THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Co-Development of Products and Manufacturing Systems Using Integrated Platform Models

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Cover:
The cover illustration is an adaptation of Figure 26 on page 54 of this thesis. It illustrates the platform-based co-development of products and manufacturing systems.

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Abstract

Product first, manufacturing system second. While manufacturing companies in fact make their profits by selling products, the successful development and proper functioning of both the product and the manufacturing system need to be ensured. This consideration poses a challenge that must be met in a joint effort because the product and the manufacturing system are two technical systems that mutually affect each other. They do so not only inside the factory building, but also on the drawing board, before their final design is determined.

With an emphasis on the mutual effect between the manufacturing system and the product, this thesis addresses the co-development of the two technical systems. It follows the idea of conducting development based on a strategy for managing change and variety, called platform. Rather than just regarding the reuse of physical parts, the thesis considers a platform approach that involves the definition of generic resources, such as systems, interfaces, and functions. The approach allows for the description of products and manufacturing systems with information about how they may change to produce variety and enable flexibility.

Based on several industrial studies, the thesis explores how platforms can be devised for products, manufacturing systems, or both. It elaborates on how technical systems can be described for defining such platforms. Specifically, it proposes an integrated model that combines function-means trees, component structures, manufacturing operations, and their interactions. The model allows defining platforms that can be expanded over time and used continually to derive product and manufacturing system variants. Thus, it helps manage change and variety in products and manufacturing systems.

Keywords: product development, manufacturing development, production development, concurrent engineering, platform-based design, configurable component, configurable product, reconfigurable manufacturing system, function-means tree.

Acknowledgements

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Doctor Lars Almefelt, my co-supervisor, has taken a soft approach to giving advice – during lunch breaks, while on a sailboat, and with examples from the kitchen. I thank him for the impact he has made. Also, I thank my co-authors, Doctor Stellan Gedell and Christoffer Levandowski, for good discussions and productive collaboration.

From the industrial partners I thank Doctor Anders Claesson and Magnus Johansson from *Saab*, Professor Ola Isaksson, Doctor Ulf Högman, Håkan Jakobsson, and Simon Samskog from *GKN Aerospace*, and Lennart Holmberg from *Kongsberg Automotive*.

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Finally, I would like to thank the many students I had the honor of supervising parallel to conducting research. There is a lot to learn from those we are supposed to teach.

Gothenburg, November 2013 Marcel Michaelis

Appended Papers

The following papers form the foundation for this thesis. They are listed in the chronological order in which the research work progressed.

Paper A Gedell, S., Michaelis, M.T. and Johannesson, H. (2011). "Integrated Model for Co-Development of Products and Production Systems – A Systems Theory Approach”. *Concurrent Engineering: Research and Applications.* (19)2: 139-156.

Paper B Michaelis, M.T. and Johannesson, H. (2011). "Platform Approaches in Manufacturing – Considering Integration with Product Platforms". *Proceedings of ASME DETC.* Washington, D.C., USA, 29-31 August, 2011: Paper No. 48275.

Paper C Michaelis, M.T. and Johannesson, H. (2011). “From Dedicated to Platform-Based Co-Development of Products and Manufacturing Systems”. *Enabling Manufacturing Competitive and Economic Sustainability*. H.A. ElMaraghy, Ed. New York, New York, USA, Springer: 197-202.

Paper D Michaelis, M.T., Levandowski, C., and Johannesson, H. (2013) “Set-Based Concurrent Engineering for Preserving Design Bandwidth in Product and Manufacturing System Platforms”. *Proceedings of ASME IMECE.* San Diego, California, USA, 15-21 November, 2013: Paper No. 63624.

Paper E Michaelis, M.T., Johannesson, H. and ElMaraghy, H.A. (2013). "Function and Process Modeling for Integrated Product and Manufacturing System Platforms". First revision submitted to *Journal of Manufacturing Systems*.

Paper F Levandowski, C., Michaelis, M.T. and Johannesson, H. (2013). "Set-Based Development Using an Integrated Product and Manufacturing System Platform”. Submitted to *Concurrent Engineering: Research and Applications*.

The work on the appended publications was distributed among the authors as follows:

Paper A: Stellan Gedell conducted the data collection for the industrial example and drew the basic conclusions on which the paper is based. Stellan Gedell and Marcel

Michaelis jointly elaborated the findings and synthesized the theory and models. They wrote, reviewed and edited the paper in close joint collaboration. Hans Johannesson contributed with comments and feedback.

Paper B: Marcel Michaelis planned and conducted the data collection for the industrial example and wrote, reviewed and edited the paper. Hans Johannesson provided comments and feedback for these steps. Both authors contributed to the analysis of data and synthesis of models.

Paper C: Marcel Michaelis conducted the data collection for the industrial examples, synthesized the theory, and wrote, reviewed and edited the paper. Hans Johannesson contributed with comments and feedback.

Paper D: Marcel Michaelis and Christoffer Levandowski synthesized the theory and elaborated the example. They wrote, reviewed and edited the paper in close joint collaboration. Hans Johannesson contributed with comments and feedback.

Paper E: Marcel Michaelis conducted the data collection for the industrial example, synthesized the theory, and wrote, reviewed and edited the paper. Hans Johannesson and Hoda ElMaraghy contributed with comments and feedback.

Paper F: Marcel Michaelis conducted the data collection for the industrial example. Christoffer Levandowski and Marcel Michaelis elaborated the example, synthesized the theory and wrote, reviewed and edited the paper in close joint collaboration. Hans Johannesson contributed with comments and feedback.

Additional Publications

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

Michaelis, M. T., Lindquist Wahl, A. and Johannesson, H. (2010). "Integrating Product and Manufacturing System Platforms – Exploring a Configurable System Approach". *Proceedings of DESIGN 2010.* Dubrovnik, Croatia, 17-20 May, 2010: 1605-1614.

Almefelt, L. and Michaelis, M. T. (2010). "Merging an Upmarket Car Manufacturer into a Global Player: Effects on Product Properties and Brand Identity". *Proceedings NordDesign 2010.* Gothenburg, Sweden, 25-27 August, 2010: 117-126.

Bengtsson, K., Michaelis, M. T., et al. (2010). "Towards Sequence Planning Based on Configurable Product and Manufacturing System Platforms". *Proceedings of NordDesign 2010.* Gothenburg, Sweden, 25-27 August, 2010: 467-476.

Michaelis, M. T. and Gedell, S. (2011). "Platform-Based Development". *Entering the Tiger's Cave – Perspectives on Japanese and Swedish Product Development.* D. Bergsjö, Ed. Gothenburg, Sweden. Department of Product and Production Development. Chalmers University of Technology: 31-35.

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List of Abbreviations

C	Constraint
CAD	Computer-Aided Design
CC	Configurable Component
CE	Composition Element
CIM	Computer-Integrated Manufacturing
CO	Component
DFM	Design for Manufacture
DFA	Design for Assembly
DP	Design Parameter
DRM	Design Research Methodology
DS	Design Solution
d-statement	descriptive statement
e.g.	exempli gratia (for the sake of example)
et al.	et alii (and others)
etc.	et cetera (and more)
FMS	Flexible Manufacturing System
FR	Functional Requirement
IA	Interaction
IBM	International Business Machines Corporation
iaio	is an implementation of
icb	is constrained by
icu	is composed using
i.e.	id est (that is)
I/F	Interface
iib	is influenced by
ipmb	is partly met by
isb	is solved by

iw	interacts with
JIT	Just-In-Time
No	numero (number)
O	Operation
p.	page
PC	Personal Computer
PFMP	Product Family Master Plan
PFMP^2	Expanded Product Family Master Plan
pp.	pages
p-statement	prescriptive statement
PV	Process Variable
rf	requires function
RMS	Reconfigurable Manufacturing System
RQ	Research Question
SAR	Spiral of Applied Research
SM	State Model
TPM	Total Productivity Maintenance
TPS	Toyota Production System
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
VP	Variant Parameter
VPV	Variant Parameter Value

1 Introduction

Manufacturing companies strive to sustain relevant change and desired variety in their products. Their guiding principle is to follow, or better, to be ahead of developments on the market, at competitors, and inside their own organizations. What must be realized is that change and variety in products are strongly interconnected with change and variety in the apparatus used to manufacture the products: the manufacturing system. In two steps, this chapter introduces one general idea of how companies can go about managing this interconnection and presents the general prerequisites for following this idea. This depiction is connected with the research focus of this thesis. For this purpose, the industrial and scientific goals are outlined along with the research questions and a clarification of what this work is not.

1.1 Platform as a Strategy for Coping with Change and Variety

Change and the need for providing variety arise from many sources. With respect to the product they can, for instance, be traced back to an increase in the rate at which new products are introduced and fluctuations in the demand and mix of products (Koren *et al.*, 1999). While change brings about opportunities for renewal and innovation, forcing individuals and organizations to think differently, it is not an end in itself.

Rather, there is value in not having to reinvent the wheel each time. In engineering, norms, standards, and guidelines are one manifestation of this elementary insight. Another situation to be avoided is to invent several fundamentally different wheels for similar purposes. Therefore, a course of action often proposed is to strategically define:

- What is subject to change over time and what is not.
- Where variety is desired and acceptable, and where it is not.

The strategic considerations concerning these questions include a temporal component: the change over time. In addition, they include a component addressing diversity: the variety across entities.

In the manufacturing industry the term *platform* is used to sum up this approach. Also in literature, the term platform is proliferated, though definitions vary and different reasons are emphasized to motivate the approach (see for example Meyer and Lehnerd (1997), Robertson and Ulrich (1998), Halman *et al.* (2003), Thevenot and Simpson (2006), Jiao *et al.* (2007), and Simpson *et al.* (2013)). Mostly, when talking about platform approaches, the entities in focus are the products manufactured by the companies. Beyond that, platform approaches have for example been proposed for managing manufacturing processes (see for example Jiao *et al.* (2003) and Zhang (2007)) and for managing technologies (see for example Kim and Kogut (1996) and Jolly and Nasiriyar (2007)).

The development and management of complex systems is another aspect in the application for platform strategies. For this development and management, systems can be broken down into smaller constituents that are easier to understand and handle. For products, for example, these constituents can be defined in *physical* and in *functional* terms. This means the physical components that the product is made of and the notional subsystems that provide certain functionality (Ulrich and Eppinger, 2004). The product's *architecture*, "the scheme by which the function of a product is allocated to physical components" (Ulrich, 1995, p. 1), holds the information on how the *physical* world and the notional world of *functionality* relate to one another.

Considerations of the architecture close the loop back to the theme of managing change and variety. That is because the constituents or the subsystems may be changed, both internally and regarding how they are arranged towards one another in a process called *configuration*. The architecture can remain unchanged, thus defining allowed change and providing for variety (Ulrich and Eppinger, 2004).

Research efforts have been directed at detaching the configuration of subsystems from a rigid architecture. With inspiration from how this can be achieved in software engineering, Claesson (2006) proposed a framework that aims at more autonomy of the systems that are configured to span a range of products. Through several mechanisms this so-called *Configurable Component* framework becomes a method for modeling and thus defining platforms.

The above principles and ideas are applied to products. Beyond that, research on the development of manufacturing systems has taken to their adaptation. In fact, the principles of architecture and configuration are the subject of research in the area of Reconfigurable Manufacturing Systems (see for example Koren *et al.* (1999), ElMaraghy (2009), and Koren and Shpitalni (2010)).

1.2 Co-Development of Two Technical Systems

Adopting a platform approach has implications for a range of activities within manufacturing companies. This thesis looks specifically into how it affects and constitutes prerequisites for the development of two types of entities: products and manufacturing systems. Both are man-made, technical systems designed for their respective purpose. Moreover, they have numerous effects on each other when they are designed and when one is used to manufacture the other. In other words, they depend on each other, or also: they *interact* with each other.

This interaction is reduced to a unidirectional dependency if they are designed in sequence – the products first and the manufacturing system in a subsequent step. While this *over-the-wall* scenario does not truthfully reflect industrial practice, there is still potential for improvement that adheres to the integrated and concurrent development of products and manufacturing systems (Andreasen *et al.*, 1988; Boothroyd *et al.*, 1994; Prasad, 1997). The development specifically of the two technical systems in concert is called *co-development* in this thesis.

Companies can adopt platform strategies for both systems: one for the development of each. Going further, they can also adopt a joint strategy for co-development of the two. In this thesis, the second mode is called *platform-based co-development.*

1.3 Research Focus

The work presented in this thesis focuses on exploiting some of the potential of platform strategies as described above in a twofold approach. It explores prerequisites for and steps towards platform-based co-development. In essence, this aims at better understanding the context of this kind of development.

With the insights gained from this, the research seeks to advance the available modeling methods for the two technical systems. Here, the objective is to develop understanding and devise support for conducting co-development. Support in general can be understood as the “means, aids and measures that can be used to improve design” (Blessing and Chakrabarti, 2009, p. 4). In this thesis, the focus is providing support by means of *modeling the technical systems*.

For conducting the research, the following underlying assumptions are made about products and manufacturing systems:

- Although they are built for different purposes, they share the common characteristic of being technical systems. This means they are designed and redesigned over time, for example.

- They can each be developed based on their own platform strategy, or based on a pervasive platform strategy that addresses the dependencies between both systems.
- They can both be designed to be configurable.
- They can be modeled to help understand how they can be changed and redesigned or to formalize how they can be configured.
- An *integrated* model that describes both systems can facilitate these activities.

1.3.1 Industrial Goals

The thesis and the appended papers are based on several studies conducted in collaboration with industrial partners in the *Wingquist Laboratory VINN Excellence Centre*. The partner companies in the center commit to research projects that are jointly funded by governmental agencies, Chalmers University of Technology and themselves. They take part in identifying research needs and shaping research questions that evolve from their specific challenges. However, the research followed the ambition of addressing industrial research needs that also concern companies beyond the ones active in the research center.

Specifically, the industrial goal of this work is to contribute to enabling companies to model their technical systems, product and manufacturing system, in such a way that they can formulate their individual platform approaches. This includes modeling the variety across products and variety in matching manufacturing system setups. This, in turn, is to pave the way for companies to conduct the platform-based co-development of the two systems.

1.3.2 Scientific Goals

The scientific goal of this work is twofold. First, it seeks to increase understanding of the prerequisites for platform-based co-development. Second, this is to lead towards the refinement of concepts and methods based on the modeling approach taken for the Configurable Component framework (Claesson, 2006; Gedell, 2011) to enable co-development.

Seen in a wider scientific context, the research seeks to address that existing literature on the development of technical systems at large either focuses on products or manufacturing systems rather than considering them together. The evolving research opportunities are in detail discussed in the following chapter, after the available theory is presented.

1.3.3 Research Questions

With the above goals in mind, the following research questions were formulated to drive the research:

RQ1 How do the architecture and configurability of a manufacturing system affect the transition to platform-based co-development?

RQ2 How can products and manufacturing systems be represented in an integrated model to support platform-based co-development?

1.4 Delineation of the Research and Terminology

While this thesis addresses the development of products and manufacturing systems, it does not pursue the objective of prescribing *engineering processes*, the activities of engineers and the developing organization as a whole. It is acknowledged that modeling methods cannot be entirely detached from these engineering processes. However, the ambition is to leave companies as much flexibility as possible for choosing the engineering processes they deem suitable. Papers D and E prescribe steps of engineering processes. While these process models are integral parts of the respective publications, this thesis focuses on the artifact models proposed in them.

Product development can be regarded as including activities that go beyond designing, thus, for example, extending into marketing and manufacturing (Ulrich and Eppinger, 2004). Here, however, development is to be explicitly understood as the activity of designing. Manufacturing is included because the development of the manufacturing system is addressed. Development can also mean continual phases of redesigning over time. In this sense, development includes a long-term perspective of managing results of earlier decisions of designing and combining them with new ones.

The terms *manufacture* and *production*, as well as their derivatives, are often used interchangeably. When trying to differentiate between them, it can be argued that one is superior in scope to the other, but also the other way around (see Bellgran and Säfsten (2009) for a comprehensive discussion). *Manufacturing* is the term chosen in this thesis because it clearly marks the field of application: the manufacturing industry.

Consequently, the concept of product in this thesis is limited to discrete entities of physically manufactured goods, which may include software and electronic components. In accordance with this, the term *manufacturing system* includes the factory, facilities, cells, machines, tools, and operators that contribute to the act of making of the product (Groover, 2008). However, the research in the appended papers focuses on the level of cells, machines and tools; and it includes, to some extent, operators. Moreover, it does not address supply chain considerations.

Paper A uses the term *production system* because the ambition for the scope of this particular publication was broader. The intention was to not limit the idea of modeling so that it excludes the manufacturing support systems (business functions, product design, manufacturing planning, and manufacturing control, for example). However, the other papers and this thesis do not pursue this ambition.

The differentiation between *parts manufacture* (sometimes simply called manufacture) and *assembly* is acknowledged along with the different natures of their related processes. However, modern manufacturing systems often combine part-manufacturing operations with assembly operations. Thus, in this thesis, the term *manufacturing system* is used as a generic term and also denotes assembly systems.

The presented work adopts the view that products and manufacturing systems can be made configurable. While configuration of a product leads to different entities, for example a sedan or a convertible car, configuration of a manufacturing system typically yields only one manufacturing system. This manufacturing system assumes different setups, or *configurations*. The use of the first prefix in the established term *Reconfigurable Manufacturing System* reflects the fact that it is usually the same physically existing entity that is configured continuously.

1.5 Outline of the Work

Chapter 1 has introduced the topic of the thesis, covering its background in two steps and explaining the research focus with the underlying assumptions, goals and research questions. It further explained the scope by pointing out what the thesis does not include.

Chapter 2 gives a more detailed account of the underlying theories relevant for this thesis, and Chapter 3 discusses what research approach has been taken based on this theory and the research questions. In Chapter 4 the results of the conducted research are presented, ordered by the appended papers.

Chapter 5 discusses the implications, the shortcomings, the reliability, and the validity of the results. Finally, this results in a conclusion and an outlook on future work in Chapter 6.

2 Frame of Reference

This chapter presents a selection of theories and approaches that are relevant for the research work presented in this thesis. Some of them form the foundation of the research while others provide perspectives for the general context of the work. After a short introduction the chapter addresses – at large – the development of products and manufacturing systems, different paradigms for development and manufacturing, and the modeling of artifacts and manufacturing processes. Its main focus is on theories that aim at connecting the development of products and the development of manufacturing systems.

2.1 Joint Development for Products and Manufacturing Systems

The development of products and the development of manufacturing systems can be studied from many perspectives. Generally, these perspectives are entwined with the object of study. Adopting this view, Hubka and Eder (1988) present a rough classification where the object of study is used to characterize research efforts connected with the development, or designing, of systems (see Figure 1).

According to this model, research can focus on the technical system, also known as the artifact, or concern itself primarily with the processes of designing these artifacts. Moreover, it includes an axis that indicates whether the goals of research are descriptive statements (d-statements) about the observed phenomena or prescriptive statements (p-statements) aiming at impacting development.

Bearing the imprint of engineering design, it has a scope that goes beyond the product's design and its creation. It also includes the aspect of manufacturing through addressing Design for X, which encompasses among others Design for Manufacture

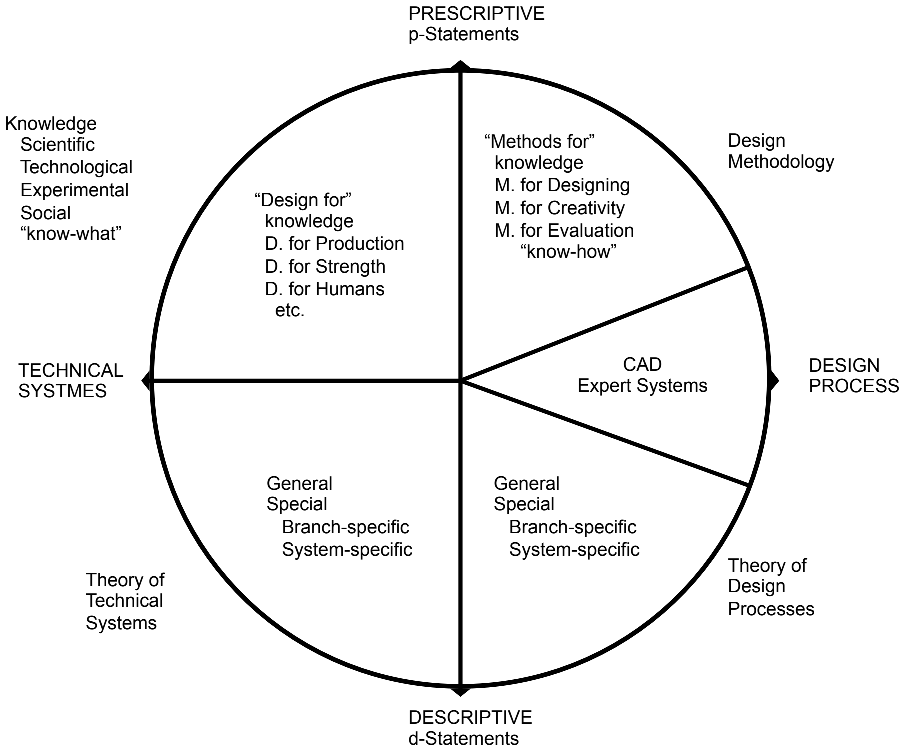


Figure 1. Two dimensions of Design Science (Hubka and Eder, 1988).

(DFM) and Design for Assembly (DFA) (Andreasen *et al.*, 1988; Boothroyd *et al.*, 1994). Both Design for Manufacture and Design for Assembly are, in their original sense, methods aimed at empowering the design engineer to design products that are easier to manufacture and assemble, respectively. The design engineer is provided with design guidelines in combination with a methodical procedure for finding improvements (Boothroyd *et al.*, 1994). The corresponding mindset is that the product design determines the manufacture of the product. Although it acknowledges the mutual effect between the manufacturing system and the product, it does so in general terms without addressing the designs of specific manufacturing systems.

Concurrent Engineering and *Integrated Product Development* emphasize the interdisciplinary nature of development (Andreasen and Hein, 1987; Prasad, 1996). Efforts here are directed at organizing the processes in a company, among other things, through the study of the product and manufacturing system. Conversely, the product design is subject to changes driven by the organizational prerequisites. Examples of business areas addressed are marketing, engineering design, and production (see Figure 2).

Systems Engineering focuses on the decomposition of the structure of the product, or system, to be designed in order to assign development tasks (Stevens *et al.*, 1998). Here, the goal is not to rearrange the tasks and thus change the development process. Rather, Systems Engineering wants to ensure that the constituents of a system can be integrated to form a working whole (Prasad, 1996).

