts.

Perhaps even more interesting is that it is not only a way to gain the benefits of scale in production, but also development (Jiao, et al., 2007, Meyer and Lehnerd, 1997, Robertson and Ulrich, 1998). Platforms decrease the time it takes to develop new designs because they provide a head start; not all parts need to be redesigned. In product development, the single largest cost is engineering hours. Thus, by reducing the lead-time and engineering time for new designs, platforms enable companies to be bring products to the market earlier at a lower cost.

To be able to increase the utilization of expensive production equipment, traditionally, research in platforms has focused on finding ways to provide manufacturing with a low number of parts. However, to cut lead-time and gain first mover advantages, platforms need to support efficiency in the product development phase as well (Wheelwright and Clark, 1992). Platforms based on parts alone do not provide the support that product development needs in order to attain such efficiency (Gedell, 2011). A designer needs more information than just the physical form of a design, for example why a subsystem looks the way it does and what function it realizes in order to reuse a design. These subsystems must also be scalable, or re-configurable, to fit many different products while fulfilling the same function. These types of platforms are henceforth referred to as *technology-based configurable platforms* or *development platforms*.

1.1 Supporting Product Development

The benefits of platforms are rigorously examined in research (Jiao, et al., 2007) and depend not only on definitions in theory, but also on how the platform effort is supported and how that support is implemented. For long, IT-tools have been used to manage knowledge and knowledge reuse (Abramovici, 2002). However, no software tool has the perfect fit for all business processes of a company, e.g. technology development and product development. The combined capabilities of different tools may, on the other hand, very well satisfy the needs (Burr, et al., 2003).

In technology development there are no established or commonly used data management systems similar to those used product development and production. On the product side, the rapid growth of product requirements in both number and complexity demands increasingly accurate analyses to be able to decide if a concept is feasible or not. Furthermore, the complex processes of configuring products require vast databases that can store and mine complex relations, much different from the flexible structures required for technology development.

It is apparent that different stages of the product lifecycle require different support, yet there needs to be an integrated approach on how to leverage the knowledge created throughout the lifecycle.

Product Lifecycle Management (PLM) is a business approach that aims to integrate the business processes of an organization, as well as managing the information generated during the lifecycle. Integrating software tools to make the engineering design work run smoothly is a major part of PLM as well, all aiming at supporting the system needs of the system users (Stark, 2005). Managing complex platforms requires a great deal from the business and PLM has proven useful to many. PLM is about giving all members in an organization *the right information, in the right context, at the right time* (Dutta and Wolowicz, 2005).

1.2 Research Focus

The research presented in the thesis elaborates on platforms – in particular platforms based on the reuse of technologies and generic configurable concepts – and how to support the development and use thereof. Special consideration has been given to Product Lifecycle Management as a means considering not only the development phase, but also incorporating greater parts of the product lifecycle. More explicitly, many of the results aim at supporting the actual platform-based design process.

When speaking of PLM, people generally imagine a *PLM system*. Even though system support certainly is one of the major parts of PLM, there are several equally important aspects needed to fully support platform-based design. Thus, the focus of this thesis is to adopt a holistic view on support for platform-based design throughout the lifecycle of a product. In summary, the foci of the research presented in this thesis are the following:

- Support for a new paradigm of platform-based development based on core technologies and re-configurable systems as platform elements
- Supporting platform-based development that is integrated across the lifecycle of a product

1.2.1 Industrial Goals

In order to survive in the competitive environment in which manufacturing companies reside, efficiency in producing new products is a necessity. Platform-based design is the reality of many companies, yet their tools and processes are often best suited to single product development. The results from this thesis aim to provide manufacturing companies with insights into what is required to fully utilize the potential of platform-based design. Further, in terms of software tools and methods, the goal is to provide industry with demonstrators of what is possible with platform-based development, exceeding the tools that are used today.

1.2.2 Scientific Goal

PLM as a strategy for platform-based development has, from a scientific point of view, been studied previously. The focus has, however, been on PDM, rather than on the full spectra of PLM, and has further supported a platform paradigm where the platform is viewed as a set of physical parts or assemblies that are combined in different ways, resulting in different product variants. The aim of this thesis is to elaborate on design support for platforms based on core technologies and generic configurable systems that contain knowledge other than solely the physical representation of a part – by instead focusing on subsystems that fulfill functions. Finally, another goal is to present support for platform-based development conducted in an environment that is integrated across the lifecycle, creating a closer connection between technology development, product development, and manufacturing.

1.2.3 Research questions

To put the research focus into concrete words, four research questions are posed below. The questions are contextualized through the research focus. The research goals are met by answering these questions. The focus for this thesis is on the first two questions.

RQ1. What current business processes and IT tools can support design using technology-based configurable platforms, and how can they be improved to better suit them?

RQ2. What is the benefit of integrating platforms across the lifecycle, and how can PLM enable it?

RQ3. What are the benefits of using PLM as enabler for platform-based design, and how may drawbacks be managed?

RQ4. What constitutes good PLM support for platform-based design?

1.3 Delineations of the research

This thesis will focus on the technical aspects of supporting platform-based development. Thus, it will not prescribe ways to scope the platform to fit certain markets, including determining the bandwidth of parameters based on market requirements. It will, however, elaborate on the technical possibilities of defining bandwidth based on core technologies within a company.

As this is a licentiate thesis, the research will continue, leaving room for validating the research further after the thesis has been presented. Thus, the verification of the results in a real industrial development project remains.

2 Frame of Reference

This chapter brings attention to literature on which the results and reasoning of thesis rest. Further, this chapter explains important concepts, phenomena and the context to which the research in this thesis relates. As Isaac Newton expressed it, while citing Bernard of Chartres:

> *"If I have seen further, it is by standing on the shoulders of giants".*

2.1 Engineering Design

Engineering design has been a vital part of our civilization for as long as anyone can remember. Traditionally, skilled craftsmen developed and manufactured products based on solving everyday problems. As for the consumer market, blacksmiths and shoemakers, for example, would craft their products based on what their customers needed, producing unique products to fit each and every customer. At best, they would use drawings to describe their products. Often, it was sufficient to describe a product with a list of parts (Claesson, et al., 2001).

The industrial revolution (1770-1800) was the start of a new era during which goods and consumer products were mass produced, rather than customized to a specific customer. By 1850, it was the dominant manufacturing principle in the U.S. Products were described as hierarchical structures. Efforts were made to customize products by changing parts, but perfect interchangeability was never achieved (Duguay, et al., 1997).

As products grew increasingly sophisticated, more advanced ways of describing both the products, and the variability of the products emerged (more about that in section 2.4.3). More advanced products, and the requirement for efficiency resulted in large organizations dispersed across the world.

To achieve efficiency across the lifecycle, it is now common that several business processes run in parallel (Prasad, 1996). This type of concurrent engineering (CE) allows for example technology development, product development and manufacturing development to start sooner than in pure sequential development, thus shortening the lead time. On the other hand, it requires integration of teams, tools and product information. Having reusable digital product and process models, such as seen in a platform is a way to facilitate concurrency (Prasad, 1996).

2.2 The engineering design process

Numerous researchers throughout the years have studied the process of designing a product. Several of the approaches have in common that they prescribe a model for how to proceed; a product development process (Hubka and Eder, 1988). Pahl and Betiz (Pahl, et al., 1988) as well as Ulrich and Eppinger (2008) contribute to the area of systematic design, describing processes and methods to manage complex product development. Both are examples of approaches that have been revised (Pahl and Beitz, 1996, Ulrich and Eppinger, 2012) to encapsulate new areas of product development, including for example considerations of additional lifecycle stages.

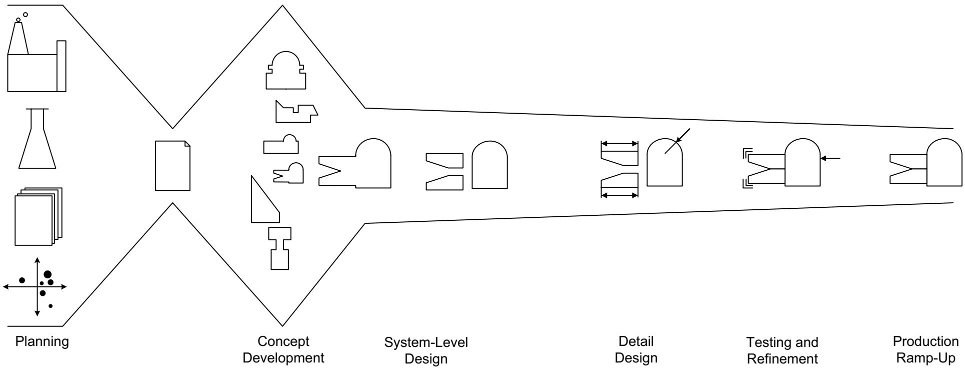

Figure 1 - The development funnel, as proposed by Ulrich and Eppinger (2012)

Ulrich and Eppinger (2008) describe the different steps in a typical product development process as depicted in Figure 1.

- *Planning* usually precedes the actual start of the project, and includes outlining strategies and approving investments in new technology. Here, the goals for the project are established.
- *Concept development* identifies market needs and targets and creates alternative product concepts. A concept can be described by function, form, and features, usually accompanied by a set of specifications.
- *Detail design* includes the complete specification of geometry, material selection and tooling design for each part of a product. Issues such as production cost and robust performance are managed in this phase.
- *Testing and refinement* focuses on development of prototypes and preproduction series. The design is verified against customer requirements, such as performance and reliability.

- *Production ramp-up* initiates the production of the final design. The purpose of this phase is to train the production work force and work out any remaining errors in the production process before proceeding to full-scale production.

2.3 The platform design process

The design process is the driver for all types of reuse throughout the lifecycle (Inns and Neville, 1998). The design process for platform-based design will therefore look different from the process of single product development. As opposed to designing single products, platform-based design is about modeling a wide set of potential solutions. These solutions need to share characteristics, but at the same time be distinct (Pedersen, 2009). On a higher level, design processes such as Ulrich and Eppinger (2008) and Pahl and Beitz (1996) apply, but the design philosophy behind these methodologies differ a great deal. Matters such as identifying the proper bandwidth of a subsystem and making designs reusable are inferior in single product development, but crucial to platform-based development. Further, it is within platform-based design necessary to distinguish between developing a platform, and using an existing platform as a means from which to derive product variants.

2.3.1 The platform lifecycle

Pedersen (Pedersen, 2009) defines three fundamental phases in the development of a platform: *platform preparation*, *platform execution*, and *platform maintenance*. Roughly, most design decisions are made during the preparation phase. The subsequent execution phase, however, is where the product variants are actually generated – something that should be considerably less effort if the preparation was done correctly. Upgrades and maintenance are conducted during the maintenance phase during which issues are addressed and the platform is kept updated.

While preparing the platform, a first step is often scoping the platform (Pedersen, 2009). As a part of the scoping segmentation is utterly important (Meyer and Lehnerd, 1997) and often time consuming. It incorporates the early phases of market segmentation and mapping the future product platform to customer needs, or in other ways identified market segments. The methods for scoping platforms are many, some of which use information from previous products to improve the accuracy of the mapping between market and product (Meyer and Utterback, 1992).