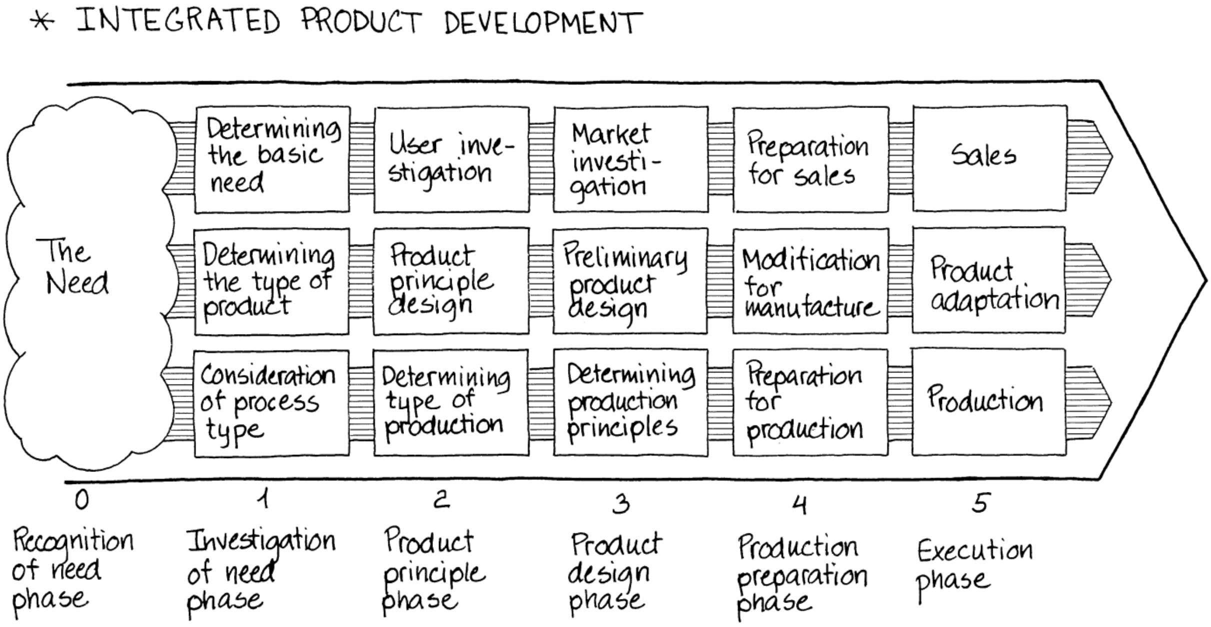


Figure 2. Integrated Product Development (Andreasen and Hein, 1987).

The research areas, or rather approaches, presented above with their different perspectives are far from clear-cut. For instance, Integrated Product Development can be seen as a part of Concurrent Engineering rather than as a neighboring area (Prasad, 1997). Another example is that the solution to Design for Manufacturing is prospected for by means of increasing cooperation between design engineers and manufacturing engineers, rather than through design guidelines and rules (Andreasen *et al.*, 1988). The common goal, however, is to prevent an over-the-wall scenario as outlined in the introduction. It is a general goal that this thesis shares with these overall approaches.

The following sections will go deeper into additional fields with the ambition to point out wherever there is an overlap or correlation with other fields. The outline of the chapter is chosen such that the underlying frameworks, mindsets, and paradigms are presented first as a whole, before introducing further theories and applications that build upon them.

2.2 Developing Products and Manufacturing Systems

Although industrial products and manufacturing systems are, in general, strongly interconnected, a viewpoint expressed in this thesis is that research efforts often are directed towards the development of one or the other. The theories presented in this section mirror the ambivalent nature of the matter, with product on one side and manufacturing system on the other side. However, they also include numerous methods and viewpoints for integration and alignment.

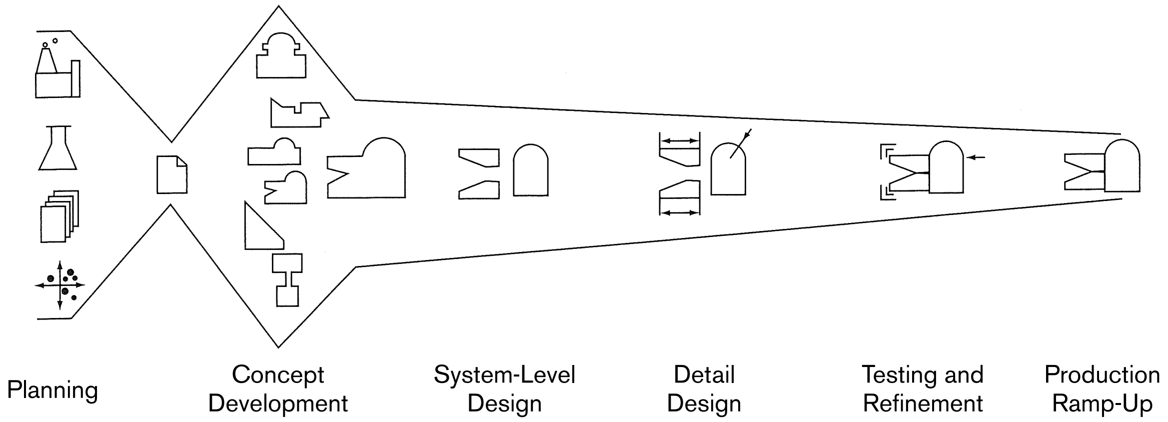


Figure 3. Generic development process (Ulrich and Eppinger, 2004).

2.2.1 Developing Products

Significant attention in the research on Engineering Design has been given to systematic methodologies for product development. They are for example related to Integrated Product Development, as much as they are concerned with the process of designing. A common trait of such methodologies is that they represent activities and recommend applicable methods for designing. They thus constitute a "a heuristic prescription (and model) of how to proceed" (Hubka and Eder, 1988, p. 216).

Procedural approaches of this kind have for example been proposed by Pahl and Beitz (1977), refined continuously (Pahl *et al.*, 2007), in the guideline VDI 2221 (1993), and by Ulrich and Eppinger (2004), schematically illustrated in Figure 3. Questions of manufacturability have their place in different process phases through various methods borrowed from, or in the spirit of, Design for Manufacture and Design for Assembly (Dixon and Poli, 1995). However, while applicable for the development of products, or artifacts in general, procedural models proposed in literature do not address the co-development of products and manufacturing systems used to produce them.

Accompanying the process of designing, driving it and guiding it, the systematic management of requirements is to ensure that the final product meets a need or a set of needs (Almefelt, 2005). This is done by translating those needs into technical terms and by connecting them to other prerequisites in the company, which also may evolve from the given manufacturing system. The subsequent stage of managing then follows up and refines the requirements. Requirements management can be carried out within the framework of systems engineering (Hood *et al.*, 2008).

On reflection, procedural models and the management of requirements might be primarily placed onto the right side of Figure 1. Complementing those and placed on the left side of the figure, there exist various models for describing the product as such

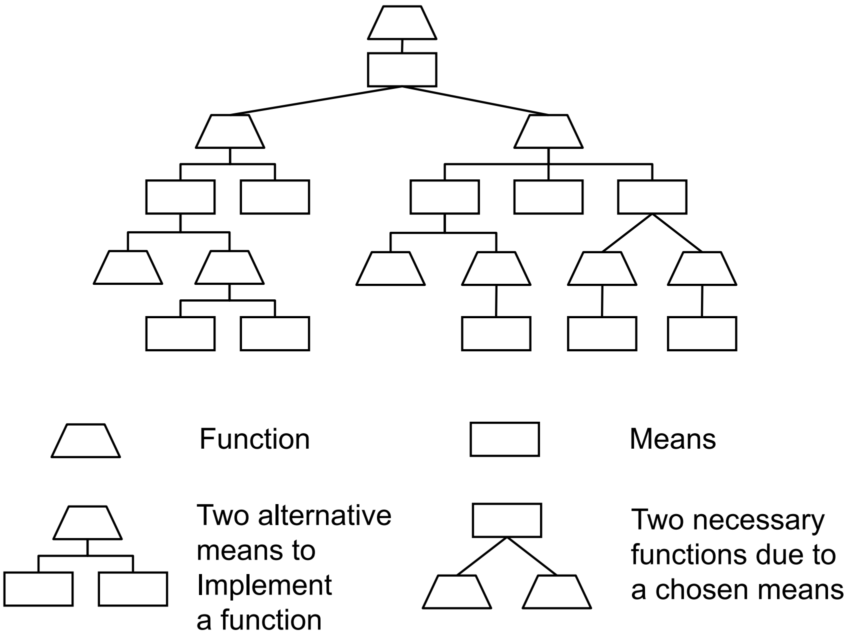


Figure 4. Example of a function-means tree (adapted from Svendsen and Hansen (1993)).

rather than the process of it being designed. These models try to capture information about the product that goes beyond what parts it is composed of. They are devised with the intention to help engineers in the process of designing.

Relevant in the context of this thesis are models aimed at linking the behavior of a product, its functions and the rationale behind its design to its physical embodiment. Through connecting these aspects, such models span a gap from abstract and conceptual to concrete and detailed information, reflecting a design process that is mainly directed top-down, but also requires bottom-up activities (Andreasen, 1992).

An example proliferated in academia is the modeling of the product's functions that are decomposed to successively increase the degree of detail (Tjalve, 1976). In an alternating effort, those functions are connected with the means to realize them, also called *design solutions* (Johannesson and Claesson, 2005). An instance of such a model is illustrated in Figure 4. Section 2.4 will return to this approach and provide further context on models of products and manufacturing systems that make use of it.

2.2.2 Developing Manufacturing Systems

Bellgran and Säfsten (2009) acknowledge that the development process for manufacturing systems varies and that terminology is not stringent. Nevertheless, they find significant similarities in the structure of procedural models in literature. Wu (1994) proposes one of the generic processes for the development of manufacturing systems. It covers the following steps:

- Analysis of situation,
- Setting objectives,
- Conceptual modeling (functional requirements, organization of functions, analysis of control system)
- Detailed design (selection of production technology, organization and layout of production technology, development of manufacturing information system), and
- Evaluation and decision.

The development of manufacturing systems is carried out differently concerning the detailed design, but is also subject to general differences in how it is perceived as a whole. Bellgran and Säfsten (2009) present a compilation of such perspectives in industry on one side, where the development tends to be based somewhat more on trial-and-error, and in academia on the other side, with partial and holistic theories (see Table 1).

The partial theories are devoted to solving sub-problems in manufacturing. In contrast, philosophies that include sets of techniques and methods, like Just-In-Time (JIT), Computer-Integrated Manufacturing (CIM), and Total Productivity Maintenance (TPM), address the more intricate issues, for example lead-time reduction. Design by Philosophy, exemplified by the Toyota Production System (TPS), goes even further and tries to change manufacturing through changing mindsets.

Most relevant in the context of this thesis are the remaining holistic strategies from Table 1. *Frameworks and strategies* for manufacturing are discussed further in Section 2.3, especially in the light of different market and product strategies. Section 2.4 takes a closer look at the notions of *Systems Design* as a basis for developing products and manufacturing systems.

Table 1. Perspectives on the development of manufacturing systems (Bellgran and Säfsten, 2009).

Industrial perspective	*Academic perspective*	
	Partial theories	Holistic (integrated) theories
Trial-and-error	Resource allocation	Framework and strategies (e.g. manufacturing strategy)
	Layout Material flow	Philosophies with sets of techniques and methods (e.g. JIT, CIM, TPM)
	Buffer capacity	Design by Philosophy (e.g. TPS)
		Systems Engineering/Design Frameworks

Process Planning is often brought forth as an important part of the design process for manufacturing systems. In fact, some see in process planning the interface between product design and manufacturing (Scallan, 2003). As manufacturing processes, in a broad meaning of the term, can range from material flow and layout issues to the single movement of a robot or tool, this view certainly has validity. However, the reflection in this thesis is that the scope of process planning may be limited to questions of detail if the layout is already determined and not subject to change for example.

2.2.3 Different Domains

Two conceptualizations that categorize different domains in the context of development work have bearing on the research of this thesis. The first conceptualization is the *Theory of Domains*. It uses the term domain to delineate relevant views and models of a product with different levels of abstraction (Andreasen, 1980). Four different domains are described:

- The *Process Domain*, in which processes and operations are expressed.
- The *Functional Domain*, which captures what the product is to achieve.
- The *Organ Domain*, populated with the organs that realize the functions.
- The *Assembly and Parts Domain* with the actual physical parts the product is composed of, the implementations of the organs.

The respective models of the different domains are connected by causal links between their constituents. In this manner different types of information about a product are captured while it is designed and developed. As the conceptualization includes the functional domain, it is apparent that it is related to the function-means formalism described above. Later modifications to the Theory of Domains replace the first two domains with a new one, the Transformation Domain (Andreasen, 1998). The motivation for this step was to allow differentiation between the concepts of *behavior*, simply put, what the system *does*, and *structure*, simply put, what the system *is*.

The second conceptualization that categorizes different domains is also closely connected with function-means modeling. In what is known as *Axiomatic Design*, originally three domains were defined (Suh, 1990):

- The Functional Domain with Functional Requirements (FR) that express what the product must achieve.
- The Physical Domain with Design Parameters (DP) specifying the product.
- The Process Domain with Process Variable (PV) specifying the manufacturing process.

The general idea of these approaches is that developing products and the manufacturing systems used to materialize them is achieved by jointly determining

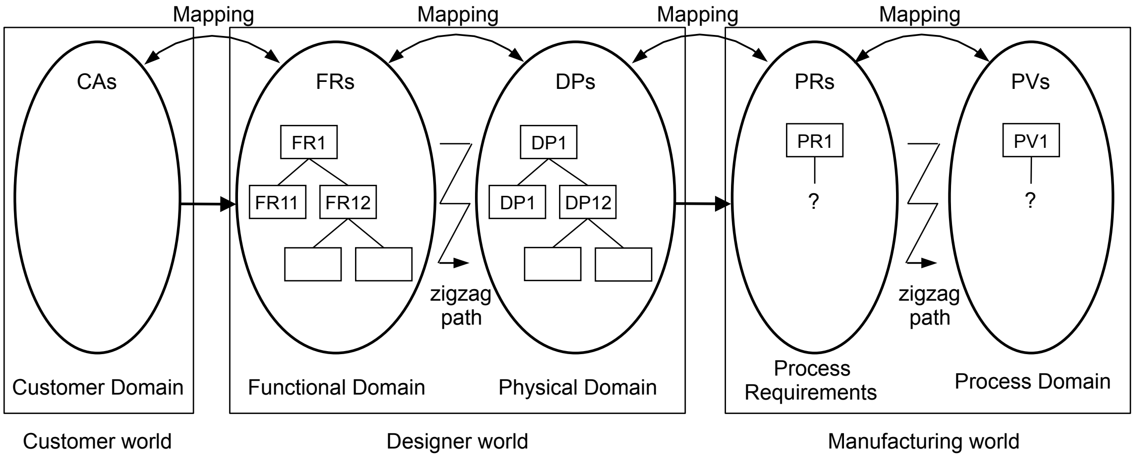


Figure 5. Different domains in the context of product development and manufacture (based on Sohlenius (1992), adapted from Vallhagen (1996), and redrawn).

parameters from different domains. The final solution for product and manufacturing system is determined by going along a zigzag path from the left to the right and successively from the top to the bottom in between each domain. This is schematically illustrated in Figure 5.

Suh's original domains have inspired numerous expansions. These essentially focus on supporting the development of manufacturing systems. They are further described in Section 2.4.3.

2.3 Paradigms for Development and Manufacturing

Both products and manufacturing systems can be developed by applying various mindsets and frameworks. The utilization of a platform strategy was already named in the introduction, and the previous section introduced frameworks and philosophies that have a bearing on the development of manufacturing systems. The different modes of how manufacturing companies set up their business, their market strategy, and their development efforts are influential factors in the context of this thesis. They are discussed below along with some specific paradigms for manufacturing systems.

2.3.1 Platform Approaches for Development

The idea of defining platforms for managing the product mixes of manufacturing companies is proliferated in many branches of industry and in academia. Jose and Tollenaere (2005) and Jiao *et al.* (2007) compiled comprehensive literature reviews on various perspectives and approaches connected with the concept of a platform. Both enter the topic via the idea of product families, which implies that products made by a manufacturing company are in one way or another related.

As a strategy, a platform generally aims at achieving benefits of scale while balancing distinctiveness and commonality across products (Robertson and Ulrich, 1998). However, even in the delimited context of the manufacturing industry the term itself is ambiguous. The fact that different definitions can be found reflects this circumstance. According to these definitions, a platform can for example be regarded as:

- The physical parts and assemblies the products are composed of, for example the common underbody of a car used across several models.
- 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” (Meyer and Lehnerd, 1997, p. xii).
- A “collection of assets that are shared by a set of products”, including components, processes, knowledge, as well as people and relationships (Robertson and Ulrich, 1998, p. 20).
- A “collection of common elements, particularly the underlying technology elements, implemented across a range of products” (McGrath, 2001, p. 53).

The differences between these definitions suggest not only that varying degrees of abstraction can be addressed. They also point at a difference of scope and a difference between goals that a company may pursue when applying a platform strategy.

The view expressed in the third definition is relevant for this thesis because it allows for including the manufacturing system as part of the platform. In fact, *manufacturing process platform* is one example of how the term *platform* can be used beyond the product (Zhang, 2007). The second definition points at another idea relevant for this thesis. The common structure is a significant point of interest when devising derivative products and when devising matching setups of the manufacturing systems.

For creating these derivatives and setups, configuration is an important mechanism. By means of configuration, variety can be created across products (Hvam *et al.*, 2008) and within manufacturing systems (ElMaraghy, 2009), while at the same time reusing a common structure. While clearly numerous views on platform strategies exist, this thesis looks at them as a paradigm or framework for developing products and manufacturing systems with a joint strategy.

2.3.2 Settings for Development and Manufacturing

Various concepts can be identified with respect to the overall process of how companies develop, manufacture, and sell their products. Going from little to increased customer proximity, these are:

- Make-to-stock,
- Assemble-to-order,

- Make-to-order,
- Engineer-to-order, and
- Custom-engineered.

In these settings, the customer order is only decoupled from the process of composing the product from idea to its finished state in *make-to-stock*. In the other concepts, the customer order affects the actual process while it is carried out. In *make-to-stock*, however, the customer perspective might be included as an input without later interaction. Giesberts and van der Tang (1992) express the customer's proximity to the process by means of the *customer order decoupling point*.

In addition to this question of proximity of the customer order to the process, abandoning *make-to-stock* in favor of one of the other concepts has implications for inventory management, or stock management (Popp, 1965). While in *make-to-stock* entire products are stored, the other concepts merely require storage of subassemblies and components (Cheng *et al.*, 2002), if at all. The two aspects of customer proximity and inventory management are reflected in Figure 6.

Configure-to-order is another term often introduced in this context. Its meaning is not marked-off clearly. Cheng *et al.* (2002, p. 2), for instance, see it as a hybrid of *make-to-stock* and *make-to-order* where "a set of components (subassemblies) are built to stock whereas the end products are assembled to order". Their view focuses on the question

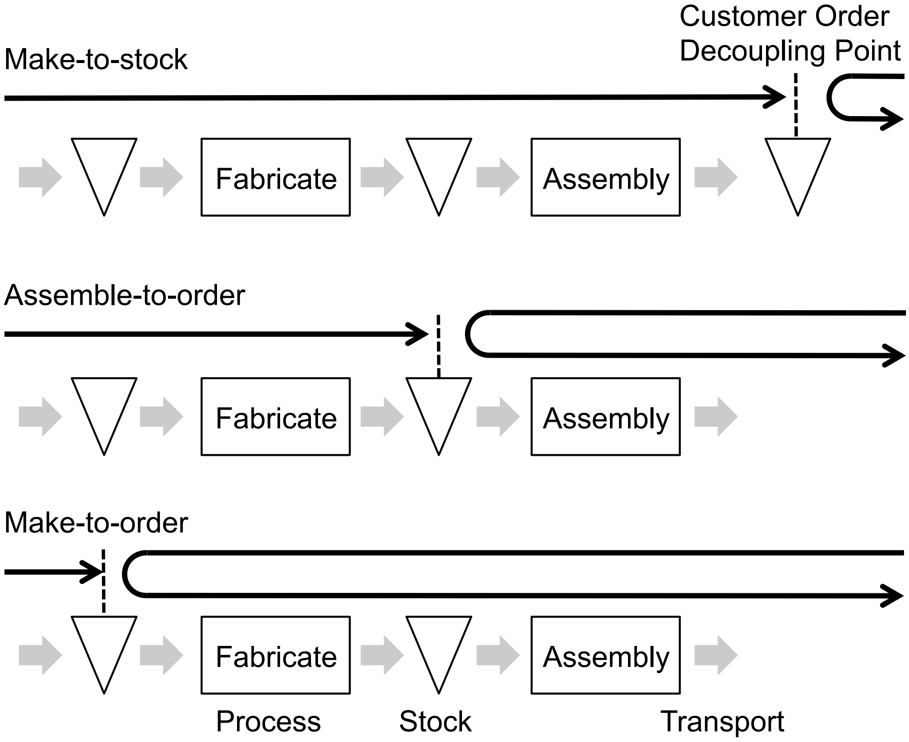


Figure 6. The dividing line between stock- and order-based production (redrawn from Hvam *et al.* (2008)).

of inventory management. However, with a stronger perspective on development work, Jiao *et al.* (2005) see *configure-to-order* rather from the perspective of customer proximity and implicitly place it somewhat closer to the concept of *engineer-to-order*. This thesis adopts this second view and expounds the question of configuration with respect to how development work can be conducted and supported.

The concepts introduced above are often connected with specific kinds of products. For example, satellites are not made to stock, and can openers are rarely engineered to order. Hence, the focus of this thesis lies on those concepts that provide a setting for platform-based development: assemble-to-order, make-to-order, and engineer-to-order.

Also frequently used when discussing customer proximity connected with how companies should develop, manufacture, and sell their products is the term *mass customization*. Here one tries to achieve befits of *custom-engineered*, such as fulfillment of customer needs, together with the price and efficiency of *make-to-stock* (Piller, 2004). While it is not impossible that the results of this thesis might contribute to enabling mass customization, this is not an aim of the presented work and outside the scope of the considered case studies and theoretical models.

2.3.3 Manufacturing System Paradigms

Together with the above-described paradigms for how manufacturing companies setup their business, their market strategy, and their development (including platform strategies), a number of paradigms for the actual manufacturing systems have a bearing on this thesis.

Three distinct paradigms can be identified (ElMaraghy, 2009):

- Limited or focused flexibility to suit a narrower scope of product variation.
- Pre-planned generalized flexibility as in Flexible Manufacturing Systems (FMS) designed and built-in *a priori* for pre-defined anticipated product variants over a period of time.
- Customized flexibility on demand by physically reconfiguring a manufacturing system (RMS) to adjust its functionality and capability.

The first paradigm is, for example, represented by dedicated manufacturing lines that produce "a company's core products or parts over a long period and at high volume" (Koren and Shpitalni, 2010, p. 131). In general, the three paradigms differ in application scenario, including capacity, cost of investment, and product mix or variety. Table 2 gives a more detailed account of the differences.

Table 2. Different characteristics of the three manufacturing system paradigms (adapted from Koren and Shpitalni (2010)).

	Dedicated	*FMS*	*RMS*
System structure	Fixed	Changeable	Changeable
Machine structure	Fixed	Fixed	Changeable
System focus	Part	Machine	Part family
Scalability	No	Yes	Yes
Flexibility	No	General	Customized (around a part family)
Simultaneous operating tools	Yes	No	Possible
Productivity	Very high	Low	High
Cost per part	Low (for full utilization)	Reasonable (Several parts simultaneously)	Medium (parts at variable demand)

Reconfigurable Manufacturing Systems were proposed in the attempt to combine some of the characteristics from dedicated systems with those of Flexible Manufacturing systems. More specifically, the goal is to allow “rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements” (Koren *et al.*, 1999, p. 529).

In this thesis, Reconfigurable Manufacturing Systems are examined in the context of product development based on platform strategies, and the joint development and configuration of manufacturing systems.

A range of examples, developed in cooperation between academia and industry under the concept name *Factory-in-a-Box*, incorporate some of the characteristics from Flexible and Reconfigurable Manufacturing Systems. Specifically, these examples aim at achieving flexibility and scalability through mobile manufacturing modules that can be transported to the site where they are needed (Jackson *et al.*, 2008).

Together with the introduced manufacturing system paradigms, the Factory-in-a-Box concept raises the question of how manufacturing systems are configured and what architectures facilitate co-development with products. At the same time, development of such manufacturing systems must be supported by models that can capture their flexibility and configurability.

2.4 Modeling Artifacts and Processes

For purposes of facilitating analysis and synthesis of technical systems, they are modeled with focuses on different aspects. In other words, a limited, but purposeful representation of reality is established. Below, some general principles for modeling technical systems are explained, followed by proposed modeling approaches.

This thesis follows the line of interpretation that these modeling approaches evolved from different needs for synthesis work and thus reflect different purposes of modeling. The resulting models contain more information than simply the final design of the system.

2.4.1 Modeling Technical Systems

The *Theory of Technical Systems*, proposed by Hubka and Eder (1988), models technical systems, or *operators*, with *input* and *output* and focuses thus on the *transformation* accomplished by the system; see Figure 7. This focus can be explained with Hubka and Eder's observation that most technical systems perform transformations and change one or several *operands* (material and biological objects, energy, and information) by means of various *effects*. Acting as *execution system*, *humans* and *technical means*, exert these effects.

While the effects indicate *with what* the operand is transformed, technology and the *transformation processes* are seen as answering the question of *how* this is done. Further, the *state* of the system is defined as the "aggregate of values of properties of a system at a certain time" (Hubka and Eder, 1992, p. 6). Hubka and Eder also acknowledge that not only the operator affects the operand, but also vice versa, as a reaction of the secondary output. They denote this mutual effect as *interaction*.

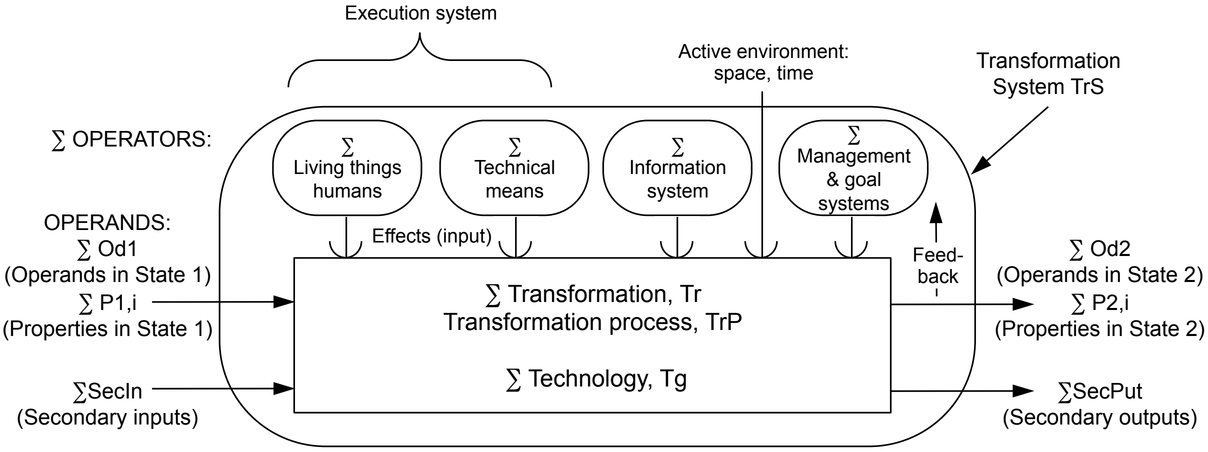


Figure 7. A transformation system (redrawn from Hubka and Eder (1992)).

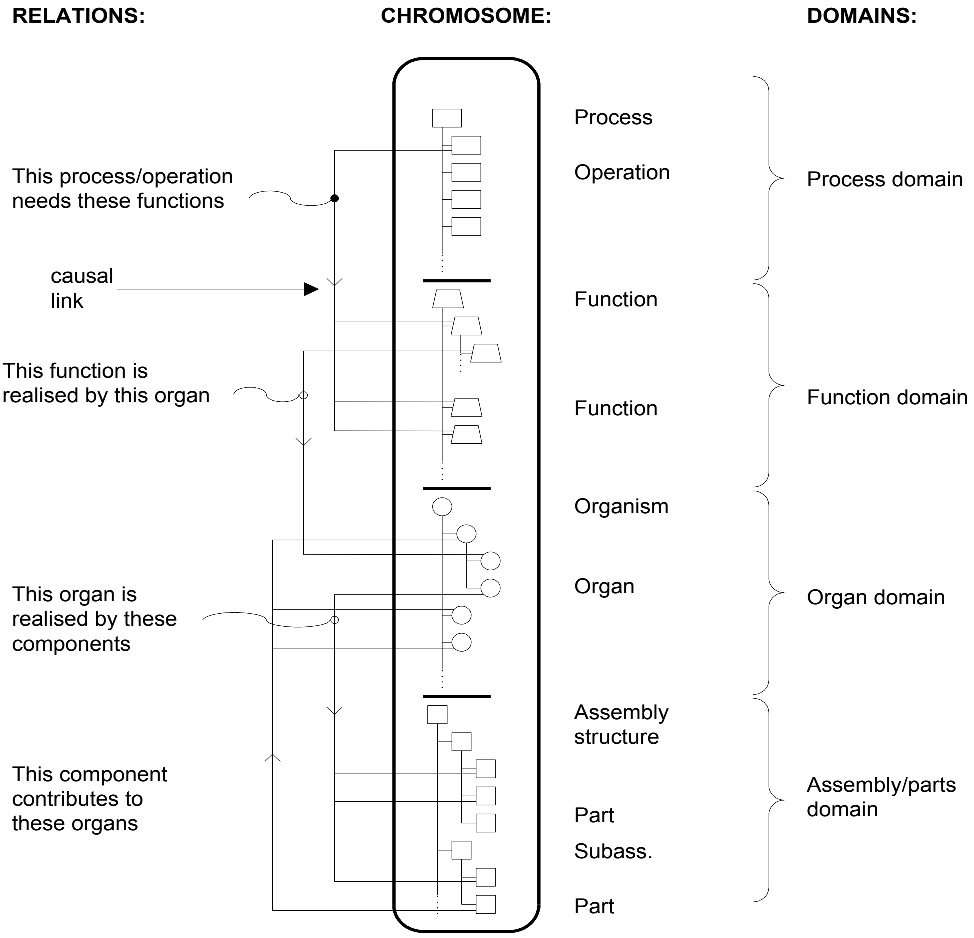


Figure 8. Chromosome model connecting concrete product information from different domains (Andreasen, 1992).

Hubka and Eder apply their model even to non-technical systems and processes. In particular, they present the process of designing as a transformation process. The Theory of Technical Systems is interesting in the context of this thesis because especially manufacturing systems are seen as executing transformations (Bellgran and Säfsten, 2009). Moreover, the idea of interaction as used in Theory of Technical Systems is relevant for this thesis. It is contrasted with a different notion presented in Paper A.

The general purpose of models is to support analysis and synthesis. The different domains introduced in Section 2.2.3 reflect how some aspects of a system are deemed relevant contents for models, especially when intended as support for the activity of designing. With the *Chromosome Model*, Andreasen (1992) devised a product modeling concept that includes causal links to connect elements from those different domains. It is schematically illustrated in Figure 8.

The model was devised in conjunction with the Theory of Domains, and it connects concrete information about the product, the structure of *parts* and *subassemblies*, with the abstract constructs *process, function, and organ* and their structure. In the chromosome model, the realization of a certain process accomplished by the product requires certain functions. Further, Andreasen (1992) proposed an additional process domain to cover the manufacture of the system. The components in the assembly and parts domain are connected to the processes that materialize them. This additional domain is not illustrated in Figure 8.

The Chromosome Model is interesting in the context of this thesis as organs allow modeling products and manufacturing systems platforms on an abstract level while component structures can represent concrete materialized instantiation of such platforms.

2.4.2 The Concepts of Function and Process

The concepts of function and process have been studied thoroughly, and this thesis cannot provide a comprehensive overview. Rather, some of the aspects concerning the notions of function and process that are strongly connected with the research of this thesis are highlighted here.

Function is a broad term that, despite its proliferation, lacks a universally accepted, clear-cut definition (Eckert *et al.*, 2011). The *Theory of Technical Systems* reflects the notion of a system's functions as transformations of operands from input states into output states. It is thus close to the action, or processes, carried out by the system. Andreasen (1980) pointed at the limitations of this notion of function that is based exclusively on transformation processes. He framed the concept broader to express *purpose* in general. A bookshelf supporting the weight of a book can thus also be regarded as accomplishing a function, for instance. This type of *purpose function* is based on a single, unchanged state.

Chittaro and Kumar (1998) denominated these two notions of function and their corresponding representations as *flow-based* and *state-based*, respectively. Pointing out various additional characteristics that differ, they argued that the two notions are similar while focusing on different aspects.

Further, Andreasen (1980) argued that a function is not a building block which can be used to compose a structure of its own, as for example presented by Pahl and Beitz (1977). This idea corresponds to the zigzag path that is to be followed when bridging different domains, as explained in Section 2.2.3.

Andreasen (1980) expressed this in what he denoted *Hubka's First Law*: "In the hierarchy of functions, which contribute to the product's overall intentioned function there are causal relations, determined by the organs, which we chose to realize these function" (as translated by Andreasen (2011, p. 300)). The function-means tree in

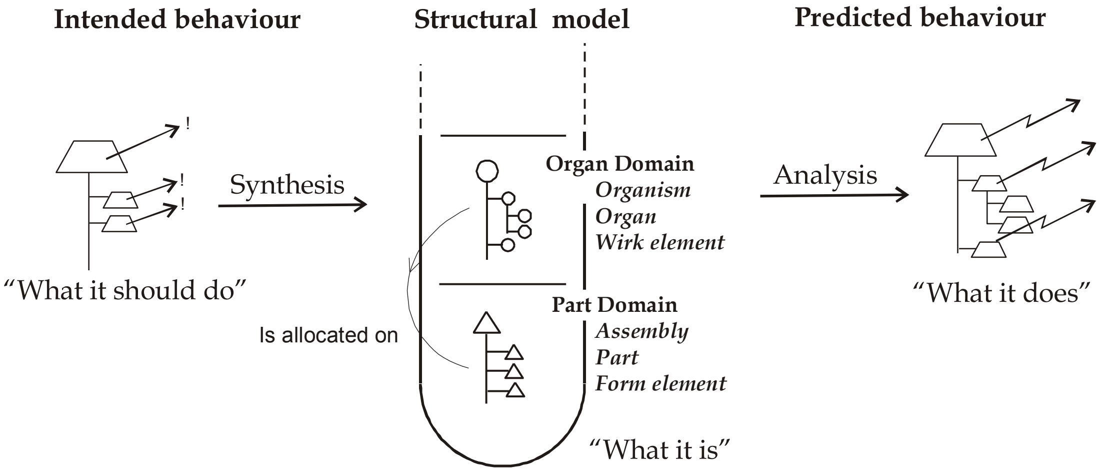


Figure 9. An organ-based mapping of behavior and structure (Jensen, 1999).

Figure 4 is an implementation of this idea. Functional decomposition, the decomposition of a system with respect to its intended purpose, can thus only be done in combination with decomposition of the organ and part structures.

Following this idea, Jensen (1999) argued that the intended purpose should be separated from the organ and part structures, which are structural models. The *intended* behavior together with the structural model then allows deducting its *predicted* behavior. Moreover, Jensen proposes that behavior be connected to the organs, rather than the physical parts. Through this, the part structure remains "purely structural" and includes only the information about "what it is". Figure 9 illustrates Jensen's idea. The model of the "intended behavior" on the left helps synthesize the structural models.

Adding to this idea, Johannesson *et al.* (2004) introduced a third mode, the actual behavior, which can be included further to the right. Consequently, behavior can be divided into what the system *should do*, *is predicted to do*, and *actually does*. Conclusions about the predicted and actual behavior require analyses based on structural models and testing of the finished product, respectively.

Roozenburg and Eekels (1995) argue that the functions of a product depend on the product's design and external factors. Specifically, the functions of a product emerge from its properties and how it is used (see Figure 10). Thus, a product may afford functionality that was not intended when it was designed. Further, the ability to provide a function depends on neighboring systems with which the product interacts.

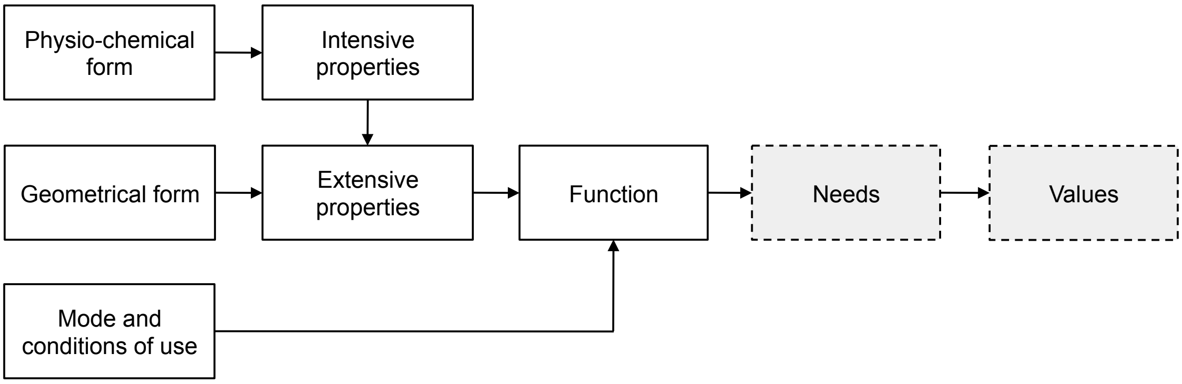


Figure 10. Function as a result of the system's design and its mode and conditions of use (Roozenburg and Eekels, 1995).

2.4.3 Function-Means Modeling and Axiomatic Design

The wish to facilitate the activity of designing drives the functional modeling of systems as described above. In particular, the resulting models support the synthesis of new designs based on existing ones. In part, they do so by capturing the underlying reasons for why the system is designed the way it is. In this thesis and the appended papers, this type of information is called *design rationale*, and it is incorporated in the models proposed.

It should be noted that this term, together with the related terms *design intent* and *design history*, is used diversely in literature, as pointed out by Andersson (2003). For instance, Lee (1997, p. 78) defines design rationale as capturing “not only the reasons behind a design decision but also the justification for it, the other alternatives considered, the tradeoffs evaluated, and the argumentation that led to the decision.”

Several similar methods aim at representing a system’s design rationale. They are based on differentiating several domains and establish a logic of how functions, solutions and other modeling elements are connected. In addition to the Chromosome Model, function-means models and approaches originating from Axiomatic Design are considered here.

Function-means modeling captures the designs of technical systems and their rationale, creating a decomposition of functions alternating with the means used to solve these functions. It distinguishes between functional requirements (FR) that are solved by means and non-functional constraints (C) that limit selectable means. Each means accomplishes a single function, while several constraints can limit its selection.

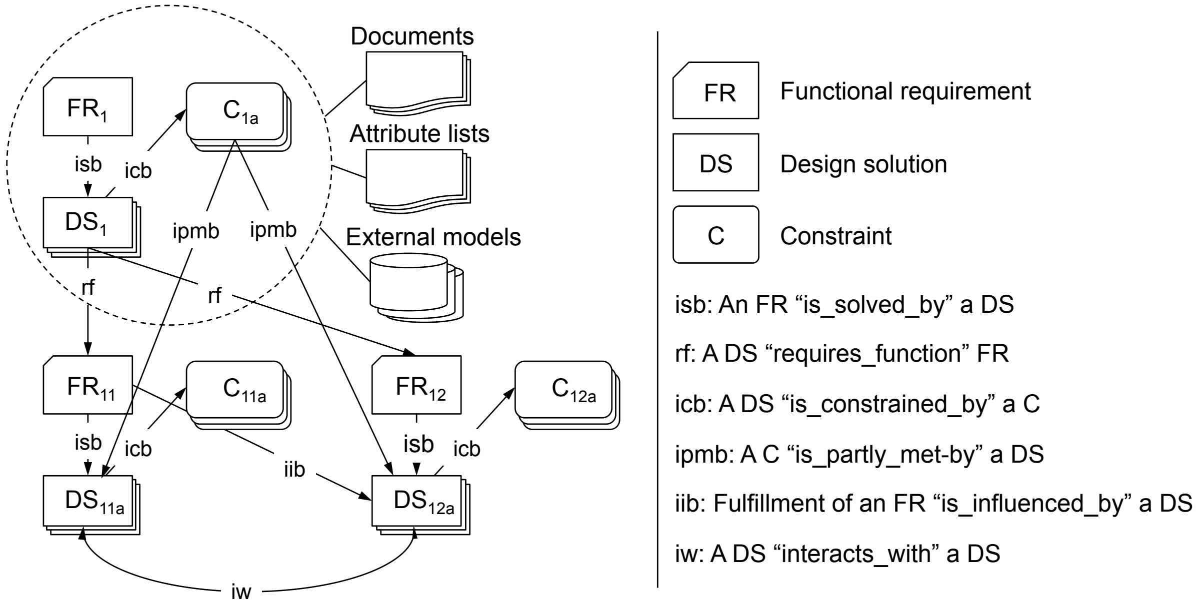


Figure 11. Enhanced function-means tree with linked information items (adopted from Johannesson and Claesson (2005)).

Adding additional modeling elements enhances function-means models. Malmqvist (1997) proposed using function-means trees for capturing design history and included constraints and objectives in the resulting tree structure. Schachinger and Johannesson (2000) further added to the function-means trees supplementary design information, such as documents, attribute lists and external models. Moreover, they showed how constraints are decomposed and how this leads to new relationships connecting different tiers in the trees. Figure 11 schematically illustrates a resulting function-means tree with the defined relationship types between modeling elements.

The modeling of manufacturing systems with the functions-means formalism is generally conceivable. However, the formalism provides a primarily state-based view of the artifact at hand. Consequently, it provides a rather indirect view on manufacturing processes.

In contrast to this, Axiomatic Design connects the product design explicitly to manufacturing processes with so-called process variables (Suh, 1990). Suh applied broad notions of the terms functional requirement, design parameter, and process variable. A *functional requirement* is seen as the objective of designing, or as Suh expresses it: "what we want to achieve" (1990, p. 25). Thus, *reduce the material cost by 20%* falls within the scope of a functional requirement, for example. Further, Suh's notion of *process variable* is also a broad one. It includes people, financial resources and material, for example (Suh, 1995).

The insight that process variables alone do not account for the design of the manufacturing system led to several adaptations. Suh himself and his colleagues (Suh *et al.*, 1998) applied the functional and physical domain to the manufacturing system, thus making it the artifact to be designed. Cochran *et al.* (2001) took a broader view and proposed a framework that supports development by elaborating on strategic generic objectives of a manufacturing system and generic solutions to these. Houshmand and Jamshidnezhad (2006) go further and reinterpret process variables as the tools, methods, and resources, required for implementing a lean manufacturing system. These models facilitate decisions in the development of manufacturing systems and document their rationale. However, the notion of a functional requirement they apply adheres strongly to an objective rather than to a function that explains the functioning of the artifact.

Other approaches based on Axiomatic Design maintained the connection to the product design. Sohlenius (1992) proposed to add a domain with process requirements to the original three domains (see also Figure 5). The goal was to capture requirements on the manufacturing system that evolve from the design parameters of the product and lead to the process variables of the manufacturing system. Vallhagen (1994) expanded on this and proposed differentiating between three types of design parameters: dimensioning, component and subassembly. These allow mapping product design to separated spaces in the manufacturing domain, such as part manufacture and assembly. Almström (2005), while maintaining the connection to the product design, focused primarily on the manufacturing system. He considered the product's design parameters an input to the functional requirements of a manufacturing system, and exemplified this by a product's DP *plastic box* that spawns the FR for the manufacturing system to *manufacture the plastic box*.

Function-means modeling and Axiomatic Design capture the functions of the products and functions or objectives of the manufacturing systems. These modeling elements are relevant in the context of this thesis and used in the research presented. However, with these elements the two modeling approaches do not provide a clear account on how functions or objectives map to existing product components and existing machinery.

2.4.4 Modeling Principles from General Systems Theory

Beyond the above principles commonly discussed in engineering, *Systems Theory* combines a number of principles used to describe and explain complex phenomena where a single constituent cannot be understood without considering its context. It is stressed that a system is more than the sum of its parts, an insight that dates back to ancient times (Aristotle and Ross, 1936).

This idea is reflected by the principle of *emergence*, stating that "whole entities exhibit properties which are meaningful only when attributed to the whole, not to its parts" (Checkland, 1981, p. 314). In other words, emergence means that the properties of the parts put together cannot account for the properties of the entire system.

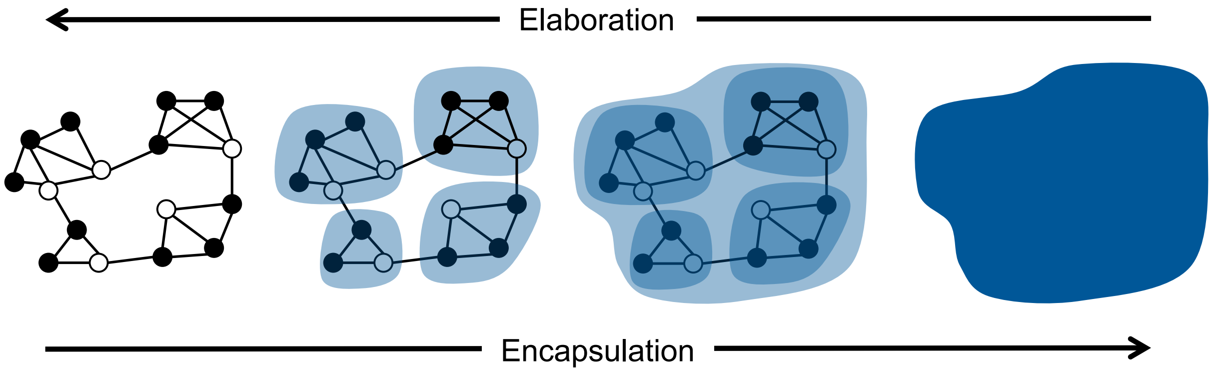


Figure 12. Elaboration and encapsulation (based on Hitchins (2003), adapted and redrawn from Claesson (2006)).

As a consequence, *decomposition*, the breaking up of complex systems into smaller, simpler parts is regarded as insufficient. That is because it cuts the *de facto* existing relationships between those parts. Instead, Hitchins (2003, p. 93) promotes *elaboration*, in order to look into the system and as a process that “does not disconnect parts, but acts rather like a magnifying glass, enabling the user to see and express more detail while that detail remains in situ; connected, dynamic, and interactive.”

As a complement, *encapsulation* is proposed as the tool for zooming out. Essentially, this means concealing the inside of a system so that only its emergent properties and external behaviors represent it as a whole seen from the outside (Hitchins, 2003). Encapsulation is, for example, applied in object-oriented programming (Gedell, 2009). Figure 12 schematically illustrates the encapsulation and elaboration mechanisms.

The ideas and concepts from Systems Theory are relevant for modeling technical systems pursued in this thesis. That is because they emphasize the need to validate performance and functionality of synthesized solutions as a whole in those cases where they are emergent properties. The quality of a product can depend on several components working together rather than on the quality of each component seen by itself, for example. This is also closely related to the question of predicted and actual behavior when emergent properties are difficult to predict.

2.5 Modeling Platforms and Variety

The principles for modeling artifacts and processes introduced above allow defining platform approaches in various ways. Among these are the structuring of systems according to their functions as well as the modeling of design rationales and interdependencies of products, manufacturing systems, and manufacturing processes. Other approaches trace the development of variety in artifacts over time and help understanding and managing changes required to achieve desired variety. This section presents a selection of these approaches that have a bearing on the research questions or inspired the research of this thesis.

2.5.1 Modularity

Being closely related to the notion of a platform, modularity is a theme that has received considerable attention in industry and academia. It is proliferated where development is aimed at creating a variety of similar systems, for example in companies that adopt the marketing and manufacturing concepts make-to-order and assemble-to-order.