Another view of the processes in platform-based design is presented by Berglund et al. (Berglund, et al., 2008) and later refined by Bergsjö (2011). The platform development framework presented incorporates technology platforms, product platforms and production platforms. Figure 2 illustrates the different components of the platform development process. A distinction is made between platform projects that deliver knowledge to the product and process platforms and derivative projects (also called variant projects) that generate product variants for the market.

What Bergsjö (2011) illustrates is that a technology platform feeds the product and process platform projects with knowledge developed during previous technology development efforts. This stands in contrast to single product development where technology development projects feed the derivative projects directly (Jolly and Nasiriyar, 2007). When it comes to technology platforms, platform execution focuses on implementing technologies into a product platform (Bergsjö, 2011).

2.3.2 Differences between single product and platform-based development

Shahin et al. (1999) use the established process in much the same way as Ulrich and Eppinger, but identify crucial steps where design reuse is facilitated. They mean that reuse can be performed on different levels and that reuse needs to be actively

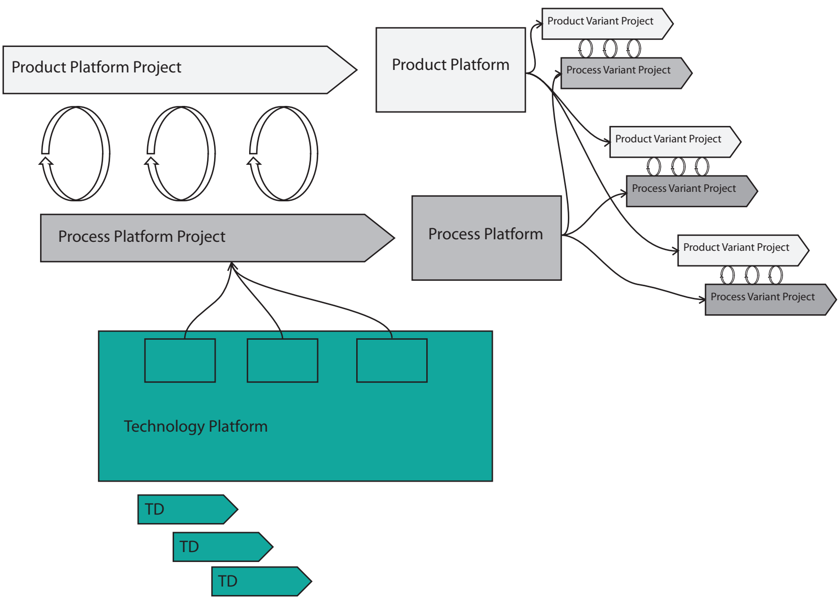

Figure 2: Platform-based development, redrawn from Bergsjö (2011).

considered. For example, modeling the functions of a product during the concept phase allows for reusing of function carrying concepts at a later stage. Pedersen (2009) identifies the presence of "intangible elements such as activities or organs" as a challenge in modeling *and* mindset. He also highlights a few key issues in platform-based design:

- The platform is both a concept and a design template – thus the design template has to be designed (preparation) and thereafter derivative products are designed (execution)
- There are profound implications for product complexity and efficiency in the links to the lifecycle phases, and in particular to the production setup.

An essential principle in the design process is that designers with the proper understanding of the design context make better decisions (Hansen and Andreasen, 2002). The same applies to platform-based design. The fundamental difference is that the basis for several product variants are created simultaneously, making the design context immensely more complex to overview (Pedersen, 2009) – elements of the platform can be both generic and varying, and trade-offs must be made that would not have been necessary in single product development.

2.4 Defining a platform

Using a platform as a means of reusing knowledge has been receiving a lot of attention over the past decade (Jiao, et al., 2007). It is not only a way to gain benefits of scale in production, but it also benefits development (Jiao, et al., 2007, Meyer and Lehnerd, 1997, Robertson and Ulrich, 1998). The common view of a product platform is as a collection of different parts that can be combined into a variety of products, such as for example Lego.

A slightly more abstract definition is provided by Meyer and Lehnerd (1997), who state that a product platform is *"a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced"*.

Robertson and Ulrich (1998) take an even wider grip on the term and define a platform as "the collected *assets shared by a family of products"* – an asset being a component, a subsystem, manufacturing equipment, a process or even an individual.

Based on this reasoning it is not far to start looking at technology platforms as a basis for the systematic reuse of solutions found in technology development projects. McGrath (2001) defines a technology platform as "a set of initiatives organized around a macro-level functionality that helps to manage and optimize technology investments across multiple product platforms". Similar definitions of technology platforms as bases for different products and markets have also been proposed by, for example, Meyer and Lehnerd (1997), Shapiro (2006), and Jolly and Nasiriyar (2007) and the concept of technology platforms has similarities to core competencies and dynamic capabilities (Jolly and Nasiriyar, 2007, McGrath, 2001).

2.4.1 Different kinds of platforms

Many describe platforms, providing different solutions for different parts of a product lifecycle. Examples of platform approaches that cover large areas of the lifecycle include the Product Family Master Plan (PFMP) by Mortensen (2000), which has been further developed (Mortensen, et al., 2008) to encompass additional aspects. The PFMP encompasses capabilities for scoping the platform based on, for example, sales volume for each variant, as well as the need for production system investments.

Other approaches target specific parts of the lifecycle. Mesehovic & Malmqvist (2004) describe how a product platform can be used as a basis for sales configuration, combining parts into different product variants, while Haug et al. (2012) describe system solutions and how to manage them. Harlou (2005) deals with strategic fundamentals and how to achieve the business goals of a product platform.

Others authors focus on a *technology platform* and supporting its use, for example Corin Stig & Bergsjö (2011) who describe a Wiki solution for managing reusable technology knowledge. Högman (2011) prescribes a technology development stage-gate process specifically aimed at the aerospace industry. Bergsjö (2011) uses a platform framework, consisting of technology, product and production platforms to elaborate on the implementation of a technology platform and accompanying IT tools. In terms of managing technologies and reusing them, Meyer & Utterback (1992) present their work on core competences and the effects of managing them well.

Production platforms in various forms are discussed by Erixon et al. (1996) as well as Michaelis (2011). The former uses modularization of the product and the production system as a way to increase the efficiency of development and production. The latter, Michaelis, describes how co-development of the product and production platforms can be performed. Gedell et al. (2011) speak of a unified product and production platform.

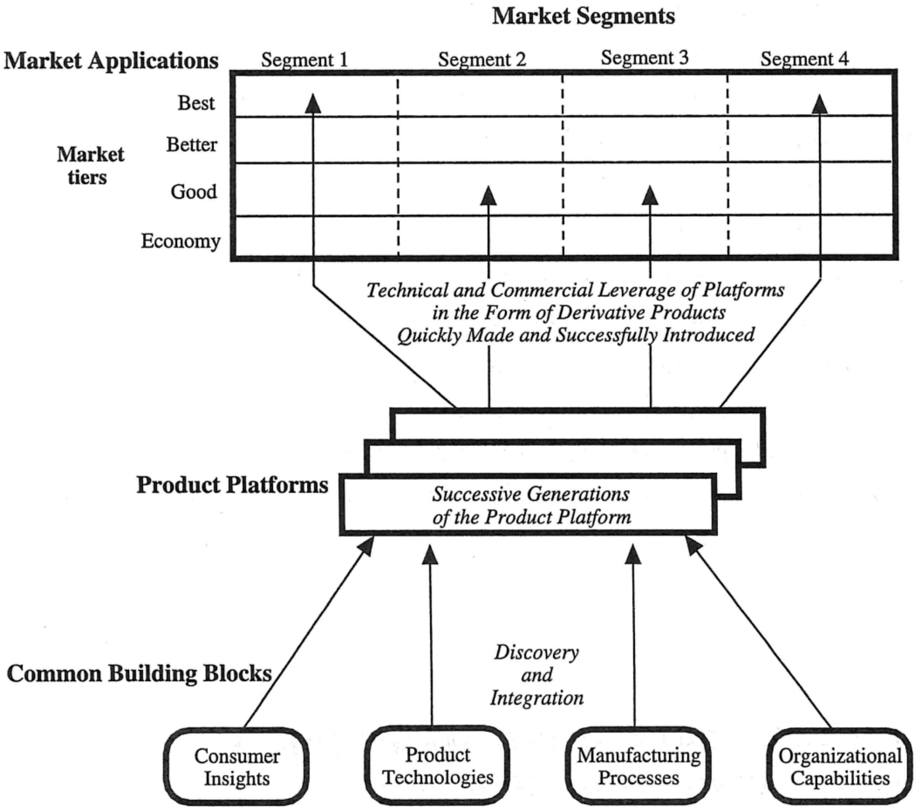

Figure 3 - Different levels of a platform, according to Meyer and Lehnerd (1997)

2.4.2 Holistic platform descriptions – technology and product platforms and their relationship

The different platform approaches mentioned above form a patchwork of tools, methods and strategies across the lifecycle. There are, however, attempts for a more holistic view of platforms.

Even though both Meyer and Lehnerd (1997) and Robertson and Ulrich (1998) base their view of a platform on the assumption of a *product* platform, they manage to encompass more in their definitions – perhaps the former pair of authors even more than the latter. Meyer and Lehnerd (1997) identify three different levels in a platform (Figure 3): the common building blocks; the product platform itself according to their definition; and variants generated from the product platform that together constitute a product family.

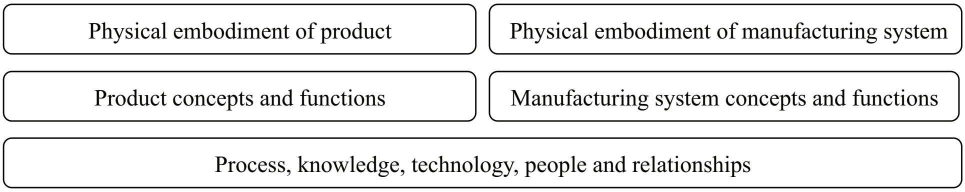

Figure 4. Levels of abstraction in platform strategies (Redrawn from Michaelis et al. (2010)

Michaelis et al. (2010) argue that on an abstract level, a product platform and a production platform can be described in a similar way. They represent the core technologies, methods and competences of a company. The common building blocks are very similar to what is included in a technology platform (Jolly and Nasiriyar, 2007).

It is difficult to use the same approach for both technology platforms and product platforms. The primary result of technology development varies from the primary result of product development. Typically, technology development has the fuzzy goal of building knowledge or demonstrating feasibility, while product development has the more concrete goal of resulting in a commercial product (Nobelius, 2002). Compared to product platforms, technology platforms capture a larger range of elements, including both physical and non-physical elements (Shapiro, 2006), and do not lend themselves to the building block modules and interface structures of product platforms (McGrath, 2001).

Generally, a company runs platform development parallel to derivative and technology development (Wheelwright and Clark, 1992). Even though the development is run in parallel, a technology platform shall, in one of its uses, act as a basis for developing the product platform in the same way as the product platform acts as basis for configuring product variants.

2.4.3 Modeling platforms

A cornerstone in product development using platforms is the variability of the platform. Van Veen (1991) approaches variability by means of generic bills-of-materials (BOMs), which constitute a configurable platform model. With the generic BOMs it is possible to describe entire product families using one unified model, as opposed to describing individual products (Erens, 1996). Similar to the generic BOM, Mannistö et al. (2001) present their *master BOM*, which is an integrated generic description of several product variants that together constitute the platform.