Erixon (1998, p. 58) defined modularization as “decomposition of a product into building blocks (modules) with specified interfaces, driven by company-specific reasons”. Many other notions of modularity exist. Gershenson *et al.* (2003) provide a comprehensive overview of these, for example. However, Erixon’s definition is especially interesting in the context of this thesis (with the reservation that *decomposition* should rather mean *elaboration*). That is the case because it stresses that the functional decomposition of a product is not the only reasons for modularization.

Ulrich and Eppinger (2004) expressed the view that the relationship of physical parts connected with specific functions is a characteristic relevant in modular designs. They introduced the term *chunk*, a physical unit of parts that allocates certain functions. Modular architectures then have the following properties:

- Chunks implement one or a few functional elements in their entirety.
- The interactions between chunks are well defined and are generally fundamental to the primary function of the product.

Grouping several functions to be implemented in one of these chunks is also called *function sharing* (Ulrich and Seering, 1990). Reflecting the domain elements in the Theory of Domains (Andreasen, 1980), modularity means that functions, organs and parts are structured to yield specific relationships. For example, the two ends of a claw hammer accomplish two functions, achieved by two organs in one part.

Claesson (2006, p. 125) stressed the idea that modules can be more abstract, for example like organs. He thus argued that modularization “is the conscious, goal-driven decomposition and grouping of design solutions in order to provide building blocks (modules) suitable for selection into several products.”

Regardless of the exact definition, creating modular designs is seen as potentially entailing numerous benefits. Table 3 lists some of the most commonly identified benefits of modular architectures and contrasts them with the ones assigned to integral, or integrated, architectures. Not included is the idea of delayed differentiation (Ulrich and Eppinger, 2004) that is vital for make-to-order and assemble-to-order, for example.

Table 3. A compilation of benefits of modular and integral designs (Mikkola and Gassmann, 2003)

Benefits of Modular Designs	*Benefits of Integral Designs*
Task specialization	Interactive learning
Platform flexibility	High levels of performance through propriety technologies
Increased number of product variants	Systemic innovations
Economies of scale in component commonality	Superior access to information
Cost savings in inventory and logistics	Protection of innovation from imitation
Lower life cycle costs through easy maintenance	High entry barriers for component suppliers
Shorter product life cycles through incremental improvements such as upgrade, add-ons and adaptations	Craftsmanship
Flexibility in component reuse	
Independent product development	
Outsourcing	
System reliability due to high production volume and experience curve	
Examples: Elevators, passenger cars, IBM PCs, Lego toys	Examples: Formula One car, Apollo Computers, satellites

Erixon *et al.* (1996) proposed the concept of module drivers, a number of generic, but not necessarily complete, criteria that motivate modularization seen from a lifecycle perspective. These criteria are grouped into:

- Variance
- Manufacturing
- Quality
- Purchasing
- After sales

With respect to manufacturing they argued, for example, that a sub-function of the product should be assigned to the product module if it:

- has the suitable work content for the respective manufacturing system or work group,
- fits the group's special know-how,
- is a pedagogical assembly, or
- differs significantly in lead time.

Thereby, Erixon *et al.* (1996) connected the modularity of the product with questions of manufacturability and aspects from other lifecycle phases. The goals of modularization specified by them go beyond aiming for high congruency of the functions of the product and the physical embodiment of the function bearers as expressed by Ulrich and Eppinger (2004). This is interesting in the context of functionally integrated products, which can still be subdivided based on manufacturability aspects rather than product functionality. Paper F reports a study on such a product with inherent function sharing.

2.5.2 Parameterization

Assigning parameters instead of fixed values to systems is a way to postpone locking their design. When given a range, parameters can be used to describe fuzziness within limits during the development process. After optimization, these parameters can then be determined for the final design. The exact idea of the design can be left undefined on the left side of Figure 13 until its parameters on the right side are locked.

Another usage of parameters is to define the variety of the systems (in other words, different configurations). The development with the consecutive configuration of products in assemble-to-order or make-to-order is a field of application for this (Hvam *et al.*, 2008). The parameters can be connected with each other by means of rules that exert constraints on the design. These rules are managed so that changing one parameter does not result in a system that, for example, does not serve the intended purpose or is not manufacturable. At the same time, the rules hold the information of which configurations are available. The values of the parameters on the right side of Figure 13 determine the available configurations on the left side.

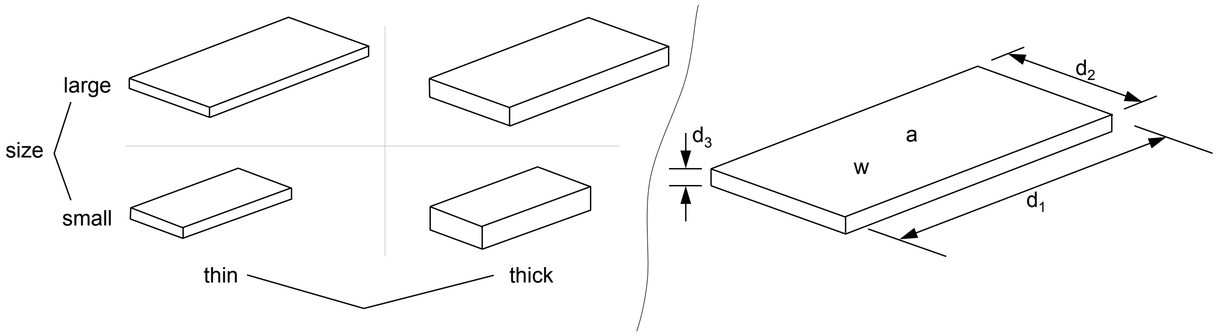


Figure 13. A simple example of a design with parameters (redrawn from Claesson (2006))

Berglund and Claesson (2005) denoted the available range of parameter values *design bandwidth*. They introduced it as a measure of variability of a single design solution. A ball bearing can be varied in several dimensions to cover a range of functionality and performance, for example. Wahl and Johannesson (2010) further connected the idea of design bandwidth to the set of available alternative solutions that provides a combined bandwidth. The two alternative solutions of ball bearing and roller bearing allow a wider range of functionality and performance than one of the two alone, for example. The research of this thesis elaborates further on the notion of design bandwidth by connecting it to function-means modeling and integrated platform models.

2.5.3 Generic Product Structures

Product structures are represented in *Bills of Materials* based on the parts and assemblies they consist of. With the *Generic Bills of Materials* van Veen (1991) proposed a formalism for more abstract product structures. By means of this formalism large varieties of product types can be modeled in one structure, defining products as *sets of product types* instead of defining *individual product types*. In a similar approach Männistö *et al.* (2001) describe a *Master Bill of Materials*, a generic description of product variants, with the ambition to capture multiple levels of abstraction in the product model.

Generic product structures have inspired or resemble some of the approaches for modeling platforms presented below. They have thus an indirect bearing on the research of this thesis as they point at the possibility of capturing the variety of technical systems in one structure.

2.5.4 The Configurable Component Framework

Claesson (2006) followed this idea of a common system structure for variety. He proposed the *Configurable Component* (CC) framework, a generic modeling concept for describing configurable products. It follows the ambition to enable platform modeling without subjecting the platform to a rigid system architecture and instead allow flexible interfaces. The concept has been adopted and developed further by Gedell (2009; 2011) and Edholm *et al.* (2009). In essence, it combines function-means modeling, to capture the design rationale, with a parametric modeling approach. Moreover, it adopts the principle of elaboration and encapsulation.

Systems and their incorporated subsystems are represented by means of a generic building block, the Configurable Component (see Figure 14). This building block includes a number of internal elements that are defined to implement the CC concept, for example in software tools for modeling. Adopting Gedell's work (2011) they can be described as follows:

- *Function-Means Trees* include the system's functional requirements (FR), their design solutions (DS), and constraints (C). With these modeling elements the function-means trees capture the design rationale (DR) in the system.
- The *Control Interface* allows access to the system parameters. This access can be given to the user or to other CCs.
- The *Composition Set* contains the information defining which other CCs are used to further define the considered CC. Both composition set and control interface are used to build a structure based on CCs as the building blocks.
- Through the *Interface Set*, the CC receives input and delivers output on the functional level, answering the question of what function the system fulfills and under which conditions it does so.
- The *Variant Definition Parameters* govern the total system's structure and the configuration of each CC. Together with the available CCs they define the system platform.

Among others not included in the above illustration of the Configurable Component structure, are the so-called *Performance Models* that capture the range of system performance that comes with different configurations.

Like the enhanced function-means tree, the CC framework provides a large palette of modeling elements and relationship types. Some of them are used and explicitly discussed in the research of this thesis while others are not pursued further. Of particular interest is the framework's capability to model technical systems in general, thus covering products and manufacturing systems.

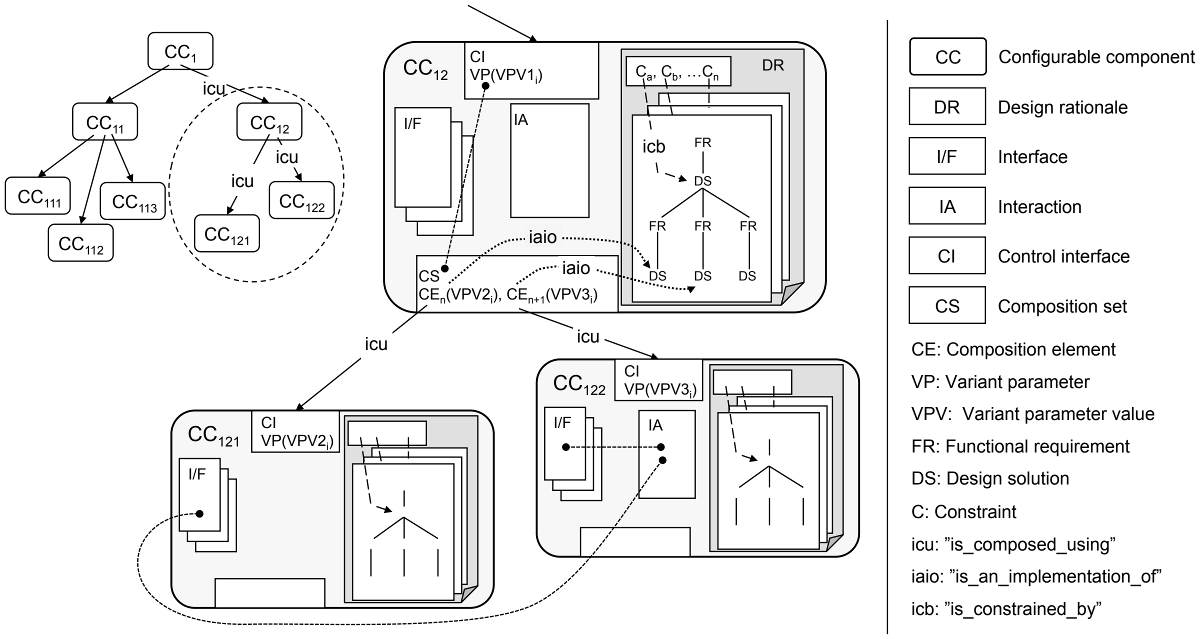


Figure 14. Composition of configurable components with encapsulated elements and relationship types (adapted from Claesson (2006)).

2.5.5 Product Structures and Process Platforms

Zhang (2007) proposed a framework that aims at reusing existing elements from generic product structures and generic manufacturing process structures. The generic product structures consist of raw material, parts, and assemblies while the connected processes are manufacturing and assembly operations. Including all product and process platform information in one single structure, Zhang's model essentially enhanced generic product structures such as the ones proposed by van Veen (1991) with generic production process elements. Zhang (2009) further formalized her approach in a diagram-based modeling formalism that visualizes the process platform together with the generic product structures.

Bengtsson *et al.* (2010) focused on the visualization of complex manufacturing processes and their operation sequences, and connected this with ideas from the modeling configurable products. Their aim is to manage the complexity of the processes that becomes evident when granularity of the model is increased to, for example, the level of single robot motions.

With a stronger focus on the product structures, the *Product Family Master Plan* (PFMP), also known as *Product Variant Master* (PVM), is a visual modeling tool. First formalized by Harlou (2006), it shares the object-oriented heritage with the modeling

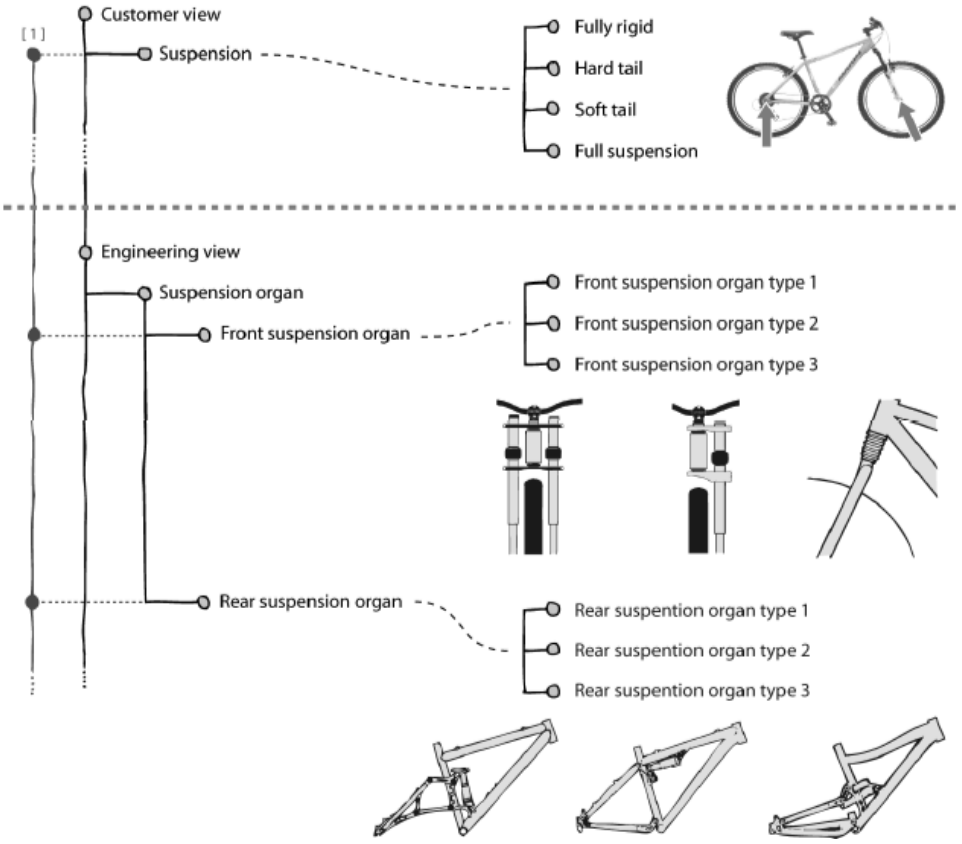


Figure 15. Example of a Product Family Master Plan (Kvist, 2010).

approaches above. The strength of the Product Family Master Plan lies in the visual representation of the entire product family. Influenced by the chromosome model, it includes different views, such as a customer view, an *engineering view* and a *part view* (see Figure 15). Kvist (2010) identified a lack of linkage in the model to manufacturing. With the PFMP^2, he expanded the Product Family Master Plan to include also the processing steps for product parts and assemblies.

These modeling approaches combine product structures with modeling of manufacturing processes. They thus address the manufacture of the product, but do not include the design of the manufacturing system, which in this thesis is considered essential for co-development.

2.5.6 Evolution Models

Inspired by biology, AlGeddawy and ElMaraghy (2012b) analyzed the development over time of characteristics in a group of individual products. They observed that the products developed distinguishing features analogous to biological organisms in the course of their evolution. This analogy allows analysing groups of products, finding their common platform, and optimizing overall modularity by integrating parts if this does not affect the products' functionalities. AlGeddawy and ElMaraghy connected this further to the design of the assembly system which profits from the increased part commonality.

Moreover, AlGeddawy and ElMaraghy (2010) found that products and manufacturing co-evolve over time. They do so like two species that share common evolution paths, such as bees and the flowers they pollinate. AlGeddawy and ElMaraghy developed this into a co-evolution model for products and their manufacturing systems that allows tracing their historical co-evolvement and predicting and synthesizing future configurations of both (AlGeddawy and ElMaraghy, 2012a). The method focuses on distinguishing features of products and manufacturing systems and represents them together in branching diagrams.

The co-evolution model is interesting in the context of this thesis because it is an integrated model that captures the design of products together with the design of manufacturing systems. Further, it addresses their co-evolution, which results from repeated co-development.

2.5.7 Engineering Change Management

Eckert *et al.* (2001) also consider development over time and focus on products that are modified continually. They stress the importance of understanding how initial changes will cause further changes to propagate in the design. Such propagation of changes results from the complex interactions among parts and systems in the design. These parts and systems can carry on a change or even multiply it. Therefore, Eckert *et* *al.* advocate developing products with design margins that allow absorbing change to some extent.

Further, they argue that a model of the most important parts and systems with their interdependency helps predict engineering change. Clarkson *et al.* (2004) proposed such a model. It makes use of dependency matrices to indicate which parts or systems interact and connect this with risk factors for each interaction. The model allows following the risk path of a proposed change in the product design.

In an application study for the approach Jarratt *et al.* (2004) observed the challenge of determining the suitable degree of detail of a model. Further, they marked out that understanding the functionality with all relevant aspects requires the consultation of several engineers with different expertise. This in turn has the beneficial side effect of increasing interdisciplinary communication.

While the above approaches adhere to structural product models, Ahmad *et al.* (2012) further developed the model to include requirements and functions. Their functional view of the product is essentially flow-based and does not include non-functional requirements. Instead, it helps identify the tasks required to implement a change and thus allows structuring the engineering change processes.

In the theory presented here, engineering change management does not include the manufacturing system design or build on a product platform or family. However, its methods for predicting and managing change provide inspiration for managing the repeated redesigning of products and manufacturing systems based on a platform.

2.6 Positioning the Work of this Research

Concurrent Engineering and Integrated Product Development aim at integrating development efforts, and thus at avoiding the over-the-wall scenario, in a comprehensive approach that addresses the technical systems involved as well as the engineering processes carried out during the development. In other words, they connect the left and the right sides of Figure 1. At the same time they require methods for modeling engineering processes and the technical systems.

The procedural models for development help in structuring and organizing these engineering processes. They provide support for the development of products and the development of manufacturing systems, each seen as separate systems with a development process of their own. Moreover, they can support the simultaneous, or concurrent, development of products and manufacturing systems. Correspondingly, for this development, companies can choose platform approaches for their products, for their manufacturing systems, or both.

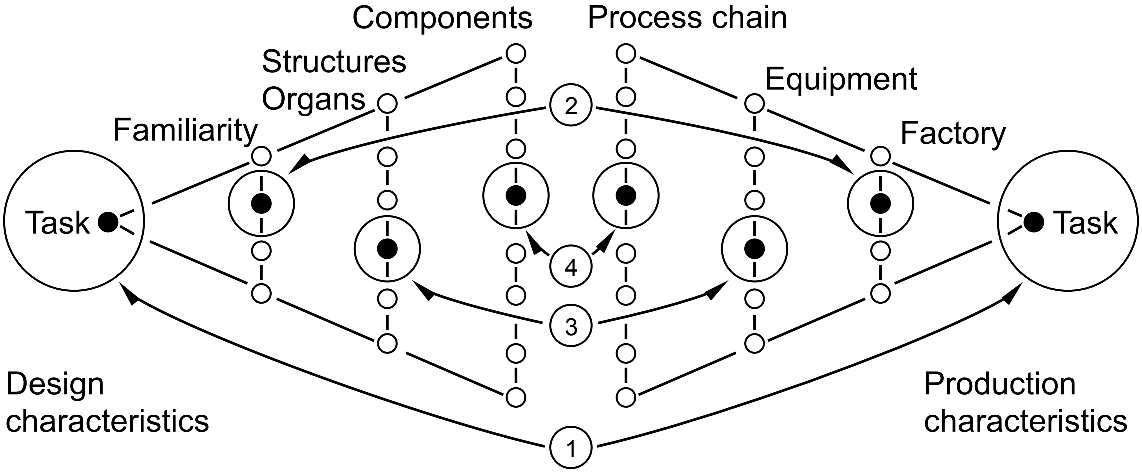


Figure 16. A system perspective on linking product design and manufacturing (redrawn from Andreasen (1992)).

Modeling product structures and the manufacturing system serves as a basis for defining such platforms. System modeling provides tools for representing product structures and, attached to it, manufacturing aspects including manufacturing processes. Moreover, manufacturing systems can be modeled covering the platform approach for this system. However, it is argued in this thesis that these modeling options fall short of representing both the product structure and the structure of the manufacturing system with relationships across system boundaries. Figure 16 illustrates a simplified model of these relationships on various levels. The right side of the figure represents the manufacturing system.

In addition to the above, platform approaches for manufacturing are expressed in terms of processes connected with the product structure rather than including the manufacturing system as a whole. Consequently, questions of modularity and configuration of the system beyond the manufacturing processes are not addressed explicitly.

While the theory presented in this chapter is strongly connected with modeling the left side of Figure 16 and pointing out some aspects on the right side there is no approach for covering the entire picture.

Reflecting upon the theory introduced in this chapter, the following opportunities for research can be identified:

- Theory on the modeling of products and manufacturing systems focuses, in essence, on one system or the other. *Thus there are opportunities for modeling approaches that represent the entire manufacturing system together with the products.*

- Theory on product platform modeling comprehensively covers questions of modularity and configuration. *There are opportunities for adapting these ideas to the modularity of manufacturing systems and modeling means for redesigning and configuration together with the products.*
- To a large extent, the theory above reflects the view that the development of the product drives the development of the manufacturing system. In other words, it does not adequately consider other drivers of development, such as changes to the manufacturing systems. *Consequently, there are opportunities for highlighting co-development of both systems and thus providing for a work mode that can start on either side.*

The work reported in this thesis aims at exploiting the above opportunities with the emphasis placed on modeling the technical systems, the left side of Figure 1. The main sources of inspiration from literature are covered in this chapter, especially in Section 2.5.

More specifically, the intention is to pave the way for further development of modeling in the spirit of the function-means modeling and the Configurable Component framework. This is not necessarily only done by adding more detail to the concept, but rather by providing additional context for its development that evolves from widening its scope to modeling manufacturing systems.

3 Research Approach

In this thesis the view is adopted that the transparency of mindset, method, and procedure is essential in the presentation of research endeavors and their results. It is to build confidence in the work and allow others to assess its quality. Therefore, this chapter gives an overview of how research in the multifaceted field of this thesis can be regarded in general, which underlying mindsets these approaches build upon, and what mindset was applied in this thesis. The selected methods, procedures and underlying reasoning for the research approach of the thesis are argued for. Evolving from this, different criteria for the assessment of the research are identified.

3.1 Research in Engineering and Development

Engineering is by nature an area of application and study that connects different scientific disciplines, such as mathematics, physics, and chemistry, with applied fields such as manufacturing technologies, logistics, and electronics. At the same time, it is firmly grounded in the everyday activities of individuals and operations of industrial companies. It thus relies on various other disciplines, for example economics and sociology. Research in engineering may therefore focus on one of the areas above or connect to several of them (Eckert *et al.*, 2003). For scientific exploration of engineering topics, looking only at one or connecting to several of these topics, this means that a multitude of views and paradigms exist. (Note that this chapter uses the term *paradigm* to denote the worldview on which the theories and methodology of the subject are built.)

Given the above view of Engineering as a whole, *Engineering Design*, or just *Design*, can be seen as a subset of engineering, concerned with designing and building technical systems. *Manufacturing Engineering*, or *Production Engineering*, concerned with the design and operation of manufacturing systems, is then likewise a subset of Engineering connected with various other disciplines. *Design* can also, by definition of the word, have a wider scope, making it difficult to speak about a subset of engineering. Looking for a common denominator, the reflection can be made that the above disciplines are all concerned with the intentional development of some sort of object, tangible or not.

In this thesis, the exact delineation is not so relevant. Rather, the observation is important that some of the theory introduced in the previous chapter comes from different backgrounds and applies different mindsets. Moreover, there exists significant thematic overlap between the disciplines above. On reflection, however, the center of gravity of the theory presented above, and constituting the underpinnings of this thesis, can be placed closer to engineering design – that is, where engineering design does not see its solemn purpose in designing products, but instead adheres to a wider scope and addresses technical systems in general.

Making the connection to research in and on those disciplines, Hubka and Eder (1988) use Figure 1 to point at two relevant dimensions. The respective research may be concerned with the technical system (the artifact) that is to be designed, with the engineering processes that lead towards its coming into being, or both.

Further, they point out that research can describe phenomena observed and prescribe means to improve artifacts and engineering processes. Blessing and Chakrabarti (2009, p. 5) integrate this perspective in their view on research and endorse that it can address two main elements: “the development of *understanding* and the development of *support*”. Moreover, they note that these two elements are entangled and should be considered together.

Blessing and Chakrabarti (2009, p. 12) also point at a goal of the respective research stating that it should “make design more effective and efficient, in order to enable design practice to develop more successful products”. Eckert *et al.* (2003) stress the significance of the goal to improve the understanding of designing. They see in it the prerequisite and result of the quest to improve designing. Horváth (2001, p. 13) takes a similar stance and states more broadly that research should be “instrumental to the development of engineering design”. This is to be done through generating knowledge *about* and *for* design. The thesis follows these views as they are reflected in the goals presented in Section 1.3.

3.2 Applied Mindset

Given the numerous fields included in, or connected with, engineering in general and engineering design in particular, there exist different notions of how knowledge is acquired – a question of epistemology. Related to those different notions is the question of what methods are to be selected for conducting research.

With respect to engineering as a whole, Vincenti (1990) argues that it cannot rely only on the natural sciences to afford all necessary theories. Further, he argues, that engineering does not depend on scientific method to acquire knowledge. This gives perspective to the idea that engineering at large is simply applying the laws of natural science and taking them as the single source of knowledge. Yet, it does not say that, *in* a single engineering discipline, knowledge is not acquirable as in natural sciences. On reflection, it may be possible to conduct research within one of these disciplines according to the epistemology of natural sciences, for example in research in control engineering.

Moreover, while it gives a hint, Vincenti's argumentation does not settle the question of how knowledge is or should be acquired in the study of engineering when it connects different disciplines especially including human or social activity, such as designing. Here, the research on topics from engineering design and on manufacturing engineering may be affected, depending on the scope of the research and its goals.

Love (1998), analyzing engineering design research from the 1960s to the mid-1990s and addressing the research behind many of the theories presented above, sees in the field a positivist tradition. This means that phenomena including human or social activities are studied by applying methods from the natural sciences, with deductive and often quantitative methodologies (Bryman and Bell, 2007).

In this thesis, all research questions are to some degree connected with the activities of humans and organizations (i.e., the engineering processes) – as indicated by the term *co-development*. Hence, despite the fact that this thesis is, for the most part, concerned with modeling technical systems, it must accommodate human and organizational elements. Moreover, this modeling of technical systems requires the interpretation of phenomena observed, connecting them with existing concepts and, possibly, refining the concepts for the particular context. Thus, the research cannot rely only on logical deduction for the purpose of building theory.

As a consequence, this thesis subscribes to pragmatic critical realism as described by Johnson and Duberley (2000). This means it adopts the view that, while the structures of the world do not depend on the observer, they can be grasped only to the extent of the available "conceptual resources" (Sayer, 1992). Although this stands in the way of directly identifying adequate beliefs about the world, they can still be marked out by how well they predict "the consequences of manipulating things in the world" (Johnson and Duberley, 2000, p. 159). Reflecting on this, research in the context of this thesis may also contribute by expanding the available conceptual resources to increase understanding and possibly help assess the adequacy of beliefs.

Pragmatic critical realism opens the scene for interpretative elements of research without following the relativistic view that truth is always subjective. Specifically, Johnson and Duberley (2000) argue that this position can maintain multi-methodological approaches, including deductive and inductive methods as well as qualitative and quantitative ones. Forslund (2009) identifies pragmatic critical realism as an interesting epistemology for research on design because of its larger methodological palette. The research of this thesis adopts this view and combines inductive steps as it argues for general models based on empirical observations. Further, it draws from theory and applies it to individual cases, thus following deductive reasoning. Ultimately, it includes a strong element of qualitative research. In other words, the observations made are not linked to theory through measurable quantities.

3.3 Methodological Approach

Criteria for good practice in research on design can be summed up as follows, stating that the research should be (Cross, 1995):

- *Purposive* – based on identification of an issue or problem worthy and capable of investigation
- *Inquisitive* – seeking to acquire new knowledge
- *Informed* – conducted from an awareness of previous, related research
- *Methodical* – planned and carried out in an efficient and disciplined manner
- *Communicable* – generating and reporting results which are testable and accessible by others.

The first two aspects have been addressed in the previous section, and the related research was presented in Chapter 2. For purposes of making the results accessible to others and build confidence in the work, this section introduces the methodology and process followed. The results are reported in the following chapter.

3.3.1 Available Generic Methodologies

Identifying a lack of scientific thoroughness in design-related research, Blessing and Chakrabarti (2009) devised a methodological framework for executing research projects to help achieve more rigor, called *Design Research Methodology* (DRM). They propose four stages:

- *Research Clarification* – This stage is directed at creating an understanding for the research problem or situation that is to be improved, establishing goals, and identifying possible criteria by which it can be judged whether the research has been successful.
- *Descriptive Study I* – Through literature, empirical study, or both, this stage aims at describing and analyzing the given situation and the context of the research.

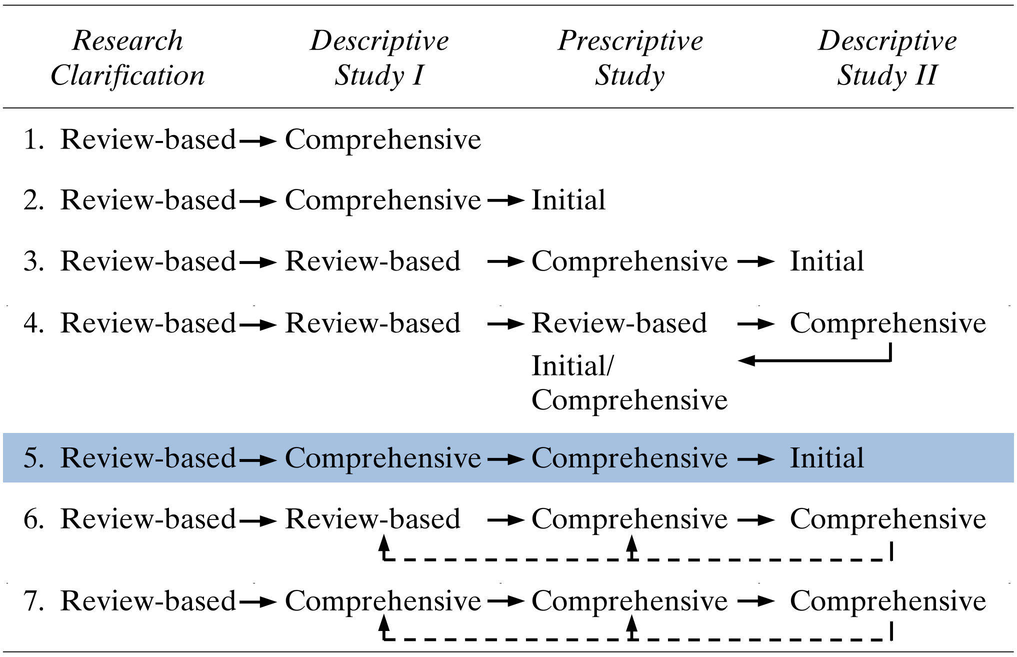
By means of these activities the basis is established on which improvements can be proposed.

- *Prescriptive Study* – In this stage, improvement (support) is developed in a systematic way and assessed with respect to its internal consistency.
- *Descriptive Study II* – As a final activity, the proposed support is tested in a realistic design context so that it can be judged whether it indeed has the desired effect.

These stages include several further activities aimed at the respective purpose of each stage. Moreover, Blessing and Chakrabarti (2009) present a number of tools which turn into deliverables of the stages, such as an impact model that illustrates a clear cause-and-effect relationship between influencing factors.

The stages are not to be passed through in a linear and exclusively sequential manner. Rather, iterations are expected. Further, it is acknowledged that not all projects follow these stages from first to last. Instead, Blessing and Chakrabarti (2009) identify seven types of research projects. They are compiled in Figure 17. The project presented in this thesis best fits with the combination of stages represented in the fifth type, emphasized by the blue background.

Eckert *et al.* (2003) propose a different model that includes eight types of research objectives, called the *Spiral of Applied Research* (SAR). Following this model, a research project may set off from one of four activities:



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 → Initial/ Comprehensive ←	Comprehensive
5. Review-based →	Comprehensive →	Comprehensive →	Initial
6. Review-based →	Review-based →	Comprehensive →	Comprehensive
7. Review-based →	Comprehensive →	Comprehensive →	Comprehensive

Figure 17. Types of design research projects (Blessing and Chakrabarti, 2009).

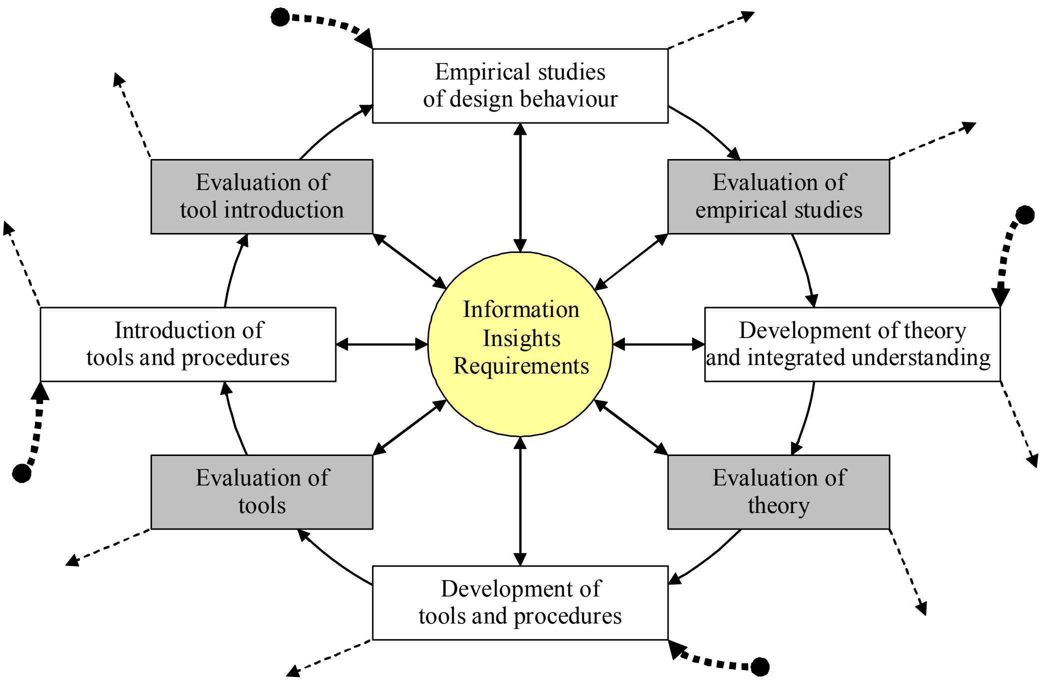


Figure 18. The Spiral of Applied Research with eight types of research objectives (Eckert *et al.*, 2004).

- Empirical studies of design behavior,
- Development of theory and understanding,
- Development of tools and procedures, and
- Introduction of tools and procedures.

Each of the activities is succeeded by an evaluation of the respective outcome. Together, these eight draw from available information, insights and requirements, or lead to new ones. Figure 18 illustrates the model.

Eckert *et al.* (2003) devised the SAR to reflect how research is conducted when it relates to the larger context of a research group and long-term research goals. They stress that research must be open to new ideas that were not anticipated in the beginning of a study or project. Further, they observe that researchers have to respond to companies' agendas. This requires researchers to seize opportunities for empirical studies that do not fit the initial research intent.

Contrasting prescriptive methodologies, Jørgensen (1992) proposes a descriptive model for how research is conducted. In it he illustrates the relationship between theory and problems identified on the basis of empirical study or experience (see Figure 19). Research endeavors can have their starting point in a problem base, a theory base, or both. Through steps of analysis and synthesis those endeavors can generate new insights that can yield practical results.

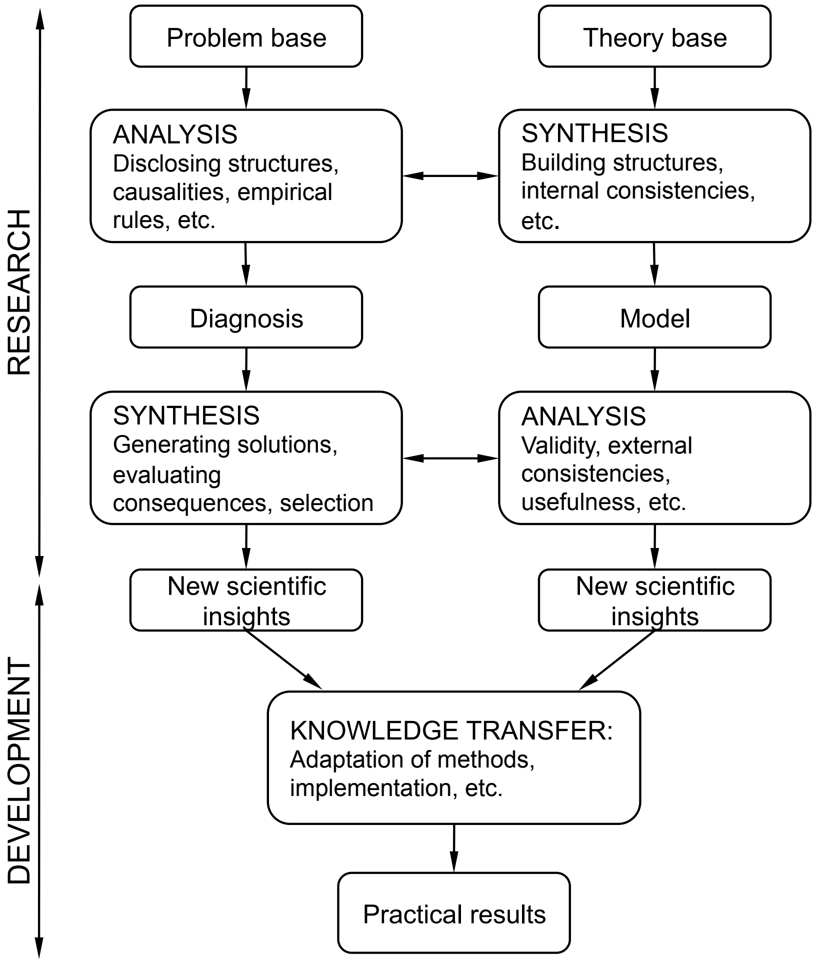


Figure 19. Basic work paradigms for research and development activities (translated and adapted from Jørgensen (1992)).

Similar to Jørgensen, Hubka and Eder (1988) express their observations on how research can unfold pointing at two main courses of action:

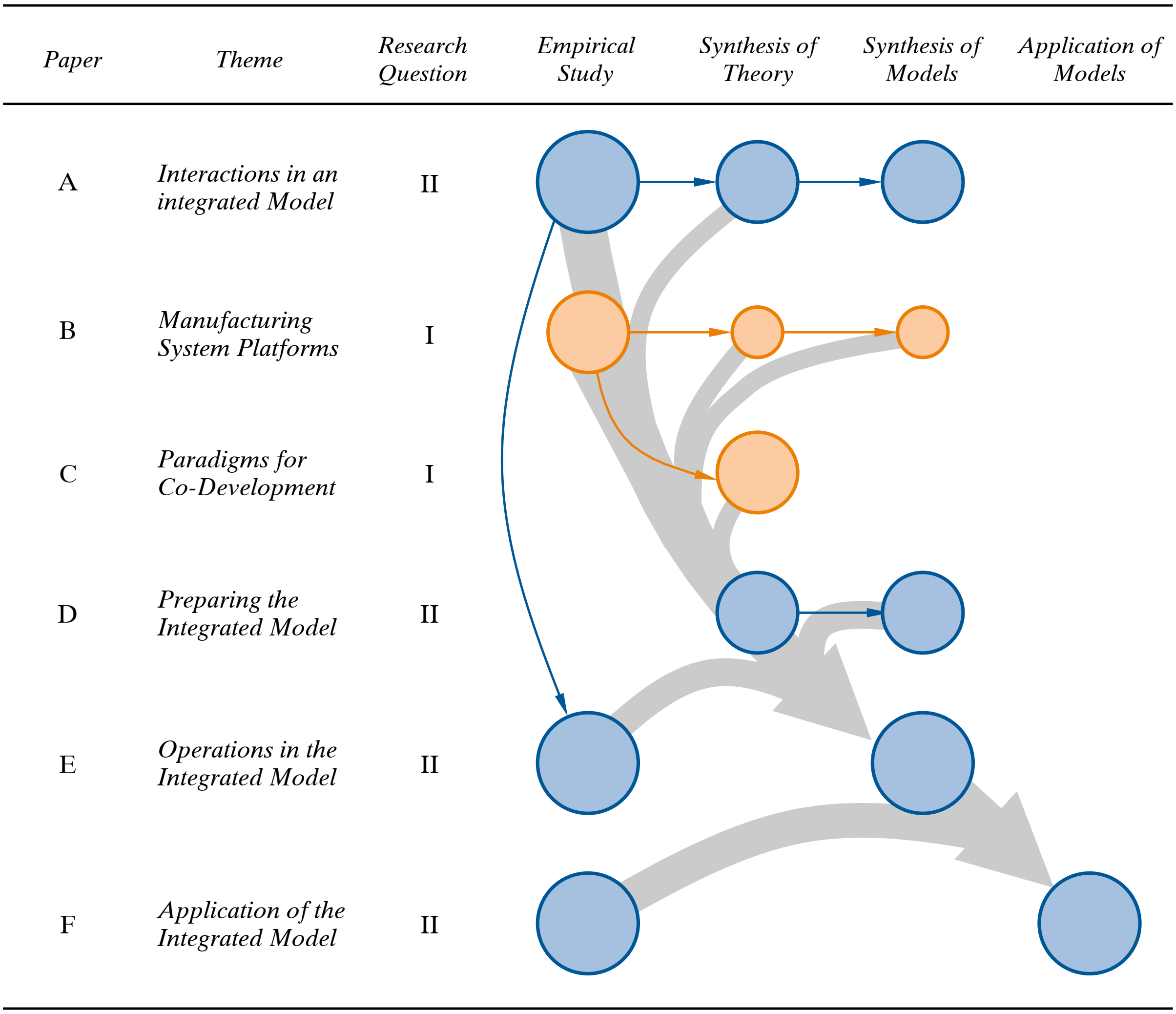
- By the conventional empirical way of observing, describing, abstracting, generalizing, formulating, guidelines, modeling, refining;
- By postulating a set of hypotheses, formulating a theory, modeling, refining, and only subsequent testing.

They note specifically that these approaches do not exclude each other.

3.3.2 Applied Methodology

On reflection, if followed strictly, the DRM framework by Blessing and Chakrabarti (2009) is a clear methodology that facilitates communicating the research project. However, it seems best suited if the problem area or research gap can be clearly marked out upon an initial research clarification. In contrast, the clarification of the research in this thesis is best described as a continual process. In this process, the synthesis of theory drove the clarification and subsequent research activities, rather than marking off a clear point of departure for these. As shown in Figure 17, the research of this thesis can be mapped to one of the types of research projects in the DRM. However, this mapping does not provide a sufficiently detailed picture to follow the process of the research.

Both the SAR (Eckert *et al.*, 2003) and the model devised by Jørgensen (1992) are generic and allow following a multitude of individual paths in the course of research. Further, they are sufficiently detailed to serve as a basis for describing the research of this thesis. However, they cannot account for the actual path followed by a specific research project, such as the one reported here. Instead, it is here argued that



Paper	*Theme*	*Research Question*	*Empirical Study*	*Synthesis of Theory*	*Synthesis of Models*	*Application of Models*
A	*Interactions in an integrated Model*	II	●	●	●	
B	*Manufacturing System Platforms*	I	●	●	●	
C	*Paradigms for Co-Development*	I		●		
D	*Preparing the Integrated Model*	II		●	●	
E	*Operations in the Integrated Model*	II	●		●	
F	*Application of the Integrated Model*	II	●			●

Figure 20. Relationship between appended papers, themes, research questions, and research activities.

individual processes must be marked out from the generic models. Therefore, inspired by the SAR and Jørgensen, Figure 20 schematically illustrates the process followed in the course of the research project of this thesis.

The figure distinguishes four research activities: empirical studies, synthesis of theory, synthesis of models, and application of models. The steps of analysis and evaluation that are found in the generic methodologies are not specifically included in the model. Rather, each research activity in the figure is followed by an analysis, which is thus not additionally indicated in the figure. *Synthesis of Theory* and *Synthesis of Models* in Figure 20 correspond to *Development of theory and integrated understanding* and *development of tools and procedures* respectively in the SAR.

Model is a broad term that can be understood as any representation of observed phenomena or theory. It is here framed more narrowly as the representation of technical systems or processes as well as engineering processes. The application of models is limited to the transfer of the proposed model to a new design context. Thus, it does not extend as far as an Introduction of tools and procedures in the sense of the SAR or as a comprehensive *Descriptive Study II* in the DRM.

Figure 20 illustrates, which papers have contributed to which research questions and activities. The sizes of the circles indicate with what gravity the activities contributed to the research. Circles of the same color correspond to a common research question. The subjacent gray arrows indicate how developed theory and models contributed to the overall progress of the research. The slimmer arrows indicate effects that one activity had on another without making a direct contribution to the overall research progress.

3.3.3 Research Process

Paper A had a theoretical starting point in earlier modeling approaches proposed by Claesson (2006) and Gedell (2009). An industrial example of a manufacturing system and its respective product was studied in retrospect (after they had been designed and put into work) at a car manufacturer in spring of 2010. The data sources for this case included observations of the physical products and the production facilities, product and production documentation, and informal interviews with engineers from the engineering design department and engineers and operators from the production.

From this empirical study, theory about the interactions between products and manufacturing systems was synthesized. In other words, deductions were made from the data about the general nature of products and manufacturing systems that produce them. This led to the development of new modeling elements for the Configurable Component, including state models to capture system behavior. However, these modeling elements were not directly used in the subsequent research efforts, as indicated in Figure 20.

The study that lead to the research of Paper B was not originally planned. Instead, the opportunity to study a special case of a reconfigurable manufacturing system presented itself at the car manufacturer from the previous study. It evolved during follow-up involvement that included weekly visits and close contact to the manufacturing development department during the second half of 2010. The studied system, a welding cell, was under development and planned to replace an existing cell in the factory. The company-internal developers of the new manufacturing cell explained the designs and provided access to documentation on the two manufacturing systems. Further, manufacturing system designs similar to the new cell could be identified proposed in literature. Together with the case example, the manufacturing systems from literature provided a basis for theorizing about enablers and paradigms for co-development.

Moreover, studying the manufacturing systems at the company inspired the use of function-means modeling to capture the design of a manufacturing system. Although, the purpose of the model was a specific one – the comparison of integrated and modular designs – the research later served as an inspiration for modeling with a more general purpose of representing the design of the manufacturing system.

Paper C elaborated further on the theory evolving from Paper B and drew from its empirical data. Data on an additional manufacturing system described in Paper C were taken from drawings and three-dimensional models. Although evolving from research collaboration with an aeronautics company during the spring of 2011, studying this manufacturing system did not constitute a thorough empirical study. Rather, the paper uses the examples for purposes of illustrating some key ideas about setups for co-development.