However, in a response to the inabilities of those early platform models to manage a number of different aspects – for example a variety of multiple design parameters, determination of the number of product variants and determination of the platform extent – other researchers (Hernandez, et al., 2003, Williams, et al., 2007) propose approaches that use continuous variable design parameters. Yet another way of incorporating variability in a product platform and managing the above mentioned problems is the Configurable Component (CC) concept, first developed by Claesson (2006) and further refined through several studies (Edholm, et al., 2010, Gedell, et al., 2011). The approach uses configurable subsystems to compose a product architecture based on input parameters, such as customer demands. The CC concept is more thoroughly described in section 2.4.4.

2.4.4 The Configurable Component concept

A platform described using the CC concept consists of several autonomous systems, each described by a CC object. CC objects can *use* other CC objects to compose themselves. The Configurable Component concept has a great deal in common with a modular product platform, allowing for concurrency while developing the different modules or subsystems (Prasad, 1996), but aims to support a platform approach based on the concept of subsystems and concepts, rather reusing parts. Each subsystem is configurable to fit a variety of contexts and fulfill the same function in each context.

A CC object may represent, for example, an entire car, a front door or a rear view mirror. Essentially, CC objects do not represent merely one type of car door, but rather every door in a product platform – being a model of a system family. Depending on the parameters inserted different variants can be composed and as a result the door will look or behave differently.

There is no unanimously accepted definition of a modular product (Gershenson, et al., 2003) other than that it is made up of modules; building blocks, but a common belief is that fixed or standard interfaces between modules is a condition for success (Schilling and Steensma, 2001, Takeishi, 2002). The CC concept goes quite the opposite way and declares a bandwidth within which platform elements, including interfaces, may vary. Thus, the interfaces are co-configured to fit each other, which allows for keeping design flexibility intact in the development process.

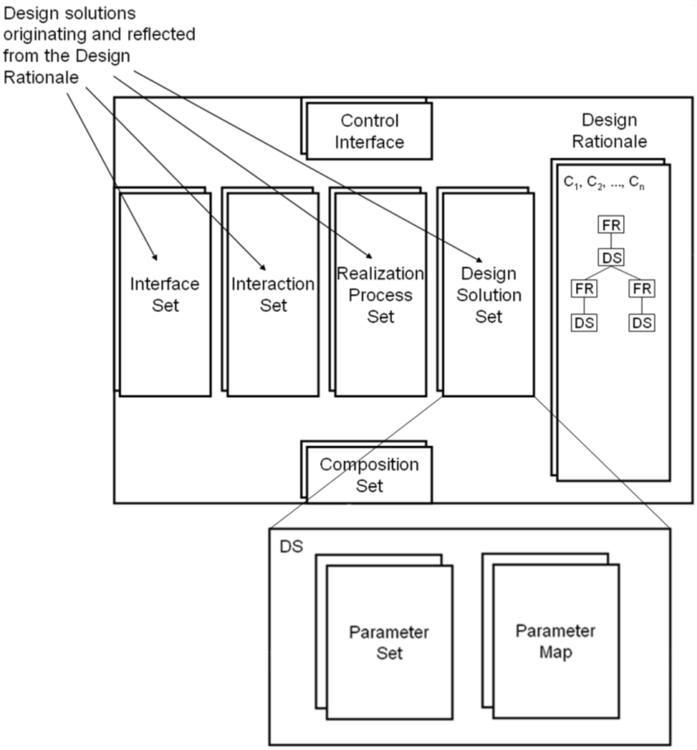

Figure 5 - The building blocks of a configurable component.

The building blocks of the CC object can be seen in Figure 5. The connections with other subsystems are realized through an *interface* (IF) object. The interfaces are configurable and can be geometric, electrical or logical, etc. An interface cannot be configured independently of its surroundings, thus the *interaction* (IA) object serve as communicator between interfaces. So far, two types of geometrical interfaces have been defined within the CC framework (Edholm, et al., 2009, Edholm, et al., 2010), i.e. *Locating Schemes* and *Mating Geometry.*

Locating Schemes are used to fix a physical part to a coordinate system, locking all six degrees of freedom (Edholm, et al., 2009, Edholm, et al., 2010). A locating scheme, represented to the left in Figure 6, is typically made up of six 3D points in a Computer Aided Design (CAD) model and is often realized physically by a pin on one part matching a hole on a facing part.

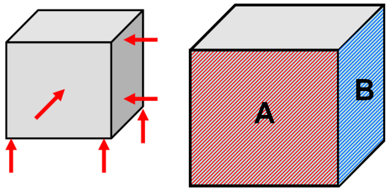

Figure 6 - Locating scheme (to the left) and mating geometry (to the right)

Mating geometries, to the right in Figure 6, are the geometries facing the surroundings (Edholm, et al., 2009, Edholm, et al., 2010). As these geometries constitute the outer boundaries of the subsystem they are crucial for packing ad other functions. Mating geometry also plays a major part in realizing functional requirements, such as transferring torque in a gearbox (the surfaces of the gears need to be in contact).

The configurable *design solutions* (DSs) are tightly connected to the backbone of the CC: the *design rationale*, which is an enhanced function-means tree where the DSs are the means. It also consists of the *functional requirements (FRs)* and *constraints (Cs)* (Schachinger and Johannesson, 2000). Each functional requirement has a bandwidth within which it can vary. Each FR is solved by a DS. To answer to the bandwidth of the FR, the DS in itself has a bandwidth within which it can vary. To cover the entire bandwidth of the FR, it is sometimes necessary to switch between different design concepts. In other words, the FRs have a bandwidth (a parameter range) which is met by a set of design solutions (a concept range) which each and every one also has a bandwidth (a parameter range) (Wahl and Johannesson, 2010).

2.5 Support for design reuse

The development of information technology for engineering applications has resulted in numerous process supporting IT tools over the past decades. At the same time, new engineering methods and processes are introduced, possibly at an even greater pace, leaving a gap between processes and process support (Burr, et al., 2004). Design reuse tools shall support the design process either by supporting the designer in retrieving and reusing knowledge, or by providing the means to capture knowledge generated during the design process (Baxter, et al., 2007).

Frameworks and IT-support for capturing and retrieving knowledge have been researched extensively (e.g. Catic (2011), Hicks et al. (2002), Matsumoto (2005), and

Wood Iii and Agogino (1996)) both by using existing support and by developing customized support.

2.5.1 Computer Aided Design and Computer Aided Engineering

Computer Aided Design (CAD) is used to create a geometrical model of a product. A cornerstone in contemporary design reuse through CAD is parametric design. A set of key parameters of the design are identified (for example the length of a shaft) and all other measurements are defined in relationship to these parameters (Baxter, et al., 2007). Andrews et al. (1999) present two ways (a generative method and a variant method) to store and reuse knowledge in CAD. They conclude that the result depends on the designer's ability to store and retrieve designs systematically.

Full support can only be achieved through the integration of engineering systems (Burr, et al., 2004). Computer Aided Design (CAD) systems are in general well integrated with the PDM system and have thus access to product meta data (Abramovici, 2002), thereby facilitating design reuse by sharing 3D models across the organization. However, there are no satisfying examples of integration of CAE systems for analysis or synthesis out-of-the-box. Information is rather transferred manually or in some cases integrated in one direction alone (Abramovici, 2002, Burr, et al., 2004).

There are, however, examples within research of successful integration of CAE systems through customized solutions. Inoue et al. (2010) argue that the reuse of design through Set-Based Concurrent Engineering may be supported by integrating 3D-CAD and CAE systems. They present an approach to optimize structures within a set of design solutions, arriving at the optimal solution within the bandwidth through the use of integrated CAE and CAD.

2.5.2 PLM architectures

Product Lifecycle Management is widely recognized as a business approach to achieve fast and efficient product development (Grieves, 2006, Ming, et al., 2005, Stark, 2005). CIMData (2010) defines PLM as a strategic business approach that supports the collaborative creation, management, and use of product definition information, spanning from concept to end-of-life of a product or plant, integrating people, processes, business systems, and information. Thus, PLM can be used to tie these varying aspects together.

Contrary to common belief, PLM is not solely an IT system. Stark (2005) argues that there are several additional parts of PLM, such as engineering methods and processes, the organization, the product and product information and IT systems which all need to be considered and coordinated. Svensson et al. (1999) share the same perspective, stating four views: *processes*, *information*, *systems* and *roles*.

Zimmerman (2008) defines a PLM architecture as an IT-centric enterprise architecture, comprised of several different layers or sub-architectures. These layers are described in Figure 7.

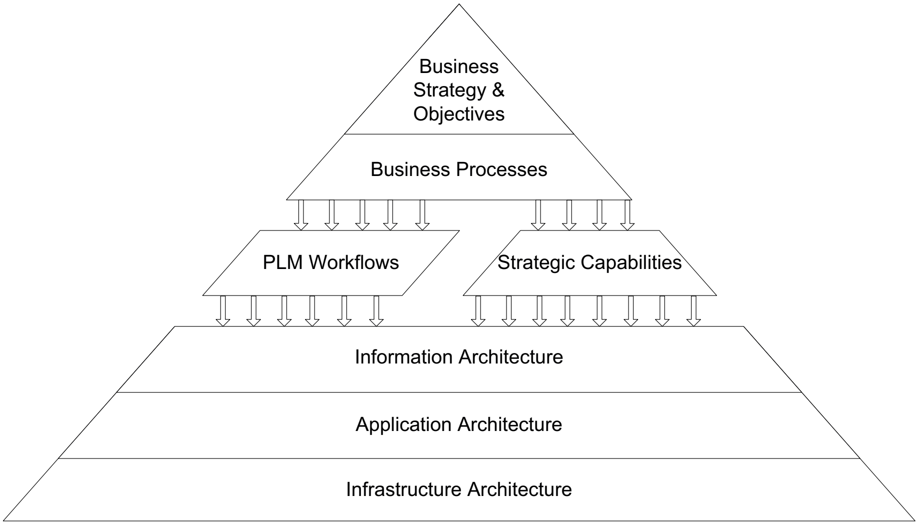

Figure 7. Describing PLM architectures, adapted from Zimmerman (2008) by Catic (2011).

In more detail, the levels may be described as the following:

- *Business Strategy and Objectives* includes the visions and goals of the architecture. It answers the question "What is to be realized by the company?"
- *Business Processes* constitutes the collective processes of the organization and their relationships, which are needed to realize the business strategy and objectives
- *PLM Workflows* are descriptions of how engineers will work with the PLM solutions in order to support the processes
- *Strategic Capabilities* make up basic functionality of the PLM system and are used in the workflows, helping to realize the business processes.

- The *Information Architecture* describes how the information that is used in the PLM workflows and by the strategic capabilities is structured and modeled
- The *Application Architecture* describes the relationship between application and task
- The *Infrastructure Architecture* constitutes the hardware that stores data and runs applications (Catic, 2011).

2.5.3 Wiki solutions

Wiki solutions for capturing abstract generic knowledge such as used in a technology platform concept has proven feasible within software development (Decker, et al., 2005), construction (Dave and Koskela, 2009) and mechanical product and production development (Corin Stig and Bergsjö, 2011). A wiki is a website structure consisting of an indefinite collection of pages in which a registered user can add or edit pages in a built-in editor. The best-known example is Wikipedia, an encyclopedia that has grown organically based on small contributions of information from users worldwide. The main ways of finding information in a wiki are through an efficient search engine and through links between pages. A version tracker is normally present to prevent any loss of information from improper use.