Paper D took the research results that were reached so far as a theoretical starting point. It proposed an integrated model and connected it with a preparation process inspired by Lean Product Development (Ward, 2007) and Set-Based Concurrent Engineering (Sobek *et al.*, 1999). Lean Thinking and Set-Based development provided a relevant context for the subsequent research, but theory about them developed in the Papers D and F does not constitute a contribution of this thesis. The model and its potential use were illustrated by a literature example on hydraulic cylinders. Further, beyond proposing the model, the paper also expanded on theory about Design Bandwidth and the relationship of Function-Means models and encapsulation with Configurable Components.

Paper E amended the model developed in Paper D. It did so by analyzing the available theory as documented in literature and as developed as part of this thesis at this point. Further, it revised the industrial example from Paper A, as indicated by the vertical arrow in Figure 20. The scope was broadened to include steps in the manufacture of the product.

Specifically, the data from the original study were amended by consultations with a manufacturing engineer with expertise in the area of sheet metal stamping to allow modeling this metal forming process and its respective machinery. The analysis of the data was conducted anew in the light of the developed theory and the model proposed in Paper D. The case example provided empirical data to test if a consistent model of a real manufacturing system and product could be built based on the developed approach.

Finally, Paper F transferred the proposed model from Paper E to a new design context. It did so based on the study of an additional industrial example of a product and a manufacturing system in the aerospace company during the spring of 2013. The goal was to gain insights into the applicability of the modeling approach in other contexts. As in the first empirical study, the example was studied in retrospect.

However, although the product and manufacturing system already were designed and in place, the modeling activities for this research study ran in parallel to a similar project in the company. The company wanted to test modeling one of their products with Configurable Components and did so internally. This provided the chance to discuss the proposed model with engineers from the company during weekly visits.

Other data sources for this case included observations of the physical product and the production facilities, product and production documentation, and informal interviews with engineers from the engineering design and manufacturing department. A comprehensive document that described the partly implemented manufacturing concept for the product constituted a rich source of information. However, following the proposed modeling approach from Paper E, the product and manufacturing system had to be analyzed and interpreted using the modeling concepts that had evolved from the research reported in this thesis.

3.4 Relevant Quality Criteria

For the purpose of assessing the quality of results of this thesis, a number of indicative criteria are selected. Quality is here understood as the validity, the "correctness or credibility of a description, conclusion, explanation, interpretation, or other sorts of account" (Maxwell, 2005, p. 106). In accordance with the mindset expressed in Section 3.2, this cannot be proven through referring to or establishing an absolute truth, as it can only be grasped through the filter of the available "conceptual resources". Thus, showing the validity of the results is here seen as "a process of building confidence" (Pedersen *et al.*, 2000, p. 4). Specifically, for verifying and showing the validity of design theories, Buur (1990, p. 3) proposed the following criteria:

Logical verification

- Consistency: no internal conflicts between individual elements (e.g., axioms) of the theory.
- Completeness: all relevant phenomena observed previously can be explained or rejected by theory (i.e., observation, from literature, industrial experience, etc.)
- Well-established and successful methods are in agreement with theory.
- Cases (i.e., particular design projects) and specific design problems can be explained by means of the theory.

Verification by acceptance

- Statements of the theory (axioms, theorems) are acceptable to experienced designers.
- Models and methods derived from the theory are acceptable to experienced designers.

Regarding acceptance by industry, Eckert *et al.* (2004, p. 6) note: “The most useful criterion for success is the perception of value in new procedures and methods by design practitioners in industry.”

In this thesis, the view is adopted that validity is not *demonstrated* by fulfilling these criteria, but rather that they give an indication of validity. For example, if a study shows that a certain product can be modeled following a proposed approach, it does not prove that such an approach is applicable. However, it is evidence that supports the applicability of the approach.

Buur’s criteria mainly address the results from synthesis of theory and models and are adopted for these. However, the criteria do not cover all relevant validity aspects for the data collected in empirical studies, such as in Papers A, B, E, and F. Instead, the reliability of the data collected needs to be argued for as well. This is done following the presentation of the results.

4 Results

This chapter sums up the results of the appended papers. The focus is set on the contributions made to answering the research questions of this thesis.

4.1 Paper A – Interactions in an Integrated Model

Paper A adopts the Configurable Component framework and defines it further to represent phenomena that have not been included before by adding new modeling elements. It does so specifically to model products and manufacturing systems in one integrated model. Thus, the paper addresses the second research question of this thesis. The results can be summarized as follows:

- The paper argues for including state models that can represent a product or manufacturing system in all its states of interest.
- It propses or refines several emerging modeling concepts: A stringent handling of interfaces and interactions enables encapsulating and elaborating systems.
- The paper shows how a particular example of product and manufacturing system can be represented with the help of the new and refined concepts for modeling.

4.1.1 Representing Systems with their States

The systems that are to be modeled are not static. Instead, products (and their constituents) and manufacturing systems (and their constituents) progress through ever-changing states. The paper introduces *state models* as a new element to account for this change of state and to capture the dynamic nature of systems. These state models can be used to represent a system's behavior (i.e., what it does). While there are infinite numbers of states, it is left to engineers to model the states they deem interesting.

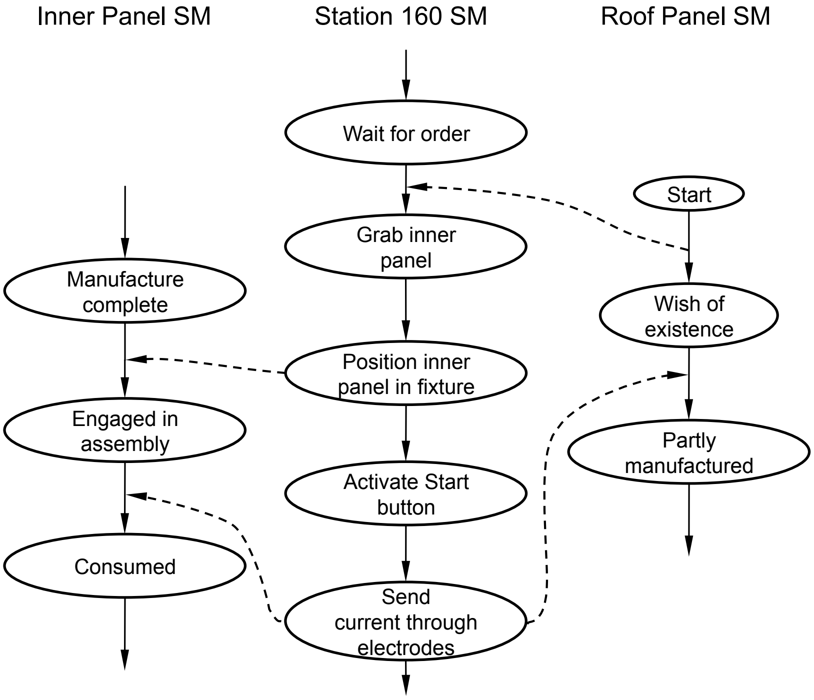


Figure 21. Interdependent state models (Paper A).

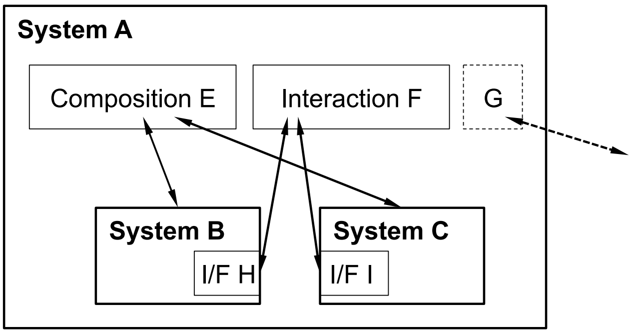


Figure 22. Interaction and interfaces in a system composed of two other systems (Paper A)

States can be modeled in all lifecycle phases, including designing, manufacture and use. This applies also to the manufacturing systems, because the modeling approach addresses technical systems in general. Figure 21 presents an example section from three interdependent state models. It shows the dynamic dependencies of two sheet metal parts with the manufacturing system used to weld them together.

4.1.2 Interfaces and Interactions

Decomposing products and manufacturing system into two entities that only interact as two separate systems neglects how they influence each other. Consequently, developing products and manufacturing systems without ample regard to their

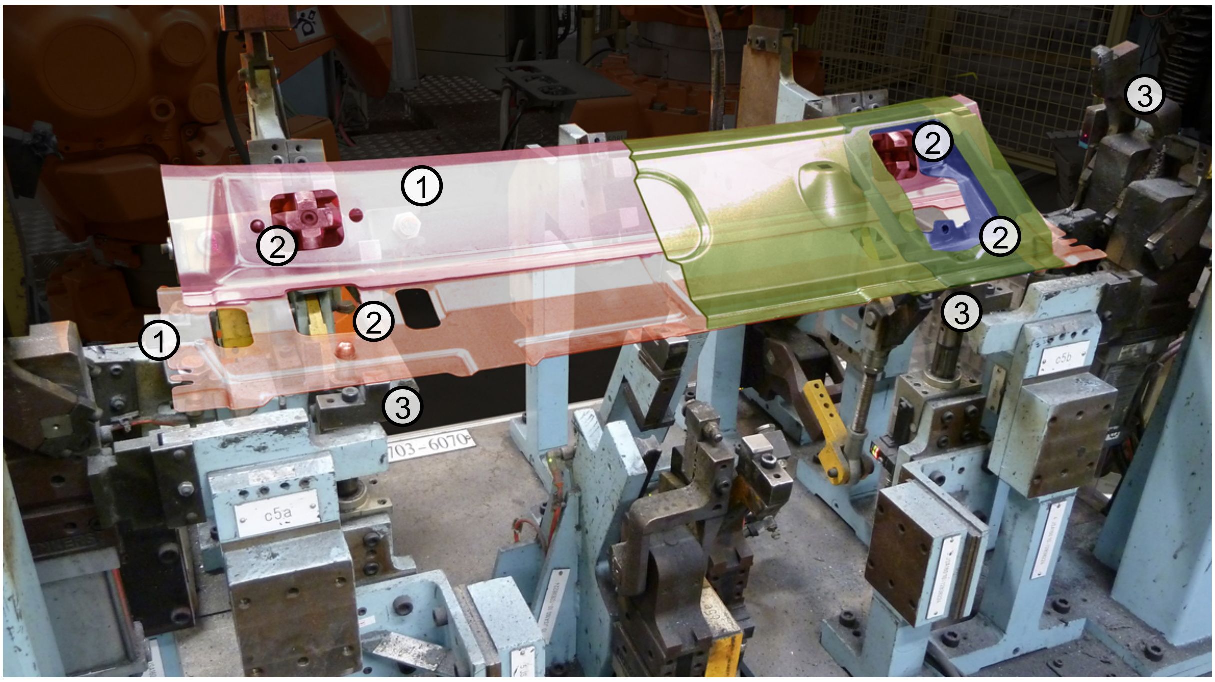


Figure 23. The fixture with the sheet metal parts in place: (1) magnetic detectors, (2) positioning pins, (3) clamps and clamping supports (Paper A).

dependencies should be avoided. The paper therefore advocates the concepts of *encapsulation* and *elaboration* for modeling the two technical systems. They allow elaborating the dependencies between the product and the manufacturing system on all levels of the system structure.

For purposes of realizing encapsulation and elaboration, the concepts of *interface* and *interaction* are refined. Specifically, the paper describes where information is to be placed in a data model that represents both technical systems. Based on these considerations, a first step is taken towards an IT-based tool that can be used for modeling.

Moreover, *interface* and *interaction* turn from mere concepts into data objects that are stored and managed. *Interface* is defined as a coupling point of a system. *Interaction* is then the coupling of two systems that affect each other through interfaces. Figure 22 illustrates where information is stored in a system (System A) about the other systems it is composed of (B and C) and the interfaces (I/F) and interaction.

4.1.3 An Integrated Model of Configurable Components

The ideas developed in the paper are illustrated in an industrial example. A part of the body-in-white of a car is modeled, including five sheet metal parts. It is modeled together with the welding station in which it is manufactured, including the fixture that holds the parts in place during welding. Figure 23 shows a reworked photograph of the product in the fixture.

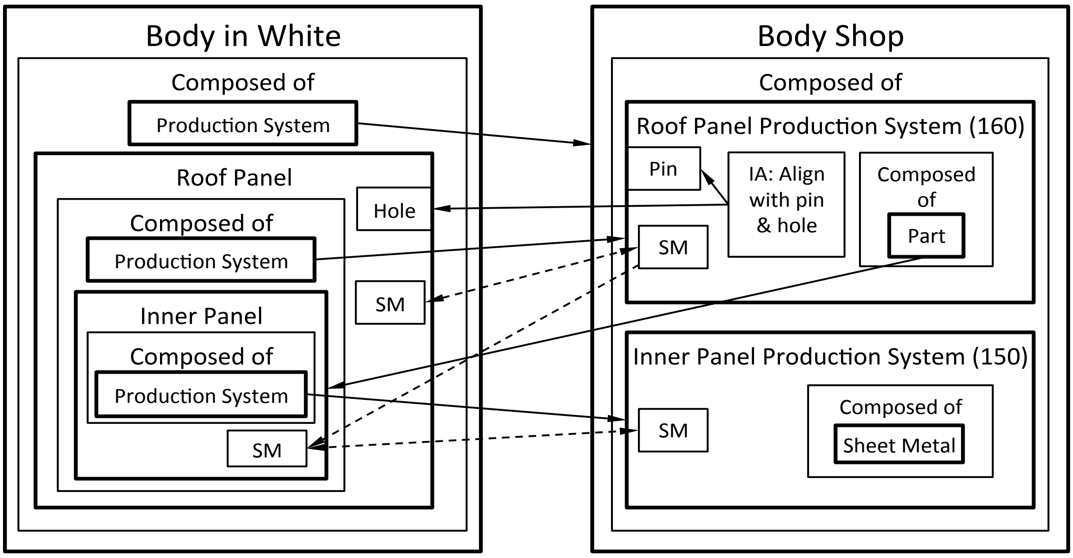


Figure 24. An integrated model with composition, interface, interaction, and state models (Paper A).

The two systems body-in-white (product) and body shop (manufacturing system) are then modeled graphically. Figure 24 emerges through the application of the mechanism of elaboration. It shows the involved systems down to the level of an interaction between a positioning pin from the fixture and a hole in one of the sheet metal parts. A state model (SM) is assigned to every system.

4.2 Paper B –Manufacturing System Platforms

The paper directs its attention towards questions of architecture and configurability of the manufacturing system. Through this, it provides answers to the first research question. In short, this results in the following:

- Connecting to basic drivers in industry, a general interpretation of the rationale behind platform strategies for developing systems is proposed.
- The paper identifies different paradigms for the joint development of products and manufacturing systems, and coins terms for these.
- It analyzes a platform concept originating from the manufacturing system rather than the product design.
- It proposes a modeling approach to elaborate the architecture of the manufacturing system with respect to system modularity and configurability.

4.2.1 General Ingredients of a Platform Strategy

Platform strategies in manufacturing do not revolve around the goal of creating distinct solutions. Rather, this is a goal that is typical of product platform strategies. Instead, strategies for manufacturing aim at exploiting commonality. In other words, they aim

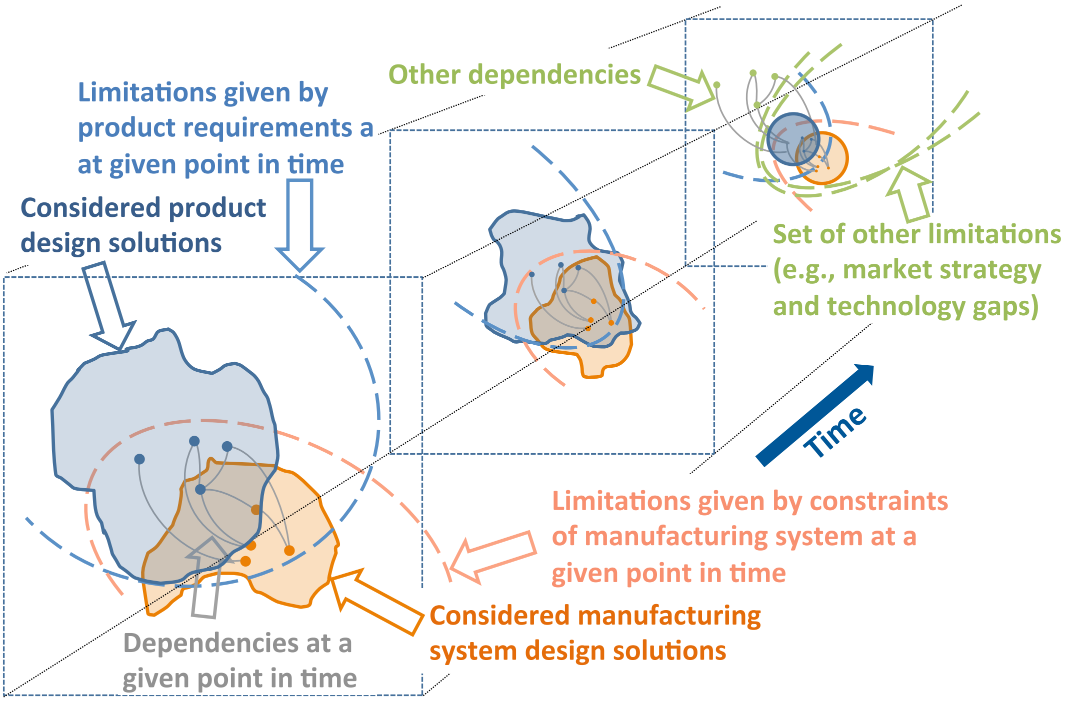


Figure 25. A simplified illustration of Dedicated Co-Development (Paper B).

at managing change and variation. Product variety is one source of variation in the manufacturing system; fluctuating production volumes and instable manufacturing processes are others, for example. Reflecting this, the general ingredients of platform strategies for technical systems are defined as follows:

1. *Planning for change*: Change and variation can be anticipated and one can plan ahead to allow for variation.
2. *Responding to change*: Change and variation can be accommodated as they appear by increased responsiveness.
3. *Excluding change*: Specializations and niche solutions can be adopted, deliberately excluding change and variation.

These ingredients can be combined in various ways to create solutions that fit a specific company.

4.2.2 Paradigms for Co-Development

Two extreme modes of development are identified. In the first one, dedicated product solutions are combined with dedicated manufacturing system solutions. While many designs are considered for both systems during the process, only a limited number of well-aligned combinations of these is expedient. The ultimate goal of the co-development process is to find at least one such expedient combination. Figure 25 provides a simplified illustration of this process, which is termed *Dedicated Co-Development*.

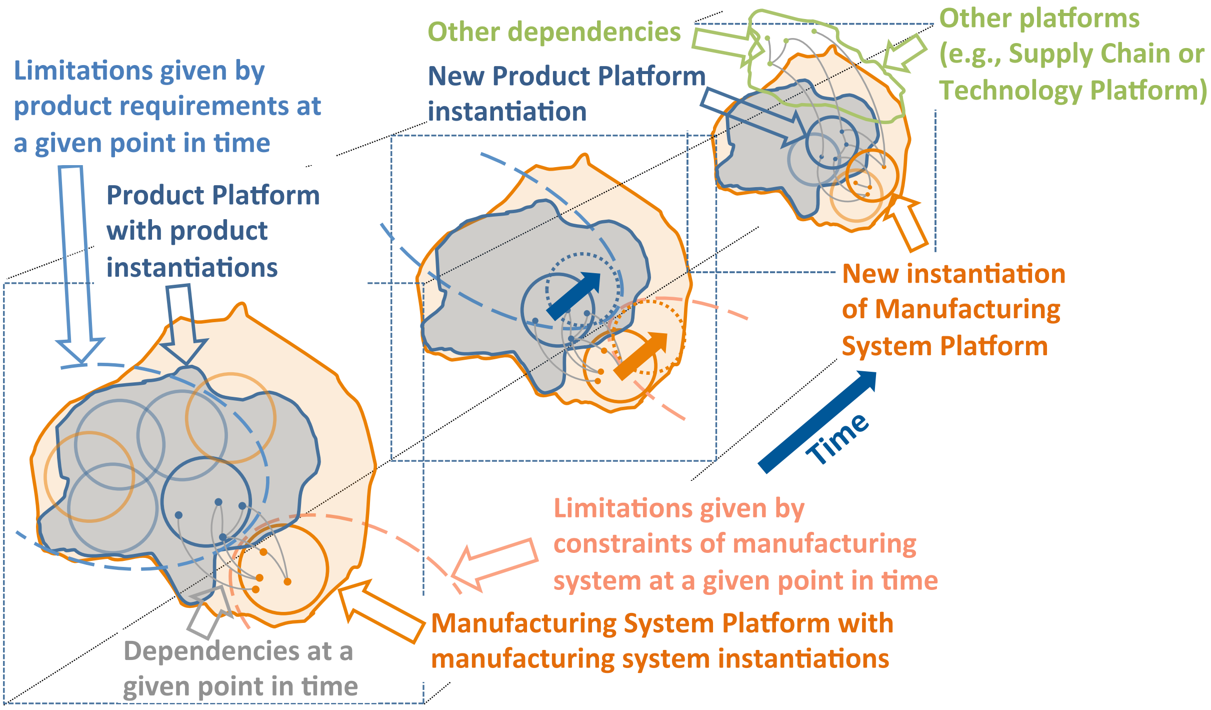


Figure 26. A simplified illustration of Platform-Based Co-Development (Paper B).

The second extreme among modes of co-development is illustrated in Figure 26. It describes the *Platform-Based Co-Development* of products and manufacturing systems. Development according to this paradigm is based on a pre-defined platform where the solution space is deliberately limited to an a priori determined design bandwidth. Multiple pairs of instantiations of these platforms explicitly exist as aligned configurations of a product and the manufacturing system. Each configuration has its origin in a particular set of limitations and requirements. As these change or new ones are introduced, a new pair of instantiations emerges in response.

4.2.3 A Platform Concept for the Manufacturing System

Beyond the two extremes presented above, there are possible intermediate steps. One such scenario is the adoption of a manufacturing system platform without a designated product platform. Looking into literature, the paper identifies Reconfigurable Manufacturing Systems as enablers of a manufacturing system platform. Turning to an industrial example, it then studies a real-life case of a system without a corresponding, designated product platform. It is an automated manufacturing cell that applies a concept that is similar to the one of *Factory-in-a-Box* (Jackson *et al.*, 2008).

In short, the studied manufacturing concept is based on a strictly modular, automated manufacturing cell as a building block and includes a larger bandwidth and certain restrictions. The modular cell is designed to replace an integrated one in the factory. It is in essence an example of a company-specific mixture of the three ingredients for a platform strategy introduced above.

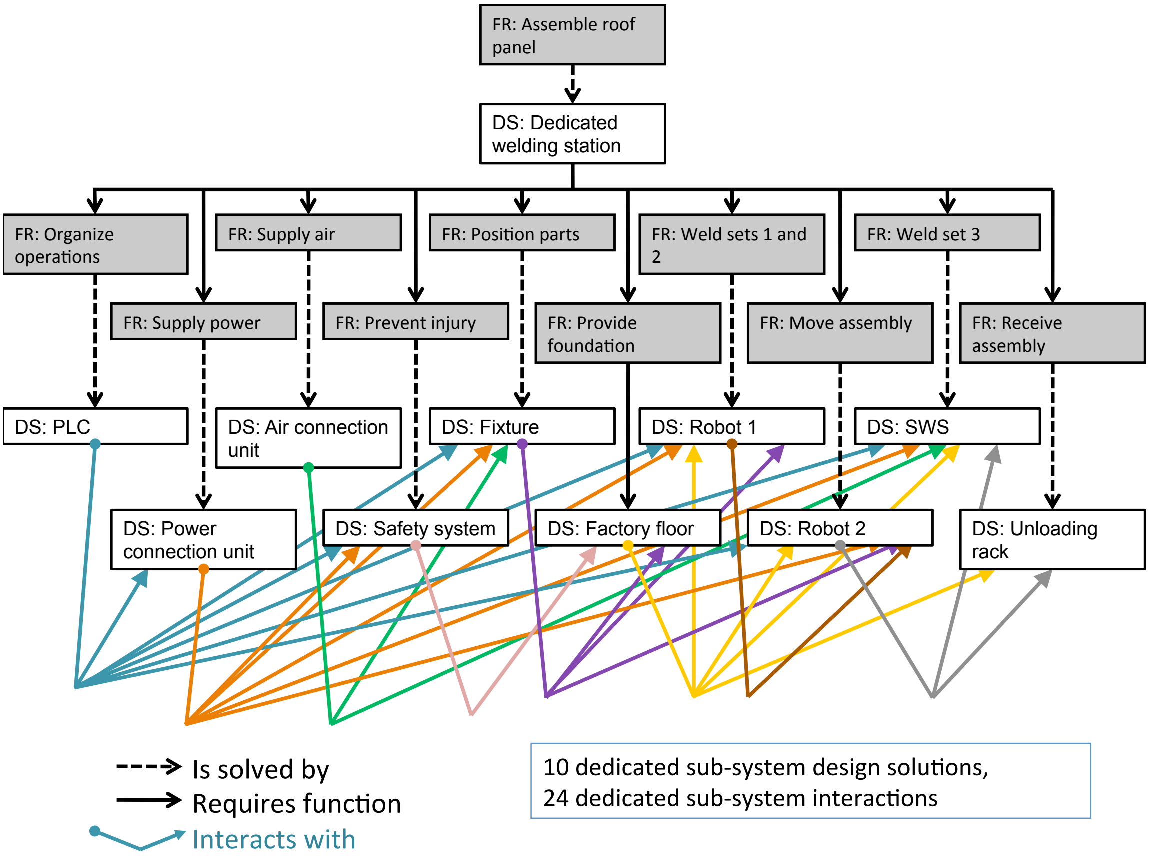
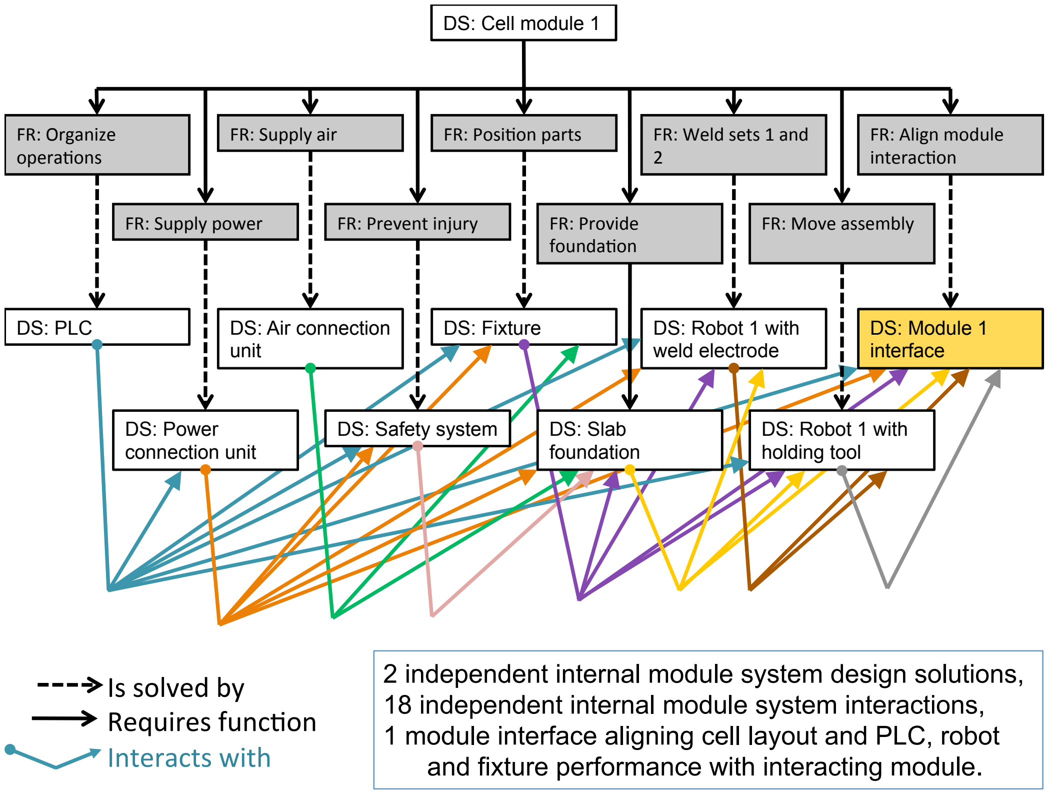


Figure 27. Example a manufacturing system with integrated architecture modeled with the function-means mechanism (Paper B)

The modular cell can be configured internally and, when combined with several other cells, configured externally to yield a manufacturing station capable of conducting more manufacturing steps. The drawbacks of the modular manufacturing concept can be compared to the ones for modular products, for example redundancy of interfaces and lower overall performance.

4.2.4 Elaborating the Architecture of the Manufacturing System

A function-means model proposed in the paper visualizes some of the above aspects. Figure 27 shows an example of an evolving model. It shows the integrated manufacturing system solution from the industrial example. Specifically, it accentuates the interactions between the design solutions in the manufacturing system. How these are distributed in the function-means tree gives an indication of the degree of modularity of the system. The tree structures also capture the architecture of the manufacturing system, which is the scheme by which the functions of a system are allocated to physical components (as an adaptation of the definition of *product architecture* by Ulrich (1995, p. 1)).



2 independent internal module system design solutions,
18 independent internal module system interactions,
1 module interface aligning cell layout and PLC, robot
and fixture performance with interacting module.

Figure 28. One of two branches in the function-means tree representing one module in the architecture (Paper B).

The modular solution of the manufacturing system is illustrated in several figures. That is necessary because the function-means tree is expanded to include two additional tiers. As a result of this expansion, two branches are included in the tree that represents the modular system. One of these two branches is shown in Figure 28. Both branches are connected via a module interface. Paper B includes additional figures that need to be considered to understand the entire model of the modular cell concept.

4.3 Paper C – Paradigms for Co-Development

Inspired by the research the previous paper, Paper C expounds further the question of paradigms for the co-development of products and manufacturing systems. Thus, it also aims at providing answers to the first research question. The results are twofold:

- Two additional paradigms for co-development expand the ones introduced in Paper B. They constitute theoretical intermediate steps towards *Platform-Based Co-Development*.
- Two industrial examples of a manufacturing system and related products are positioned among the four paradigms. They illustrate how the paradigms can be used to characterize real-life approaches for the co-development of products and manufacturing systems.

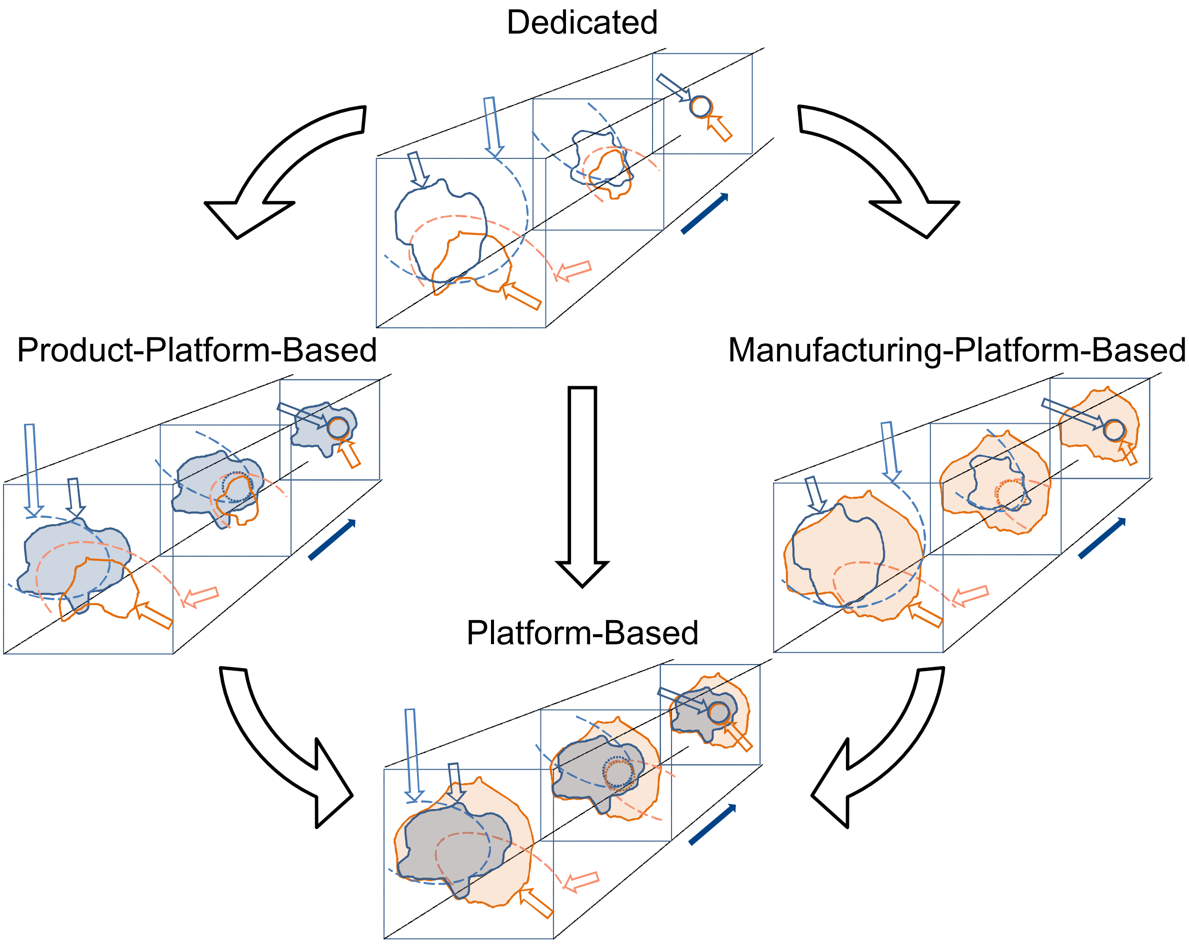


Figure 29. Different paths toward a pervasive approach for Platform-Based Co-Development (Paper C).

4.3.1 Further Paradigms for Co-Development

Paper C describes two additional paradigms in which a platform approach exists either for the product or for the manufacturing system. In *Product-Platform-Based Co-Development*, new product instantiations are created within pre-defined limits of the platform to meet new requirements. Conversely, the respective manufacturing system solution is developed with no strategy for change and variety. It is an unlikely paradigm because a product platform usually aims at reuse of resources and solutions in manufacturing.

In *Manufacturing-Platform-Based Co-Development*, a platform approach exists exclusively for the manufacturing system, but not for the products. According to this paradigm, a new instantiation of the manufacturing system platform is created within the pre-defined limits of the platform. The product, however, is developed without commitment to reusing earlier designs. However, this does not reflect industrial practice.

Both additional paradigms introduced in Paper C are thus unlikely to be found in industry. However, together with the two paradigms introduced in Paper B they can be used to characterize different approaches taken by individual companies. These approaches will be between the four conceptual extremes represented by the paradigms.

Companies that aim for a pervasive platform approach for the products and the manufacturing system can begin defining platform approaches for the product, the manufacturing system, or both in a joint effort. Figure 29 schematically illustrates the possible paths towards pervasive *Platform-Based Co-Development.*

4.3.2 Characterizing Industrial Examples

The paper considers two industrial examples of manufacturing systems with their respective products, and positions them in Figure 29. The first example is taken from Paper B and comes close to exemplifying *Manufacturing-Platform-Based Co-Development.* The manufacturing system in this example has, as illustrated in the previous paper, a modular design and can be configured by physically changing its layout.

The second example is essentially not far from the idea of pervasive *Platform-Based Co-Development*, but has a more limited scope with respect to new product instantiations and changes in the manufacturing system. The manufacturing system is flexible, but allows no physical changes of the layout, such as relocating machines. The interfaces between manufacturing system and products are the same for all instantiations with the exception of the fixtures that need to be customized.

The examples illustrate how the conceptual paradigms can be used to characterize real-life industrial examples. The conceptualization is limited as it only addresses some key aspects but helps understand the prerequisites for platform-based co-development.

4.4 Paper D – Preparing the Integrated Model

Paper D returns to the second research question that aims at devising an integrated platform model. The paper presents such a model for the product and manufacturing system that differs from the one proposed in Paper A. Rather than starting with Configurable Components, the model builds primarily on function-means trees of the product and manufacturing systems. In summary the paper includes the following results:

- An integrated platform model for continual use is proposed. It includes the modeling elements functional requirement, design solution, and constraint to model the design of products and manufacturing systems. These elements are connected using the function-means formalism.

- The paper outlines a stepwise preparation process for this model to capture existing designs.
- It further illustrates how the model can be used if an expansion of the design bandwidth in products or manufacturing systems is required.

Set-based thinking is applied to preparation and use of the model. Although it provides a relevant context for the research, it does not constitute a contribution of this thesis.

4.4.1 An Integrated Platform Model for Continual Use

The integrated model uses the function-means formalism in two ways. First, establishing the trees helps identify systems and their functions in the products and the manufacturing systems. Second, it builds a consistent logic for the system structure that connects the modeling elements DS, FR and C. Figure 30 schematically illustrates the integrated model.

A design bandwidth expressed by parameters is assigned to each of these elements. The bandwidths capture the required or available flexibility of the products and manufacturing systems modeled in the function-means trees. Elaborating the limits helps understanding and then preserving design bandwidth of a platform over time.

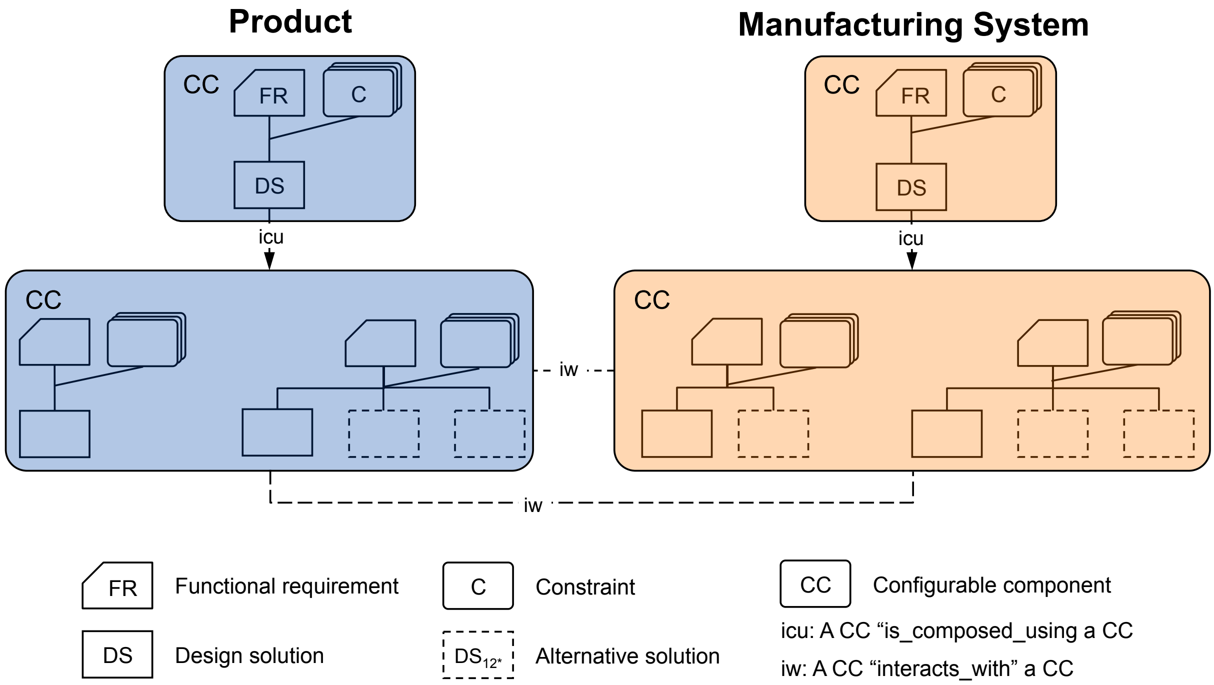


Figure 30. Integrated platform model of Configurable Components after encapsulation of function-means branches (adapted from Paper D).

The model further includes the interactions between design solutions in the product and the manufacturing system. They indicate how the different solutions mutually affect each other. A cylinder cap interacts with the turning tool of a lathe while it is manufactured, for example. Configurable Components encapsulate branches in the function-means trees; one tier per CC. The encapsulation yields a number of manageable systems that can be elaborated further while maintaining the interactions.

4.4.2 Preparation Process

The paper proposes preparing the model with the following steps: function-means modeling including the identification of the constraints, the identification of the bandwidth, the identification of the interactions, the modeling of Configurable Components, and the final validation of the design space. Figure 31 illustrates the preparation process and indicates which methods contribute to each step. A larger-scaled version of the figure can be found in the appended paper.

The paper defines two different modes of use for the model. In Mode I, the product and manufacturing system platform are flexible enough to accommodate a certain change, and all information required for configuration is available. In Mode II additional design work is required to expand and preserve the design bandwidth. For use in Mode I, the maturity of the solutions in the model and the feasibility of their interactions must be checked. Thus, the preparation process concludes with a step in which the platform model is validated.

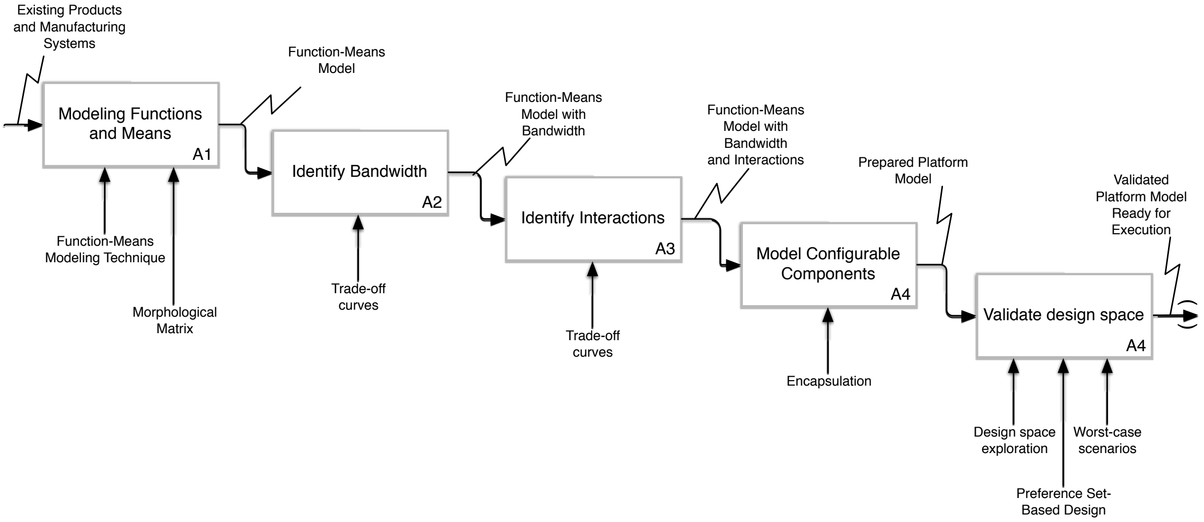


Figure 31. The platform preparation process using set-based concurrent engineering principles (Paper D).

4.4.3 Expanding the Bandwidth

The preparation process also provides guidance for using the model in Mode II. In this mode an extension of the existing bandwidth leads to two types of changes in the model:

- The bandwidth of existing solutions in the DS set is expanded or new alternative solutions within one system are developed.
- A new FR is introduced which leads to a new branch in the function-means structure and thus a new CC. One or several new DS must be generated to solve the new FR.

These changes can both occur as consequences of each other. Figure 32 illustrates an example that includes both types of changes in the model. It describes a hydraulic cylinder and its manufacture. The lighter-colored FR and DS are elements that were added to the originally prepared platform. A larger-scaled version of the figure can be found in the appended paper.

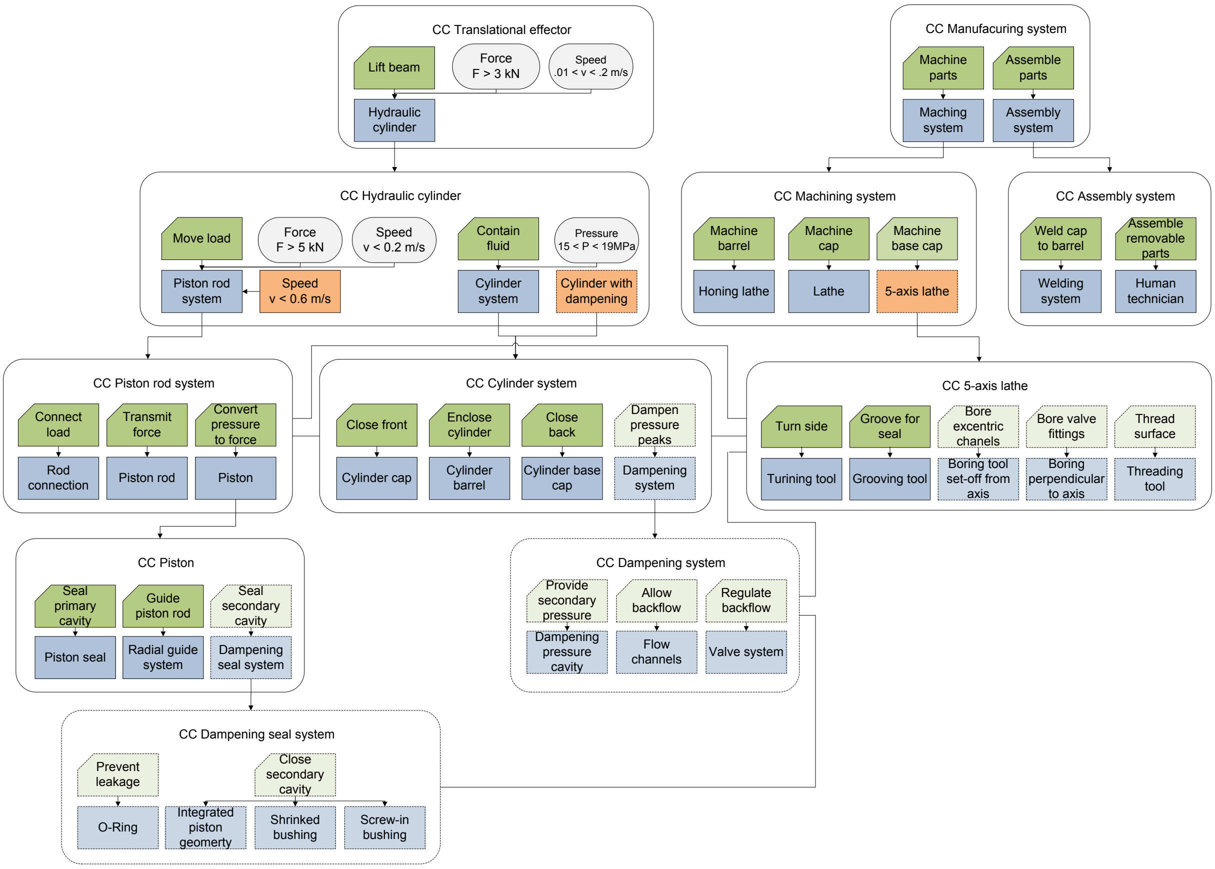


Figure 32. Example of an integrated model with extended bandwidth (Paper D).