For supporting a technology platform, the content of the pages in a wiki may include basic information about how technology works and where it is used, the current maturity for different applications, the company's plans for future use of the technology and contact information to experts in the field.

Due to the loose structure of a Wiki, a process is needed to guide a designer in creating knowledge according to a structure. Also, knowledge must be a clear deliverable in the process (Catic and Malmqvist, 2010). The loose structure is also what makes it powerful for use in early development phases, during which information is more text-based and where rigid relation databases of a PDM system fail to provide adequate support.

2.5.4 Systems integration and SOA

As a system solution, PLM is an integrator of tools and technologies to facilitate swift and accurate information flow throughout the product lifecycle (Terzi, et al., 2010). Product Data Management (PDM) systems may well be one of the components of the PLM architecture (Abramovici, 2002), but are not considered to constitute the entire PLM strategy.

System integration is an essential issue in PLM. Burr et al. (Burr, et al., 2003) introduce several ways of integrating systems of a PLM architecture. Two concepts are further refined (Burr, et al., 2004): a*ll-in-one-integration* and *best-in-class-integration*. The first is an approach with only one database to which all the systems are connected. The latter, well suited for distributed sets of data, features multiple databases for each discipline with their respective expert tools connected. These data bases are integrated through an integration software component.

Bergsjö et al. (Bergsjö, et al., 2006) refer to Burr et al. but offer four different integration approaches: *best-in-class*; *all-in-one integration*; *one system as integrator* and *peer-to-peer integration*. One system as integrator is a mix between best-in-class integration and all-in-one integration in which some tools are connected to the main database, while others go through their respective expert databases. Finally, peer-to-peer integration is an approach whereby each software component has an individual interface to each and every other software component with which it needs to communicate.

Bergsjö et al. (2008) extends the different types of integration possibilities with Service Oriented Architecture (SOA) as a possible way to integrate distributed sources of information, such with platforms that are integrated across the lifecycle.

2.6 Conclusions of the frame of reference

The definitions of what a platform is differ ranging from the very concrete, i.e. parts, to the abstract i.e. knowledge. The common denominator is reuse. Different approaches to platform-based design are appropriate for different stages of the lifecycle. Thus, different lifecycle stages need varying support. At the same time, companies require a holistic approach to design reuse to enable them to plan development efforts.

There is a big difference between single product and platform-based design. The platform-based design process is much more front-loaded. Further, a designer's task, apart from coming up with a great design, is to create sustainable knowledge that is compliant with the platform making the design context immensely more complex to overview.

There is a great deal of design support. The aim of most tools and processes is to bring about a single design of high quality at low cost. However, few initiatives really consider the phenomena of design reuse. Those that do focus on feeding manufacturing with a low number of different parts, which certainly saves manufacturing cost but has little effect on development time.

In their paper from 2004, Burr et al. (Burr, et al., 2004) conclude that the contemporary engineering systems cannot fully support the emerging engineering methods. They refer to ways of working concurrently by linking different steps in the lifecycle. When it comes to design reuse, especially across technology and product development, it is reasonable to assume that current support needs improvement to fit these engineering processes and methods.

The scope of the research presented in this thesis aims to address the issues above. How platform-based design that saves development time can be supported is particular interest. Further, the thesis means to investigate current tools and processes can be used to support this type of development, also how to achieve a coherent support throughout the product lifecycle.

3 Research Approach

Different disciplines have varying approaches to obtain credible research results. Traditionally, opinions within Engineering on how to find accurate knowledge contrasts to those in the Social Sciences. This chapter describes the research approach, why the particular approach was chosen, and how it was adopted to fit the setting of this research.

3.1 Design and research in design

Engineering Design, or just *Design*, has many definitions, with a majority describing design as the process of bringing about a product based on a need, product idea or technology. The final result is the knowledge about how to manufacture the product to fulfill the perceived needs. It includes activities such as requirements specification, concept and detailed design, process planning and manufacturing systems design, and it often involves both individuals and enterprises. The final result may be a tangible object, but it may also be a service or a process.

Research within design is an area that has grown in importance over the past thirty years, resulting in a deep body of knowledge spanning a broad area of disciplines. The area relates to Engineering Science, which is broad in itself, connecting disciplines such as thermodynamics, materials and mechanics. The paradigm that forms design research began to grow with the increasing importance of managing complexity of designs in addition to economical aspects of engineering. The following was concluded:

> *"There is a big gap between scientific research and the engineering product, which has to be bridged by the art of the engineer." (Gibbons and Johnson, 1982).*

Thus, now design research is a field of its own, connecting to Engineering Sciences. There are also several other areas used in design research, for example Behavioral Science, which plays a pivotal role in understanding how engineers work, which is key to being able to support the design process. Further, designers rarely work alone, making the Social Sciences a neighboring field.

The definition of design research and how it differs from similar fields is ongoing (Blessing and Chakrabarti, 2009). Blessing and Chakrabarti (2009) contribute with their definition of design research by claiming two different views on design research: the development of *understanding* and the development of *support*. *Understanding* is to formulate and validate theories about design and related phenomena, including all connected facets (people, product, knowledge/methods/tools, organization, micro-economy and macro-economy). To develop *support* for design is to develop tools, methods and knowledge to support the design practice. Thus, although related to Engineering Science, design research must consider the human aspect of the design process (Michaelis, 2011).

As with any other research, there are several different methods and frameworks that helps researchers to create legitimate and accurately obtained results.

3.2 Available frameworks and methods

On a high level, a research approach can be supported by a framework that defines the general process and that provides structure to the research. Closer to each activity within such a process, methods are used to aid the researcher in securing the quality of obtained results. Both the framework and methods used are accounted for below.

3.2.1 Research Frameworks

Design Research Methodology (DRM) is a framework developed by Blessing and Chakrabarti (2009) and focuses not only on aiding the process of providing understanding of design, but also to aid in the creation of support for conducting better design. Figure 8 depicts the prescribed *process* with the *means* and *outputs*. The research clarification stage aims at defining worthwhile and realistic goals for the research, using literature as the main source of information.

In the Descriptive study I stage, the researchers describe the current situation, and the factors that could be addressed to improve the situation. The output is a better understanding of the situation; an as-is description. The Prescriptive Study that follows addresses those factors depicting *how* to affect them to improve the as-is state into the *desired state*. Descriptive Study II aims at evaluating the true effects of the support implemented.

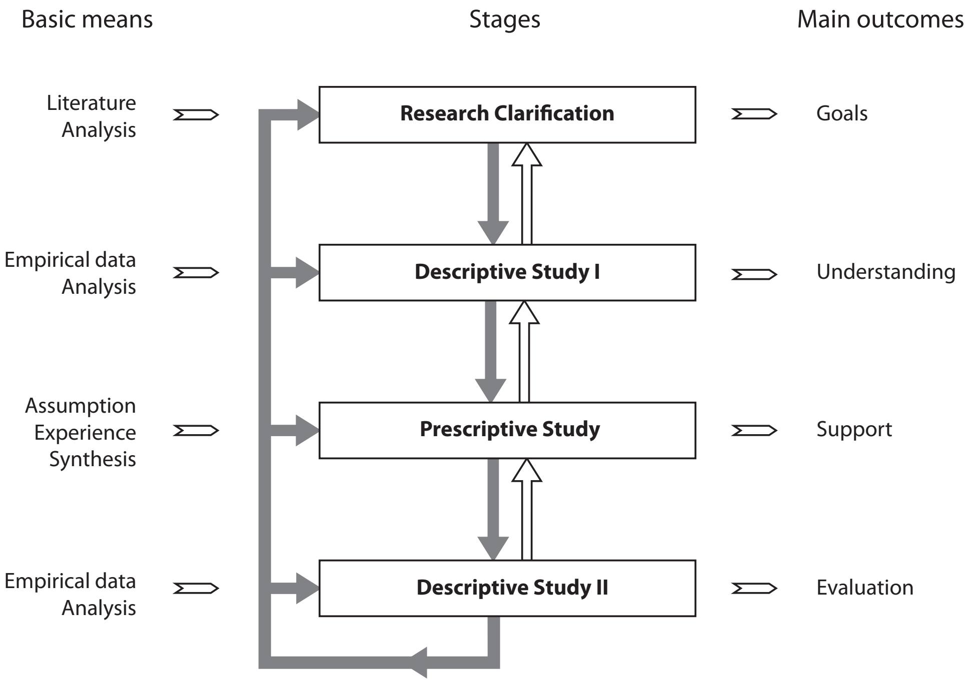

Figure 8 - The DRM framework, redrawn from Blessing and Chakrabarti (2009)

Each stage contains a selection of activities and deliverables to aid the researcher. Furthermore, the stages are not designed to be executed in a strict sequential matter, but loopbacks are instead encouraged.

Taking into account that research projects are different in their character, Blessing and Chakrabarti define seven types of research within their framework that differ by the research emphasis placed on different stages.

Jørgensen (1992) presents an approach for applied research (see Figure 9). Applied research has two starting points: the problem base, typically a phenomenon observed in reality, for example an industrial need in addition to a theory base, where the knowledge gap is established by studying the knowledgebase in literature.

The theory base is synthesized into models that are either descriptive or prescriptive. These models are tested and validated against analyzed results from the problem base and may result in new scientific acknowledgements. Though the process seems sequential, it is not as the work of analyzing, synthesizing and synchronizing between the two tracks is highly iterative (Jørgensen 1992). At the end of the research, the new scientific acknowledgements come closer to implementation in industry.

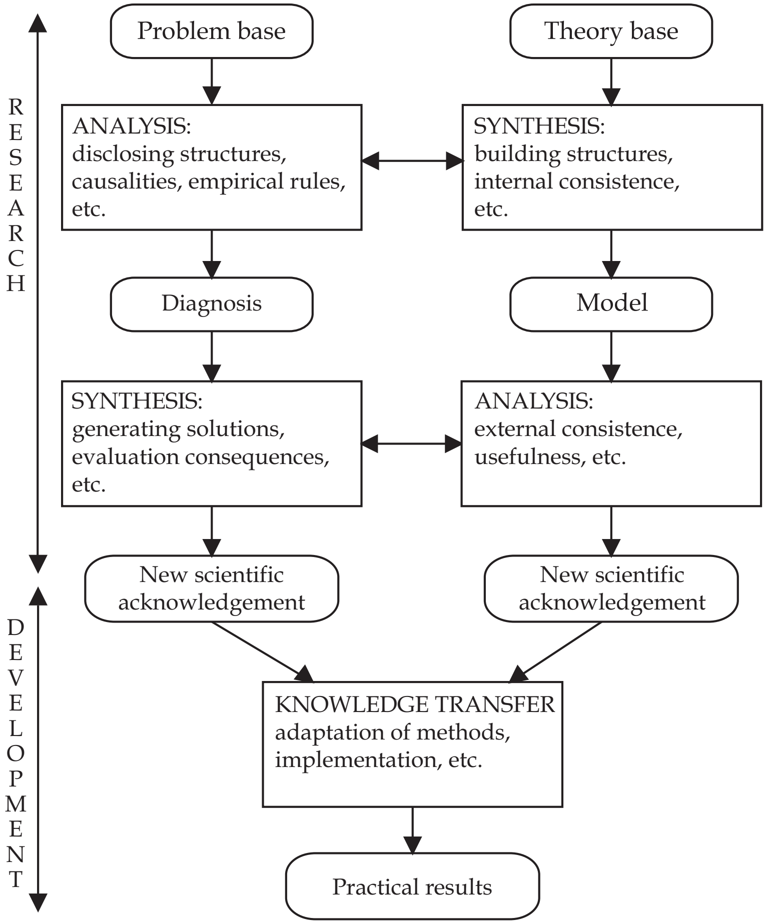

Figure 9 – Framework for applied research, redrawn from Jørgensen (1992)

3.2.2 Methods for collecting data

There are numerous approaches for collecting data within design research. The type of results generated depends largely on the approach. *Case studies* rank as one of the more common approaches within design research. According to Yin (2003), a case study

> *"investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident".*

This definition has two distinct components. First, a case study is about studying something contemporary as in that it is occurring now so that it can be observed, or that there are people alive that can tell of it. It contrasts with studying historical events, which would require another research approach.

Second, the boundaries between the phenomenon we want to study and the context in which we find it is not very clear. In a setting where a phenomenon can be isolated and studied without interference from its context, experiments would be preferred. However, if relevant parameters cannot be manipulated and phenomenon distinguished from the context, case studies are preferred. However, a case study is not a data collection method but rather a setting in which data can be collected.

Numerous methods for collecting data within the setting of a case study are available, one of the more common being the interview. Interviewing as a research method usually involves the researcher posing questions to a respondent, who hopefully gives answers. Robson (2002) and Blessing and Chakrabarti (2009) agree on three different classes of interviews. The *fully structured interview* is characterized by questions that are exactly worded and asked in a predefined order. The *semi-structured interview* gives more room for improvisation in that the questions are predefined, but the phrasing and order of questions can vary to get a better flow in the interview. Questions can also be given an explanation or excluded if found irrelevant for a particular interviewee. Finally, the *unstructured interview* is a conversation-like interview where the interviewer has a general area of interest that is discussed with the interviewee.

3.2.3 Methods for building theory and models

In the endeavor to create a supporting design processes it is common to build models of reality to condense the phenomena to be supported. These *phenomena models* describe aspects of reality essential to the design situation at hand. The phenomena models can, when appropriate, be developed into formal *information models* and later be developed into *computer models* and tools to prescribe a way of conducting design (Duffy and Andreasen, 1995).

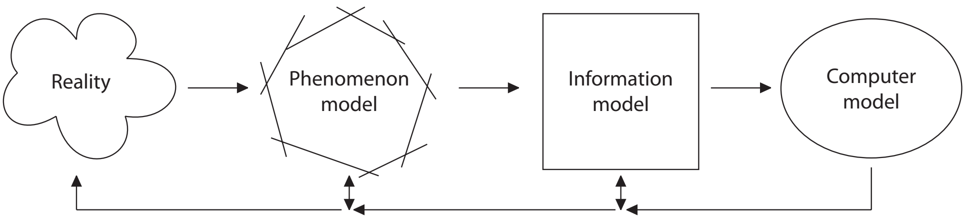

Figure 10 - Design modeling research approach according to Duffy and Andreasen (1995)

It is important to notice that implementation of any model or tool will affect reality. Therefore, models continually evolve. Each model may at any given stage be evaluated against previous models (or *alien models* – models on which the present model is not based, but that if implemented might still affect reality) to enhance the understanding of reality, but also to enhance the models themselves. Figure 10 describes the development of models in design research. The loop-backs represent the mutual relationship between model and reality.

3.2.4 Validating and verifying the results

Validity within research refers to "the correctness, or credibility of a description, conclusion, explanation or interpretation" (Maxwell, 1996). Obtaining validity in research is not about finding absolute truth, but rather provide grounds to distinguish credible results from those that are not credible. Within design research, verification differs from validation, in that verification focuses on the question *"Did we do it in the right way?"* whereas validation focuses on the question "*Did we do the right thing?"*

Buur (1990) expresses it differently by presenting two verification approaches within engineering design. One approach, *verification by acceptance* focuses on having new scientific contributions (e.g. axioms, theorems, models, methods or tools) accepted by experts within the field.

Another approach, *logical verification*, focuses on the internal consistency and completeness of the results. The results need to be consistent in the sense that there are no conflicts between individual elements. Completeness is achieved when all phenomena previously observed can be explained or rejected based on the results. Logical verification is also to established agreement with known methods and theory. A design method must also be able to support specific design problems.

Olesen (1992) adds that research can be considered to be true when it can explain phenomena found in reality too, not only phenomena found in theory. Further, beside being accepted by research community and industrial practitioners, the research has to be applicable in a real industrial setting. The research result has to have newness, i.e. have to provide new approaches or new realization.

3.3 The applied approach in this research

The research has been performed at the Wingquist Laboratory Excellence Centre. The centre has several industrial participants where research results can be tested and evaluated. The participants contribute with their time and expertise, opening up their organization as a laboratory for researchers within the centre. In return, they benefit from the results of the research.

The context in which the research is performed is important to the design of the research approach. In this thesis, the context is characterized by the consideration of both a *research challenge* and an *industrial opportunity*. With reference to Jørgensen, real life industrial observations have created the problem base whereas the theory base builds upon research performed within the Wingquist Laboratory Excellence Centre, in connection to the industrial participants, as well as state-of-the-art research within the field.

3.3.1 Design Research Methodology as a framework

DRM as a framework for this research works well because it does not only focus on understanding the problem, but also to find support for design. The purpose of the research thus matches the framework to support it.

The majority of the research has been carried out in close collaboration with the industrial partners of the Wingquist Laboratory. As the collaborating partners were involved long before the research presented in this thesis started, there is a great knowledge base imprinted in publications by, and minds of the individuals who have been working, and are working, in the research projects, both from academia and industry.

Research Clarification	*Descriptive Study I*	*Prescriptive Study*	*Descriptive Study II*
1. Review-based →	Comprehensive		
2. Review-based →	Comprehensive →	Initial	
3. Review-based →	Review-based →	Comprehensive →	Initial
4. Review-based →	Review-based →	Review-based →	Comprehensive
		Initial/Comprehensive	
5. Review-based →	Comprehensive →	Comprehensive →	Initial
6. Review-based →	Review-based →	Comprehensive →	Comprehensive
7. Review-based →	Comprehensive →	Comprehensive →	Comprehensive

Figure 11 - Types of design research projects and their main focus, redrawn from Blessing and Chakrabarti (2009).

Thus, comprehensive descriptions of the as-is state exist. As a consequence, Descriptive Study I can be based on studying already published literature, in combination with unstructured interviews with participants of the Wingquist Laboratory - the Descriptive Study I can be review based, allowing more focus to be placed on the Prescriptive Study.

The DRM framework describes seven different types of research project (Figure 11). The types are designed to match a variety of research projects. According to previous reasoning, Type 3 would match the character of the research presented in this thesis.

3.3.2 Case studies with interviews for information collection

Since most research questions in this thesis relates to the design process, aiding the designer in creating better designs, it is feasible to adopt methods from the Social Sciences, rather than solely applying a quantitative approach, as is so often done in the Engineering Sciences.

As the research questions stated in the beginning of this thesis are exploratory rather than quantifying, case studies have been adopted to serve as the main source of information for the left leg of Jørgensen's framework. Case studies are excellent vehicles by which why and how questions may be answered. A variant of the how question is "how much", which in contrast to the original "how" may favor surveys. However, from a wider perspective where the "how" or "what" questions are more explanatory than quantifying, case studies are preferable (Yin, 2003).

Semi-structured interviews are widely used in qualitative research when trying to form an understanding of a particular situation (Robson, 2002). This research adopts the concept of semi-structured interviews for all stages. In the Research Clarification stage and the review based Descriptive Study I, interviews are used to create an understanding of the problems that faced by today's industry, as a complement to the literature study.

In the Prescriptive Study, demonstrators are created to illustrate cases from industry. The demonstrators are based on the perceived needs of industry and realized through prescribed methods and tools; they are used as mediating objects in verifying and validating the results through verification by acceptance.

strategy	form of research question	requires control over behavioural events?	focuses on contemporary events?
experiment	how, why	yes	yes
survey	who, what, where, how many, how much	no	yes
archival analysis	who, what, where, how many, how much	no	yes/no
history	how, why	no	no
case study	how, why	no	yes

Figure 12 - Different research strategies are used for different research situation (Yin (2003)).

3.3.3 Validating the results in applied research

The concept of internal verification and external acceptance concurs with Jørgensen's (1992) model of the problem base and the theory base. Discussing and sharing the analyzed results with experts helps to achieve the external acceptance. More explicitly, all papers have been undergoing peer reviews as part of the publication process. Paper A, B, and C have been presented at conferences where experts within the field had opportunities to express their opinions about the results. Further, as a part of the external verification process, the results have been presented to the industrial partners of the Wingquist Laboratory at workshops, at result days, and as full papers for peer review prior to submitting them for publication. Demonstrators were used as mediating objects in the verification process.

The literature base on which this research rests is accounted for in Chapter 2. There is a large base of state-of-the-art in IT- and process support for product development, in addition to the domain of Engineering Design. Known IT- and PLM architectures models were used. Phenomena models, and in some cases information models, exist for several of the concepts used in this research. In those cases, the focus was on creating useful computer models in agreement with existing phenomena- and information models. The research was also about creating new phenomena models in which case these were verified to be complete and consistent through researching earlier studies and building upon known models.

4 Results - Summary of the Appended Papers

This chapter summarizes the papers that are appended in the back of this thesis, the same papers on which all results of this thesis build. The summary presented in this chapter focuses on the results gained throughout the studies, leaving less room for how the results were obtained and the theoretical context in which they reside. The full descriptions can be found in appended papers in the back of this thesis.

4.1 Paper A

The paper presents a case study performed in cooperation with a Swedish car manufacturer. During the study, a PLM architecture was established to support the configuration of product variants. The platform consisted of configurable system models as reusable platform elements, modeled using the Configurable Component concept. The full extent of the CC concept was not used – the study was instead aimed at configuring geometrical system interfaces (mating geometries and locating schemes).

The aim was to let the PLM architecture do the configuration and calculations necessary to ensure a functioning product variant, presenting any design decisions to the designer together with the proper amount of information to make a good decision. Two geometrical requirements were assessed, resulting in the use of two different CAE tools to optimize and evaluate the configured product variant.

To be able to create a PLM architecture in its entirety, several different aspects need to be considered. Svenson et al. (Svensson, et al., 1999) stress *Processes*, *Information*, *Systems* and *Roles* as factors to be considered in a PLM architecture. The process for going from an un-configured product platform to a product variant that fulfills both requirements is shown in Figure 13. It is this process that the PLM *information architecture* as well as the PLM *application architecture* shall support. The designer's *role* is to make any qualified design decision required to complete the configuration.

The *information architecture* consisted of a meta model of the car door, modeled with CCs and a CAD 3D model of the generic concept of the car door consisting of three parts (see Figure 14), all parameterized and configurable. The *application architecture* consisted of a configurator and modeling tool (CCM), a PDM system

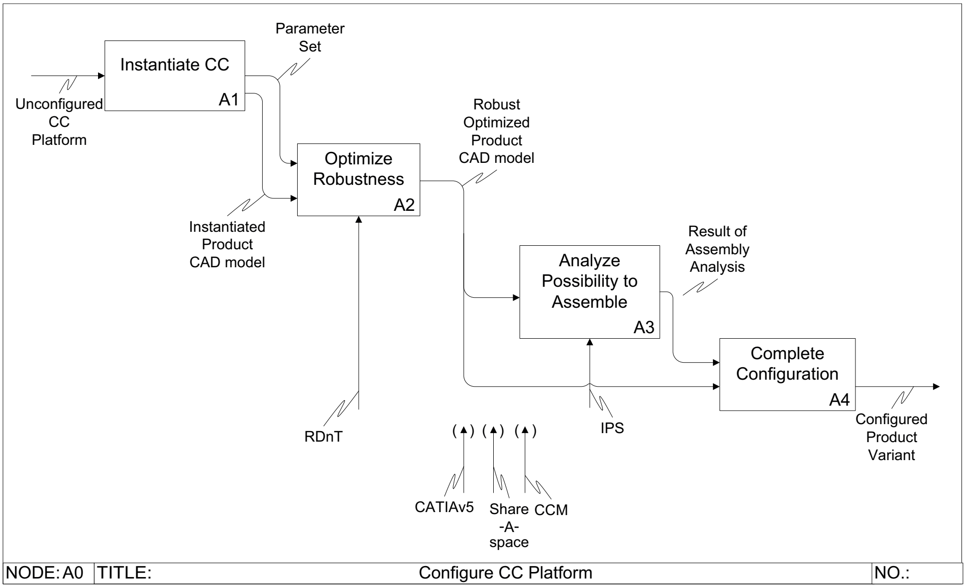

Figure 13 - The configuration process presented in IDEF0. The process is based on the requirements that product need to fulfil

(Share-A-space) to store meta data and CAD models, a CAD tool to manage CAD models and two CAE tools to perform optimization and analysis of the parts. The tools were integrated using a point-to-point approach.

The result of the study can be summarized as following:

- It is possible to create a PLM architecture that supports automatic configuration of geometrical system interfaces of platform elements modeled as configurable components.
- The requirements put on the product highly influence the configuration process and thus, the needed PLM architecture components.
- A point-to-point solution for integrating the software is beneficial for a case study, but when the requirements change and new analyses are needed, e.g. for a product aimed at different market, point-to-point integration would be too rigid. A more general integration approach, such as a SOA, would be to preferable.

The case study has a clear aim towards the execution of the platform, i.e. creating product variants based on an already defined platform. A certain amount of platform preparation was necessary to perform the subsequent execution, but in order to prescribe any processes or support for platform preparation, more studies are needed.

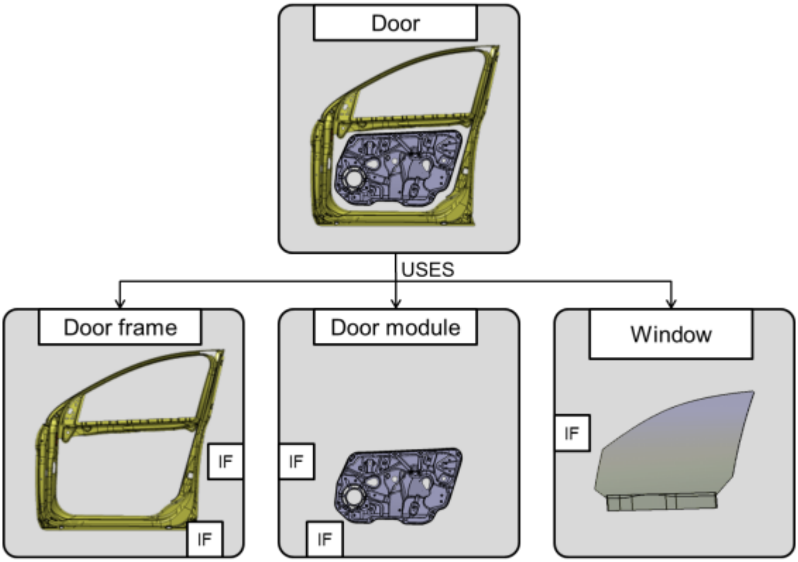

Figure 14 - Graphic model of the platform modeled using CCs

4.2 Paper B

The study that provides the backbone for paper B is based on two sources, a literature study reviewing literature on platform-based design in addition to a case study of a supplier to the aerospace industry, Swedish Volvo Aero.

The aim of the literature study was to find areas where platform-based design could be applied but where there was yet no support. The study uses three different dimensions: lifecycle stage, PLM architecture level, and platform abstraction level. In these three dimensions there are gaps, e.g. there are no studies on the connection between abstract platforms – such as suggested for the aerospace industry – through platforms represented by generic concepts, to more concrete platforms represented as readily designed components and subsystems.

The second part of the study addresses the gaps found in the literature study that matches a need of the company studied. The case company has low volume production and cannot benefit from reusing parts. The more abstract alternatives, such as reusing technologies, are instead more feasible. However, abstract representations of products and technologies cannot support product development in later stages (e.g. detailed design) during which systems need to be increasingly defined. At the final stage, the product representation has to be concrete enough to be produced.

Thus, the case study elaborates on the possibilities of bringing aspects of the Volvo Aero product platform to a less abstract level to better be able to reuse design in more lifecycle stages than technology development. In this way, current PLM support could be utilized, rather than new customized systems to support abstract models. In order to do so, a PLM architecture was established and the product modeled as a platform using the configurable systems to allow configuration using the CC concept.

The most important results of the study are the following:

- The platform approaches in today's literature do not cover the need to support holistic platform development across all stages of the lifecycle and for all levels of abstraction. They fail to do so because there are gaps in support of specific areas, for example in the stage of service and there are no studies on how platform approaches can be combined into covering the entire lifecycle.
- The study gives a first insight into the fact that platforms based on configurable system elements, modeled with the CC concept, can be used as a bridge between abstract descriptions of platforms (e.g. technology platforms) and concrete descriptions (e.g. part- and module-based platforms)

4.3 Paper C

The results in this paper are derived from a case study performed through interviews at a company called GlobalCorp (masked name). The study aims to investigate the benefits and drawbacks along the path of implementing PLM as a design reuse support.

GlobalCorp consists of eight business areas (ranging from furniture to radar equipment), residing at over two hundred sites and incorporating over 150,000 employees. Their strategy is to use a single PLM system throughout the organization to facilitate *global design reuse*. The final goal is to have a global parts catalogue from which all subsidiaries can *reuse parts*. To complete the PLM system, they have plans of implementing a common ECM process. Figure 15 shows all enablers that GlobalCorp uses to facilitate design reuse.

The study shows that the GlobalCorp approach to support design reuse has many *possible* benefits – around-the-clock design work, design reuse through a global parts catalogue and control of engineering changes, to name a few –, but the approach is

ID	Action
O1	Increased design reuse
P1	Standardised ECM Process
PW1	Standard workflow for check-in checkout
PW2	Standard workflow for ECM
I1	Standardized Information objects and attributes
I2	ECM information model
A1	Standardized PLM system
A2	Recommendation on CAD system
A3	Standardized ERP system
A4	ERP-PLM integration

	Support MCAD	Support ECAD	Integrate PLM and ERP	Support Global Parts Catalogue	Support ECM
Business Objectives					
Processes					P1
PLM Workflows	PW1				PW2
Information Architecture	I1				I2
Applications	A1, A2		A3, A4		

Figure 15 - Roadmap of the GlobalCorp PLM implementation. The columns represent stages, time going from left to right.

accompanied by several *real* drawbacks. For example, the PLM system chosen lacks support for core disciplines within GlobalCorp, such as electrical CAD (ECAD). Moreover, the users cannot resort to their old processes anymore, and have no possibility to recourse to new processes. In general, the users had a hard time seeing how they would be able to reuse parts across such a diverse organization.

Figure 16 depicts the collective distribution of benefits and drawbacks in the implementation project at the studied subsidiaries. None of the subsidiaries have reached farther than the first stage *support for MCAD*. Many benefits are long term, while the short-term benefits that work as drivers to implement the change are conspicuous by their absence. Furthermore, benefits are outnumbered by drawbacks. These drawbacks need to be managed in order not to jeopardize the realization of the benefits.

The results briefly:

- Gaps in the PLM architecture can cause serious drawbacks. In this case, lack of processes for design reuse causes lower user acceptance because of time consuming drawbacks. These drawbacks need to be managed in order to drive the implementation project forward and achieve long-term benefits.

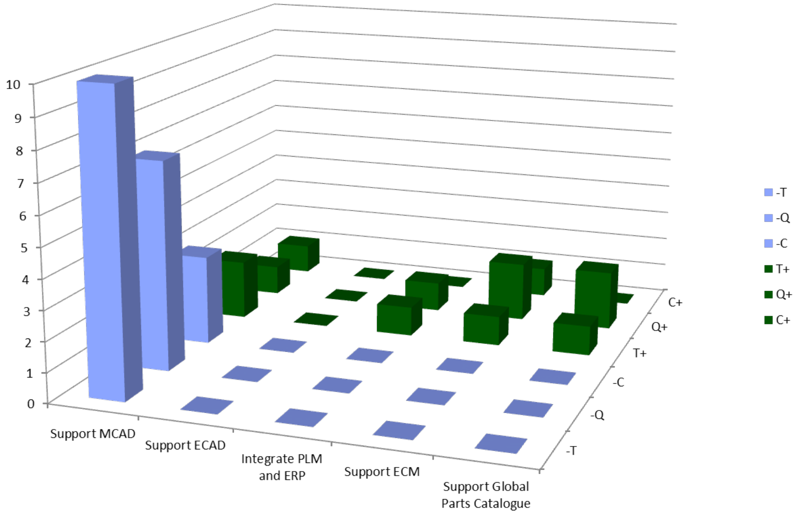

Figure 16 - Collective benefits and drawbacks and their distribution over the stages on the roadmap. T = effect on development time. Q = effect on product quality. C = effect on product cost.

- Using a part-based view of design reuse is not feasible when trying to put reuse into effect in such a diverse organization. Commonality needs to be found where it may exist, perhaps through reusing on a more abstract level, such as by means of generic concepts and technologies. This approach would also allow expanding the reuse to cover a greater part of the product lifecycle.
- On the system support side, a feasible strategy would be to create different support for different areas of the organization, creating chunks of similar subsidiaries with similar products, processes and thus tools.

4.4 Paper D

This paper proposes an integrated approach to using technology platforms and product platforms. The approach provides a holistic perspective on how to leverage benefits from reuse and as well as leveraging strategic investments from early phases of technology development to the late product variant configuration phase.

4.4.1 A holistic approach

A *technology based integrated platform* is defined as a product platform based on configurable systems elements – in this case modeled using the Configurable Component concept created using a technology platform with generic technology

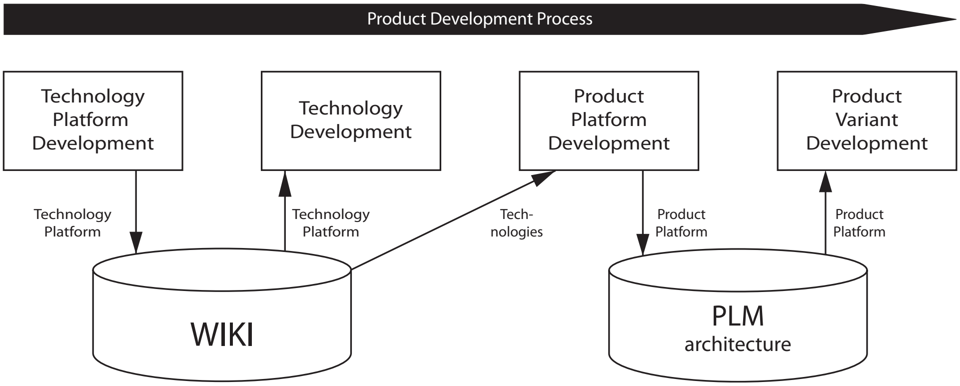

Figure 17 - A simplified product development process using platforms and suggested support. In reality, the different parts are developed concurrently and more complex relations exist.

descriptions as platform elements which may also be referred to as a *development platform*.

The processes for creating and using a technology platform are different from creating and using a product platform. As a consequence, they require different support. Figure 17 shows a simplified picture – in reality there are loopbacks and iterations – of the relation and information flow between the processes. The cylinders represent what type of support that is suitable for the respective processes.

The technology platform is supported through a Wiki solution (Figure 18) in which descriptions of the technologies and their application areas can be found, together with trade-off curves from technology development, contact information to the technology owner, etc. The product platform is supported by a PLM architecture that is partly derived from the technology platform depending on the requirements posed on the product.

The proposed process below is used to prepare the product platform, using the technology platform Wiki (see Figure 18). The result is a product platform based on configurable system elements modeled using the CC concept, and a PLM architecture able to generate product variants and automatically analyze requirements imposed on the product.

1. Model the products as Configurable Components
    a. Model the functional requirements (FRs) and constraints (Cs) of a concept.
    b. Find Design Solutions (DSs) (organs and physical parts) to match the functional requirements.

c. Use trade-off curves, limits and possibilities from technologies to define CC bandwidth.
d. Use technologies to define knowledge gaps that need to be filled. Identify technology development efforts required to bring the product to market.

2. Define activities
   a. Define the solution space by selecting parameters to vary.
   b. Match requirements to analysis activities required to analyze the fulfillment of the requirements.
3. Define the configuration process
   a. Find supporting activities, such as data transfer and storage.
   b. Find a feasible sequence of activities and define data flow.
4. Create systems architecture
   a. Map activities to IT tools or combinations thereof using engineering technologies from the technology platform.
   b. Define interfaces between tools.

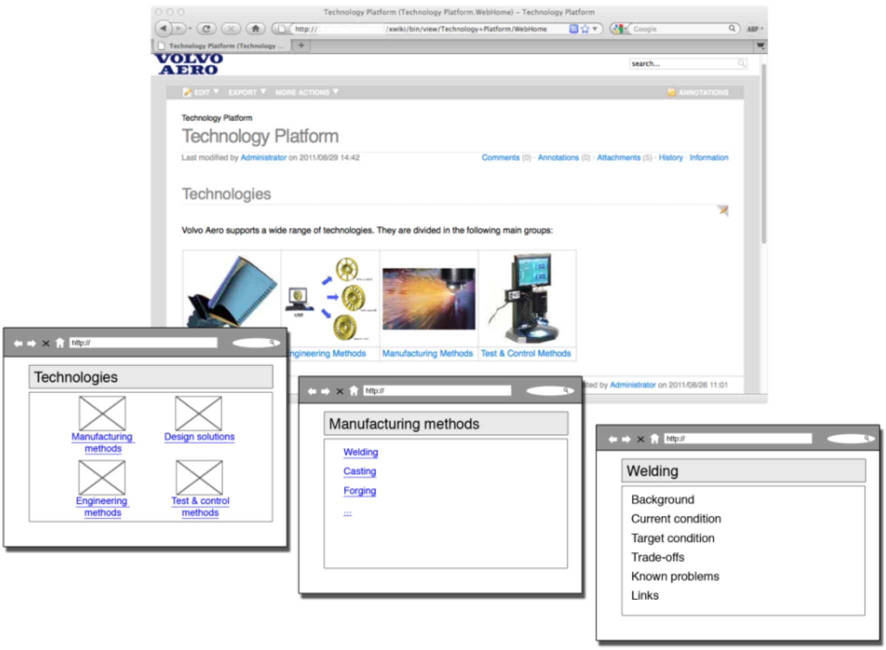

Figure 18 - The Wiki solution contains generic technology knowledge and supports the technology platforms.

4.4.2 A case study of technology-based integrated platforms

The company involved in the case study, Volvo Aero in Trollhättan, Sweden, is a manufacturer of turbofan engines framing. As a sub-contractor in the aerospace industry the Volvo Aero provides sheet metal goods for several major jet engine manufacturers. One of their business goals in implementing platforms is to quickly be able to answer quotes from their customers with high precision. If they manage to accomplish this, the can quote a low enough price to win the deal, while at the same time staying on the right side of their margins.

The study starts with a product platform prepared according to the above suggested process. The goal is to arrive at an estimate of the ability of the current design to meet customer requirements. This is achieved by generating a number of product variants and testing them with CAE tools. A PLM architecture is created based on the requirements that need to be assessed, resulting in a configuration process and the application architecture seen in Figure 19.

The configuration is done automatically, and initiated by the configurator CCM, based on the generic concept modeled using the CC concept. The two parameters chosen for this case are varied so that six different configurations are generated. These concepts are then created in the PDM system (1), and the correct CAD files

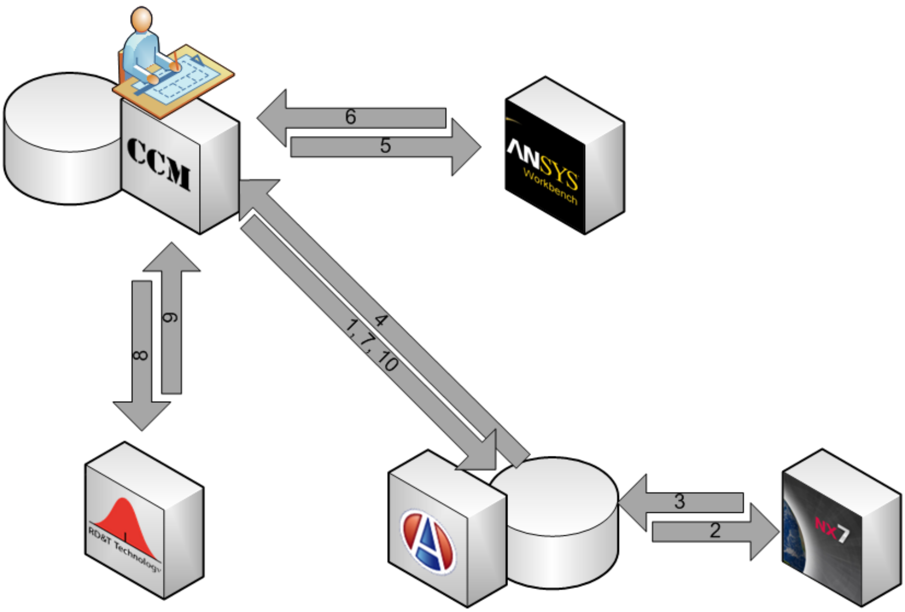

Figure 19 - The PLM architecture

are generated, based on the generic concept model (2). The respective CAD files are connected to concepts in the PDM system (3). The PDM system then sends back the six different CAD models to CCM (4).

The first analysis activity is done by Ansys, which upon request (5) uses the CAD files of the different concepts to perform a multi-criterion analysis. These analyses comprise *pressure loss*, *buckling load factor*, *thermal stress*, *over-turning moment (OTM)* and *shear compliance* for all six concepts. As the results are returned (6), they are both stored in the CCM database for later displays, as well as in the PDM system (7) for reuse at other occasions.

Subsequently, the second analysis is performed. The RD&T robust design tool carries out the flush analysis to determine how well the concepts perform if manufacturing variations are considered. The analysis is called for (8), and the result is returned (9) and stored in both CCM and Share-A-space (10).

The result of the analyses is displayed in Figure 20. Each concept is represented by a polygon. The set of concepts may be narrowed down by eliminating a concept that performs too poorly on any requirement, or a concept that is out-performed by another concept on all points (e.g. blue versus red concept in Figure 20).

The results of the paper can be summarized as follows:

- PLM can be used to support technology-based configurable platforms in the context selected for the case.

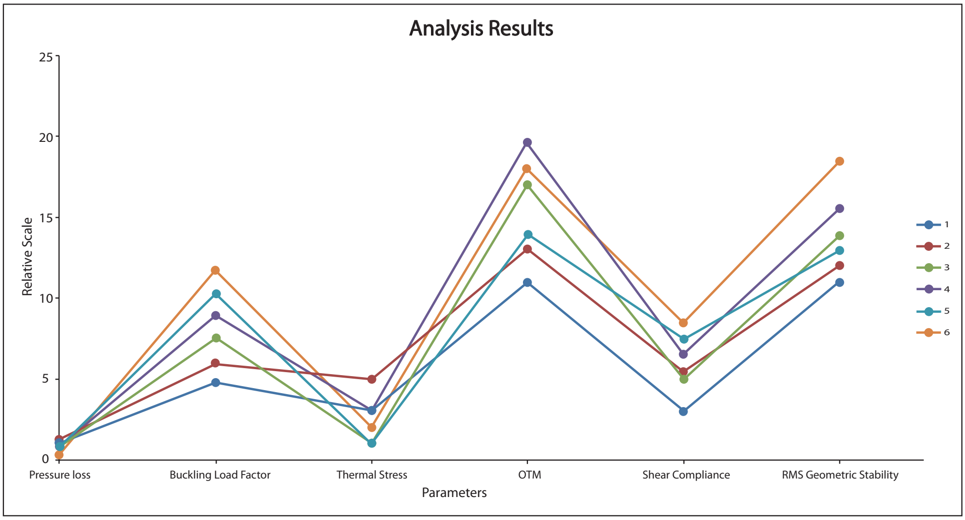

Figure 20 - the results are displayed to the designer as graphs, each graph marking a concept.

- The use of technology-based configurable platforms impacts the time-to-market by supporting and speeding up the bidding process for a supplier such as Volvo Aero.
- For a company like Volvo Aero, the product platform configuration process may be used not only as an engineer-to-order tool, but also as a tool to find performance gaps of the products and technologies. It can be used to identify customer requirements that they cannot yet fulfill, areas for expansion of the product bandwidth or where new technologies are needed.
- With a better overview of both technologies and product platforms there will be opportunities for more informed decisions on introducing technology and the risks of deploying them for different applications. This will in turn facilitate concurrency between technology development and product development.
- Cross-platform change management processes are needed to ensure the co-existence of technology and product platform. Due to different nature of the data that need to be managed, the processes would have to differ from a regular ECM process.

4.5 Summary of the results

In brief, the results of all papers can be summarized as follows:

- Platforms based on generic configurable concepts modeled as configurable components can be supported by a PLM architecture to configure product variants. Optimization tools can be used to set CC parameters, optimizing the systems to comply with requirements. CAE tools can be used to assess potential solutions within the solution space set by the bandwidth.
- The PLM architecture used for variant configuration can support engineering-to-order configuration, but also serve as a tool to inform about the knowledge gaps to be filled to get the product to meet requirements.
- Core technologies represented as a technology platform, and supported by a Wiki can be used to aid the designer in product platform development. The reusable technology elements can aid in determining product bandwidth, finding means to meet functional requirements and to define constraints on configurable system elements of a product platform. However, it is not yet

explored how such a solution would work for a development platform with a cross-lifecycle ECM process.

- There is a great risk in trying to support design reuse using IT-support alone. In order to have full support, the organization needs to consider *business objectives*, *processes*, *information architecture* and *application architecture*. More importantly, the connection between levels is crucial to get a coherent solution that really supports the goal of design reuse. These connections can be stored as generic knowledge blocks within a technology platform and then retrieved to form a holistic PLM architecture.
- The platform approaches in today's literature do not cover the need to support holistic platform development across all stages of the lifecycle, nor for all levels of abstraction. A platform consisting of configurable system elements may be used as a bridge between abstract descriptions of platforms (e.g. technology platforms) and concrete descriptions (e.g. part- and module-based platforms).
- Within a development platform, the technology platform is executed while preparing the product platform. Development platforms can be realized through a Wiki solution supporting the technology platform, and a PLM architecture that supports the product platform. This holistic approach provides a better overview of both technologies and product platforms. That crates possibilities for more informed decisions on technology introduction regarding risks in their deployment for different applications.

5 Discussion

This section aims to give a clear answer to the research questions posed in the introduction of this thesis, and to discuss the quality of the results in relation to the research approach used.

5.1 Answering the research questions

RQ1: *What current business processes and IT tools can support design using technology-based configurable platforms, and how can they be improved to better suit them?*

About processes

The business processes for developing single products compared to those for developing platforms are very different. Processes such as the ones established by Pahl and Beitz (1996) or Ulrich and Eppinger (2008) can provide support on a high level but fail to capture all detailed aspects of platform-based design. As platforms are prepared and then executed, special business processes are needed. In the preparation phase, knowledge is created with reuse in mind. In the execution phase, the processes focus on retrieving knowledge from the platform. More specifically within a development platform, the technology platform is executed while preparing the product platform.

Development platforms require new processes. One such process, supporting the preparation of the product platform by executing the technology platform is suggested in Paper D. The processes need to actively consider reuse on many different levels throughout the lifecycle. On a lower level, new processes for modeling products with bandwidth are needed, as opposed to modeling single products.

About tools

The difference in processes compared to single product development impacts the tools that are appropriate to use. Development platforms can be supported by Wiki solutions carrying the technology platform easily due to their flexible structure and ways to store different kinds of knowledge. Current PLM architectures can support platform-based design, while neither PDM systems, CAD systems nor CAE systems are optimized for managing configurable function carrying platform elements; they rather provide support for single products. Inoue et al. (2010) agree on the questions surrounding current CAE and CAD tools and propose a customized tool which has not yet been commercialized nor tested on a large scale. There are other attempts at letting CAD and PDM systems manage functional carrying organs as a part of a product platform, for example Bruun and Mortensen (2012). However, they focus on the visualization aid for stages in which parts are already developed, at the expense of the actual development process.

In Paper D, we propose a solution for being able to explore the design space and finding the optimal solution. However, this is still based on point-solutions rather than exploring the continuous design space because of the inability to do so by the CAD and CAE tools. Custom tools are needed to prepare and execute development platforms. Modeling system elements with CCM, by using the CC concept in combination with a Wiki seems feasible, with commercial tools supporting parts of the process.

RQ2: *What is the benefit of integrating platforms across the lifecycle, and how can PLM enable it?*

About Benefits

A holistic approach provides a comprehensive overview of both technologies and product platforms. Integrating the lifecycles of technology and product development creates possibilities for more informed decision-making on risks in technology introduction, in addition to their readiness for different applications.

The products will further be based on technologies that are tested and approved, which will reduce the need for technology development in the product development projects. That in turn will reduce the risk in product development and shorten lead-time for bringing new products to the market. Having a product platform that builds upon the core technologies at the forefront of technology development enables companies to respond quickly to new market demands and gain advantages vis-à-vis the competitors.

About PLM as enabler

As mentioned, PLM is a business approach by which knowledge across the lifecycle of a product can be integrated. By applying processes, information architectures *and* applications, it is possible to realize a strategy of platforms integrated across the lifecycle. However, it is only when all these layers are present that the business goals can really be fulfilled. A platform consisting of configurable system elements may be used to bridge technology platforms and readily configured variants.

5.2 Discussing the results

As discussed in 3.2.4, verification of research results can be performed by Verification by acceptance and Logical verification. *Verification by acceptance* focuses on having new scientific contributions accepted by experts within the field. Research can be considered logically verified when it is *complete*, *internally consistent* and *externally consistent*.

Verification by acceptance

All papers have been subject of peer review. Papers A, B and C were submitted to conferences where the contents are peer reviewed by experts in respective field. The results have also been subject of review in the presentations required to be published at each conference. As a journal article, experts within the field have reviewed Paper D. It has passed through to the third round of review, leaving only blemishes of presentation for the last round of reviews.

Further, the results of the papers have at numerous occasions been presented to the Wingquist Laboratory partner companies who have expressed their belief in the results.

External consistency

The results can be considered externally consistent if they agree with established literature. The research is based on known models and literature and is found to be in agreement with adjacent results. For example, in Paper C, the conclusion that missing layers in the PLM architecture can cause serious damage to the functionality of the solution is supported by a case study by Zimmerman (2008). The conclusion that distant benefits and present drawbacks may jeopardize the future of the project is found in other research (Berle, 2006, Devaraj and Kohli, 2002, Kotter, 1996).

The process suggested in Paper D concurs with the views of other authors on doing functional modeling as a first step in platform development, for example Farrel and Simpson (2003). The process and the CC concept meta model are still missing an approach to relate requirements to actual scalable factors, which is essential to be able to configure based on customer requirements. Such a relationship could be modeled according to Ulrich and Eppinger's need-metrics matrix (Ulrich and Eppinger, 2008). Further, basing the bandwidth of a design on equations and design tradeoffs, such as found in the technology platform, concurs with the work of other authors (Fisher, et al., 1999, Jiao and Tseng, 1999), but can also be accomplished by referring to customer demands (Pedersen, 2009).

Internal consistency

Internal consistency touches upon the definition of terms and how clear and non-conflicting they are. *Development platform* and *technology-based configurable platform* are used synonymously. The definitions of them do however stand firm on the same ground. The fact that they are verbal makes the vague in nature. They have however been exemplified, as well as the processes suggested to support them, to give a better understanding of them. The examples give indications for what and how development platforms can be used, but is not meant to show the only uses.

Further, Bokinge et al. (2012) uses the same body of knowledge as in Paper C, arriving at the conclusion that missing links between the layers in a PLM architecture can be the reason why the business goals that you set out to support failed. The modeling approach, for the product platform also agrees with established design theory and methodology, for example the theories presented by Andreasen (1980), Suh (1990) and Mortensen (2000).

5.3 Evaluation of the Research Approach

The long-going relationship with the companies studied provides a springboard for going forward to prescriptive studies. The vast body of research performed within the Wingquist Laboratory has sufficed for quickly leaping into prescriptive stages. Further, the research clarification did not only pertain to literature study but resembled the Jørgensen approach in which a research gap provided by a literature analysis and also an industrial need provided the setting in which the research was performed.

5.3.1 Motivation for using case studies

As for the form of case studies as a way to gather empirical data, the form was chosen for its appropriateness for answering *how* and *why* research questions (Yin, 2003). The industry is our lab and we must adopt research approaches that suit available means. For example, the setting we work in is highly contextualized and cannot be separated from the phenomenon. Therefore, we must resort to case studies to accomplish generalization. It is true that the case study, like the experiment, does not represent a sample, and thus cannot be used for *statistical generalization*, but rather for *analytical generalization*, which requires that the analysis of the results of the studies is in fact generalizing, not particularizing. This generalization is achieved through triangulating using different industries in the examples.

Some may argue that the research resembles experiments, which is not the case because it is not controlled from its context. Rather, we are aware of the context and use it for analytical generalization based on, for example, company size, business area, manufacturing volume etc.

5.3.2 Managing validity threats in qualitative research

Qualitative research does not, in contrast to quantitative research, have the luxury of being able to create controls for reducing validity threats, but it has to deal with this issue after the research has begun (Maxwell, 1996).

Both logical verification and verification by acceptance has its problems. Verification by acceptance poses a pedagogical problem (Buur, 1990). The acceptance of a design support highly depends on how the support is presented, and the knowledge of the subject to which the support is presented. As a way to manage these, the verification process included triangulation (as suggested by Maxwell (1996)) both of how the results were presented, and to whom. More specifically:

- the research was conducted at three different companies, manufacturing a range of products,
- the interviewees were from different departments and have had different roles in the company, being interviewed through workshops, tele-meetings and face-to-face individual interviews,
- apart from interviews, documents and drawings were studied,
- and the result was presented in writing to peer-reviewing conferences and a journal, as well as to experts at workshops and presentations.

6 Conclusions and Future Work

This chapter presents the core of the thesis in terms of results and future work. A general conclusion is that working with platforms has a major potential, provided that companies are willing to change. Consider what will happen if they do not change: other companies will outrun those that still cling to the old ways:

> *As the present now will later be past, the order is rapidly fadin'. And the first one now will later be last, for the times they are a-changin'. – Bob Dylan*

6.1 Conclusions from the work so far

Today's commercial tools are developed for single product development and do not have the ability to fully support development platforms. Wiki solutions may support the technology-portion of the development platform, and a PLM architecture may support the product-portion of the development platform. It is, however, unclear how well the different solutions might work in an integrated manner when it comes to Engineering Change Management. CAD and CAE tools are optimized to develop point-solutions and are not enough to represent and analyze entire design spaces, such as those used in a development platform. PDM systems suffer from the same issues. The modeling of configurable system elements, as a part of the development platform, must be conducted using customized third party software.

Although implementing IT-tools is a major issue, it is still minor compared to the organizational change that a company needs to undergo to revise their processes to conform to a platform-based thinking. More troublesome, there is still a large need for viable processes to create reusable knowledge and accompanying processes for using it.

6.2 Future work

Future research will more deeply investigate the concepts explored in this thesis, verifying them in industrial contexts and extending them to new endeavors. Future work will also address the issues below.

- The results show that it is possible to configure product variants based on modifying solution parameters. Future research could elaborate on configuring variants based on requirements, which would require developing a meta-model for linking requirements to measurements.

- A cross-lifecycle Engineering Change Management processes that can manage information from both technology and product platforms is needed to maintain the platform over time. It is still left to investigate the manifestation of such a process and the implications of integrating platform data across the lifecycle.
- The requirements of a platform approach differ based on the characteristics of the company. We have been exploring the concept in the papers, concluding that low volume manufacturing benefits from using technology platforms, rather than part-based platforms, but there may be characteristics other than sales volumes that affect the approach to use.

For future work, RQ3 and RQ4 require further elaboration. The next stage will address the issues above, including "*What are the benefits of using PLM as enabler for platform-based design, and how may drawbacks be managed?*" and "*What constitutes good PLM support for platform-based design?*"

We shall not cease from exploration,
and the end of all our exploring
will be to arrive where we started
and know the place for the first time.
- T.S. Eliot

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