4.5 Paper E – Operations in the Integrated Model

Paper E amends the integrated platform model with several modeling elements. It does so to increase the information that can be captured and to facilitate the redesigning of existing products and manufacturing systems. Thus, the paper addresses the second research question. In short, the results of the paper are the following:

- Operation elements are added to the function-means trees and represent the interface between design solutions in the manufacturing lifecycle phase.
- The model contains the component structures for the products and manufacturing system. They are mapped to the design solutions and thus capture product and manufacturing system architectures, respectively.
- The paper illustrates how the amended platform model can contribute to facilitating reuse and redesigning that affect conceptual considerations as well as existing components and machinery.

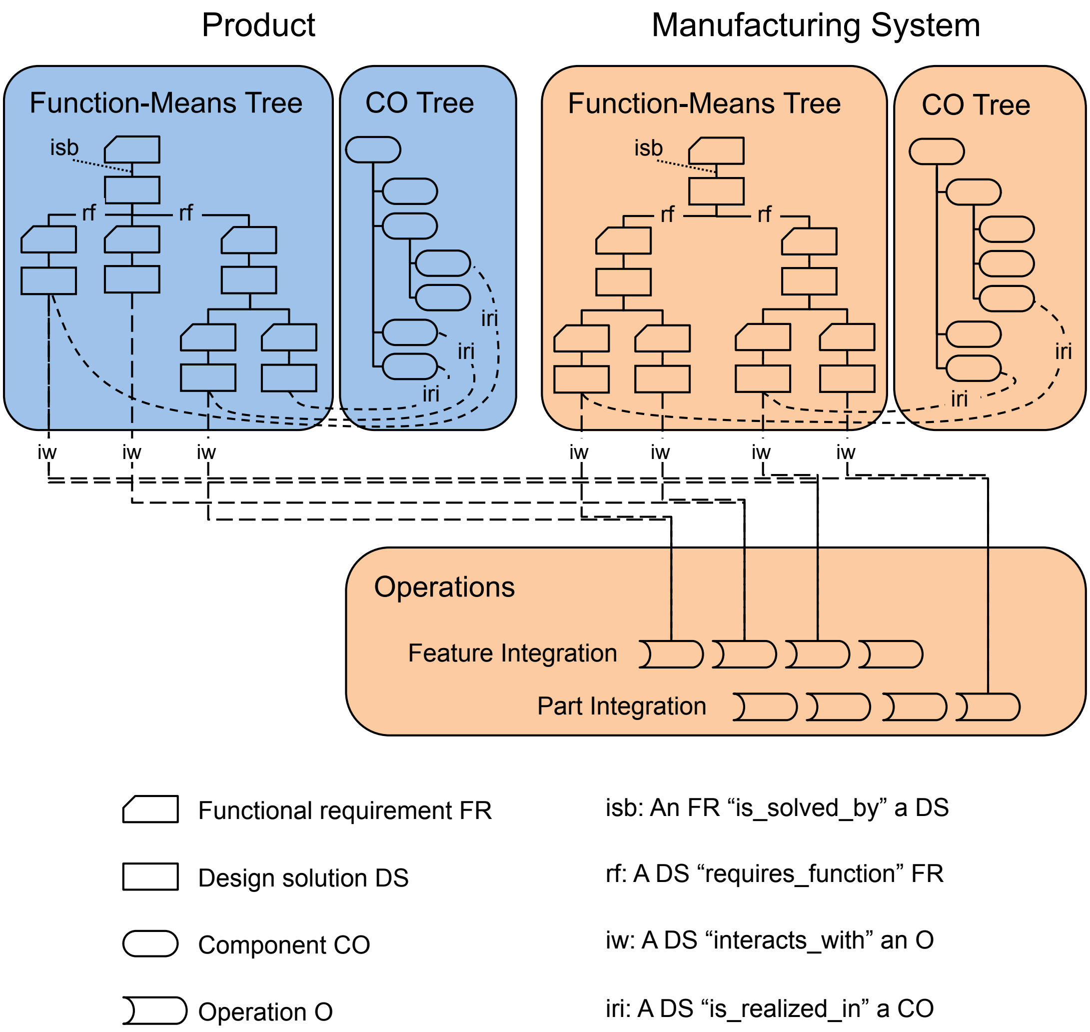


Figure 33. The proposed model including modeling elements and relationship types (adapted from Paper E).

4.5.1 Operations and Component Trees

The manufacturing processes in direct connection to the making of the products, the operations, are modeled as separate modeling elements. They represent the interactions and elicit the interdependency of the product DSs and manufacturing system DSs. Specifically, the manufacturing operations realize DSs in the product. For this, the operations use DSs in the manufacturing systems. Figure 33 illustrates the amended model with the operations and relationships between modeling elements.

With the way it models operations, the model stands in contrast to the one developed in Paper A where the state models are placed inside manufacturing system CCs. However, the external operation element allows a more comprehensive view on the functionality of the manufacturing system. The function means tree of the manufacturing system provides a state-based view, and the operations supplement this with a flow-based view. Moreover, operations are mapped to design solutions in a clear fashion.

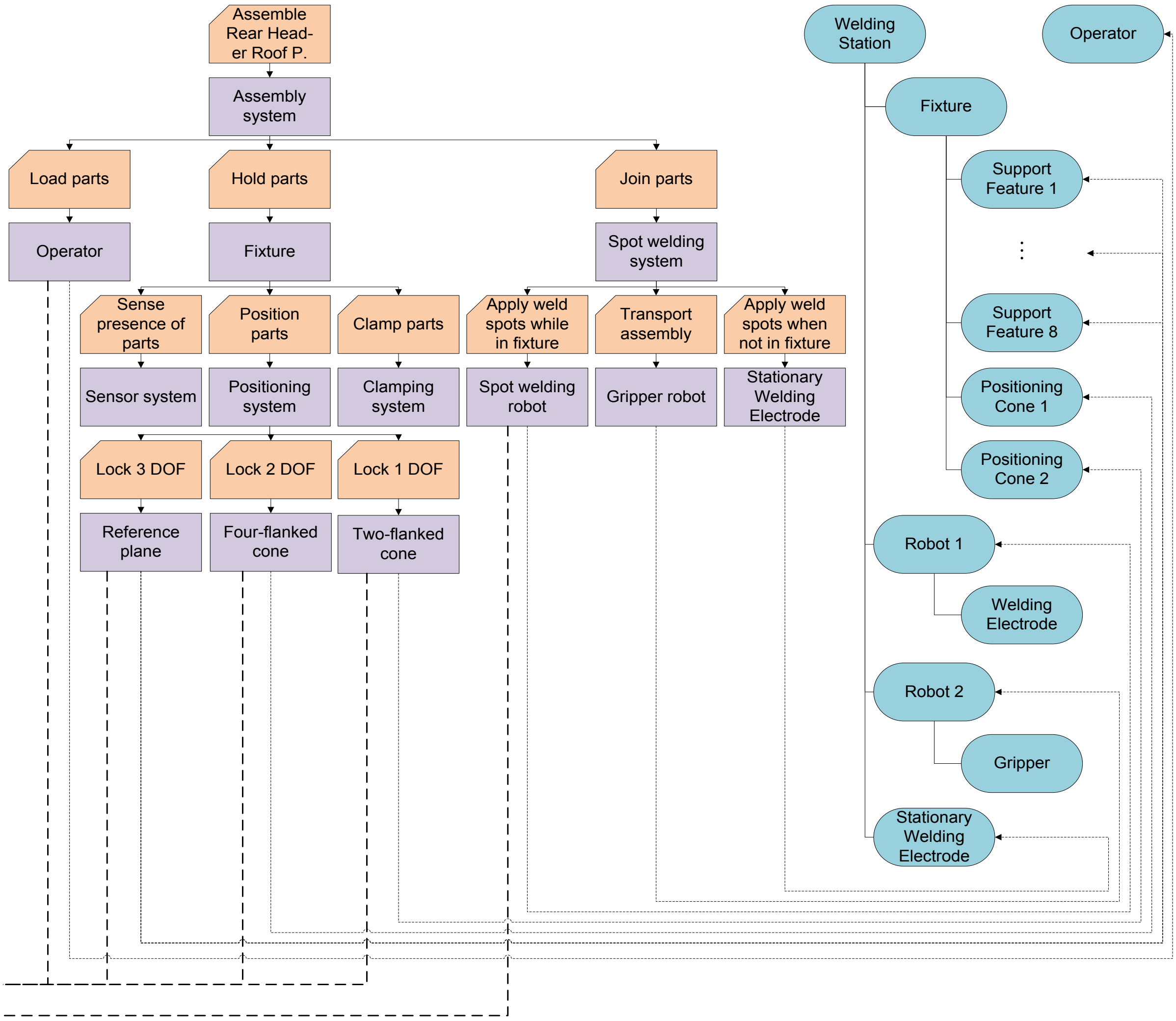


Figure 34. Welding Station described with function-means tree and component tree (Paper E).

4.5.2 Modeling the Architecture of Products and Manufacturing Systems

A component structure is introduced for both products and manufacturing systems. Components are assemblies and parts of products manufacturing systems, such as hydraulic cylinders and camshafts. On a higher level of manufacturing systems they include cells, stations, assembly lines, fixtures, and robots, for example.

Mapping the component structures to the function-means structures allows capturing the architecture of both systems. Specifically, it shows how the components realize individual design solutions, and thus by extension individual functions. The separation of the design solutions from physical parts follows the ideas Andreasen (1992) proposed in the Chromosome Model. Figure 34 illustrates the function-means tree and the component tree of the manufacturing system in the example. The example is based on the Rear Header Roof Beam and its manufacture introduced in Paper A and illustrated in Figure 23.

4.5.3 Reuse and Redesigning

The amended model also highlights that design solutions in the product provide functionality in the manufacturing lifecycle, rather than only in the product's use phase. A flange on a product component can allow the positioning in a fixture and also convey forces to adjacent components when the product is used, for example. A design engineer should not modify such a flange without consulting a manufacturing engineer. The FRs in the product's function-means tree represent thus functions needed in either of two lifecycle phases, manufacture and use.

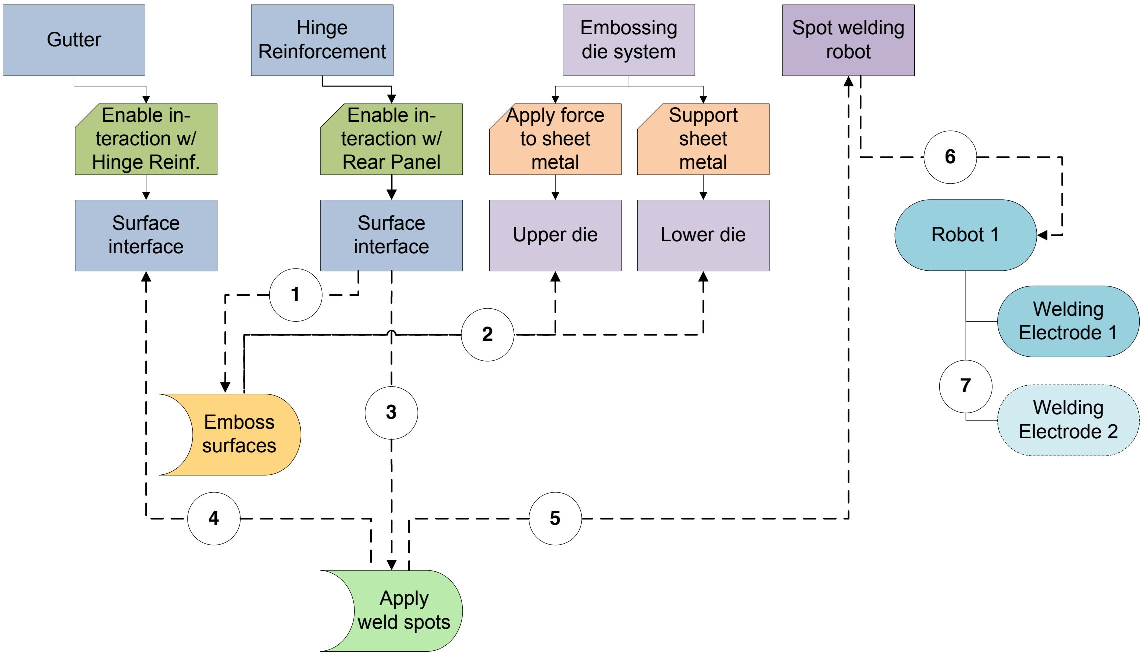


Figure 35. Example of a redesigning scenario traced in the model (Paper E).

Figure 35 illustrates an example of a change that influences the product, the manufacturing system and the manufacturing operations. With the model, the need for redesigning and possibilities for reuse upon the change can be evaluated. This constitutes an initial step before further analyses are carried out to develop and validate a customized solution.

4.6 Paper F – Application of the Integrated Model

Paper F reports an application study of the developed model. Specifically, it applies the preparation and use process developed in Paper D to the extended model proposed in Paper E. In short, the results are as follows:

- The paper presents an industrial example of a product platform and associated manufacturing system. With this material it illustrates how the extended model with operation elements can be used when an extension of the bandwidth is required.
- It further illustrates how a functionally integrated product platform can be modeled and possible derivative architectures represented.

4.6.1 Expanding the Bandwidth with the Extended Model

The product studied is a so-called Turbine Rear Structure, a static component located at the rear of jet engines. It has aerodynamic, load-carrying, and debris-containing functions. Different engine models require customized versions of this component. The customized components differ in essentially every surface and are highly adapted to

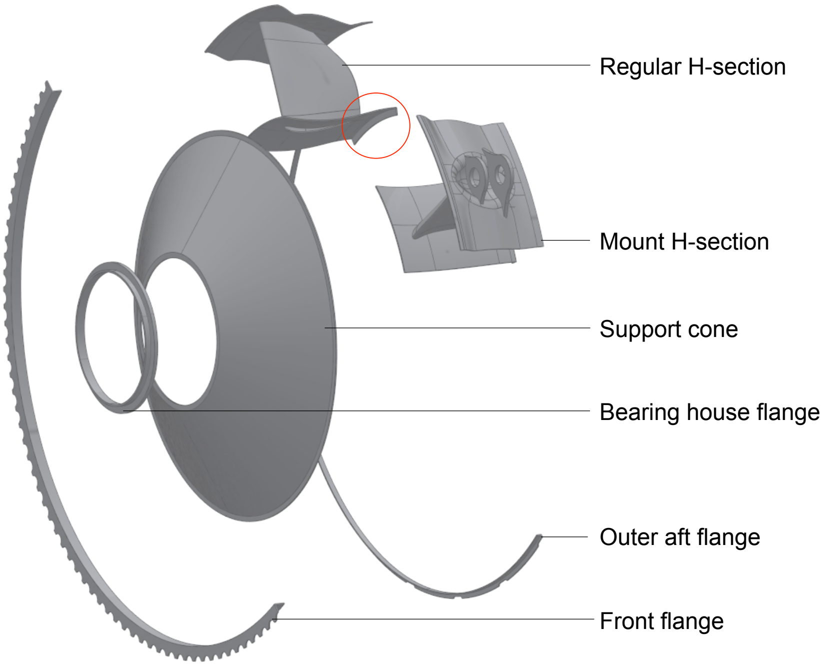


Figure 36. Example of a fabrication concept (Paper F).

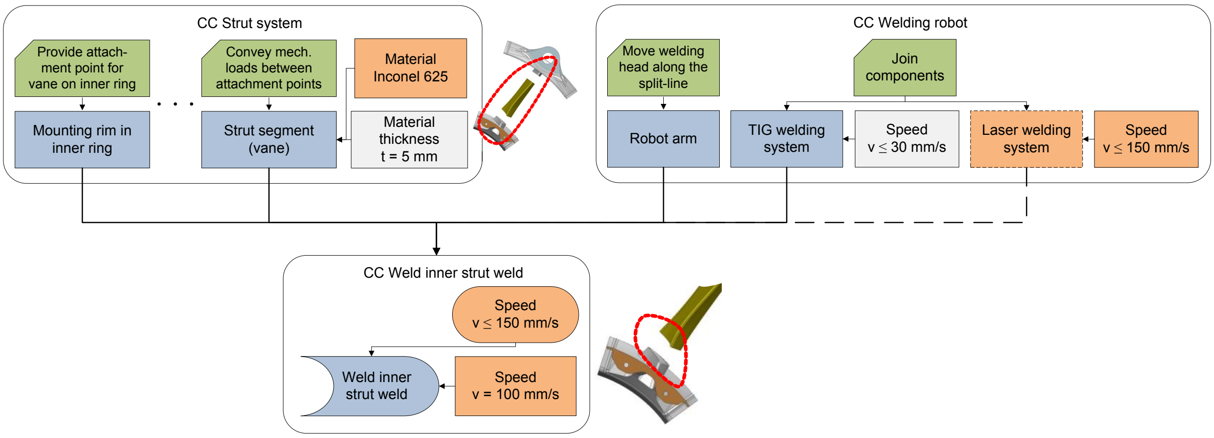


Figure 37. Extract of the Configurable Component model after bandwidth expansion (Paper F).

the individual requirements of the engine model at hand. However, they are manufactured according to a generic fabrication concept exemplified in Figure 36. It describes the ingoing parts that are joined by welding to yield the final component.

Despite the customization, the different variants share some general common design traits due to the common structure of commercial jet engines. The Configurable Component model of the product captures this generic structure. It is the same in all variants until a bandwidth expansion leads to extensive changes, such as new functional requirements.

Figure 37 shows an extract of the CC model after a bandwidth expansion. Rather than starting with a change to the product, a modified functional requirement in the manufacturing system initiates this expansion. Specifically, the welding speed is increased, which requires the implementation of a new welding technology and a material change in the product design.

4.6.2 Architecture of a Functionally Integrated Product

The customized variants differ in how the design solutions and thus their functions are realized by ingoing parts. In other words, they differ in architecture. The engine component is thus a functionally more integrated product that the ones studied in Papers D and E.

Figure 38 illustrates one conceivable architecture that can be configured based on the generic CC structure. It maps design solutions of the generic product platform (on the left) to elements of the part structure of a configured variant (on the right). The model captures two types of instances that are not one-to-one mappings between design solutions and components. These mappings lead to a functionally integrated product with a flexible architecture.

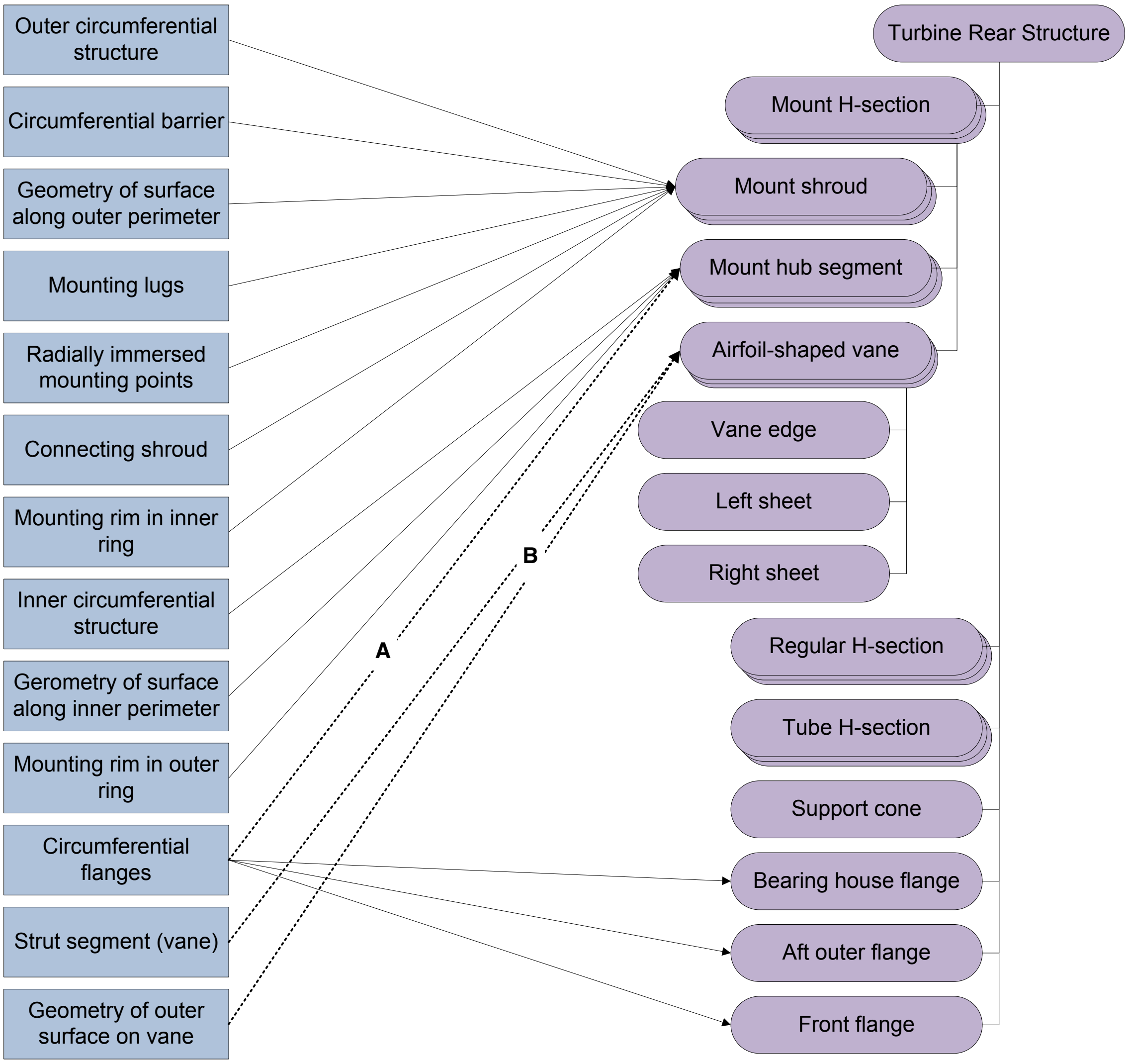


Figure 38. Mapping of design solutions (left) to component tree structure (right) representing one architecture of the integrated product platform (adapted from Paper F).

A *circumferential flange* can be realized by a dedicated ingoing part, such as the *front flange*. However, a flange can also be fabricated from several form features. Each of these features is included in a separate ingoing part, such as the *mount hub segment* as indicated by the *A* in the figure. In the concept illustrated in Figure 36, a fabricated flange is the *inner aft flange*. It does not constitute an ingoing part in the component structure and is thus not included in the component structure in Figure 38. Instead it is a form feature that evolves during the manufacture of the product.

Moreover, there are several instances of function sharing. Figure 38 indicates one of these by the dashed arrows marked with *B*. An airfoil-shaped vane realizes two different design solutions and thus solves two different functions.

These mappings are relevant for the understanding of the product and developing new solutions. Moreover, they show that the required performance and functionality of the product in use cannot be assigned to the ingoing parts. Instead, the design solutions can be connected to the FRs and Cs on the lower levels. If functional requirements for the manufacture are considered as well, the suitable manufacturing concept and part division can be determined. The emerging properties of the overall products are then subject to analysis of the synthesized concept.

The application study of this paper concludes the research results of this thesis. In the following, they are discussed to underline how they contribute to industrial practice and scientific research.

5 Discussion

Submitting the results to a critical evaluation, this chapter examines the extent to which the research questions could be answered and what remaining gaps can be identified. Moreover, the validity of the approach and the results are discussed.

5.1 Answers to the Research Questions

The results from the appended papers address the two questions formulated to drive the research. Research Question 1 is essentially aimed at increased understanding of the prerequisites for platform-based co-development while Research Question 2, at large, focuses on finding possible models for supporting co-development. The following discusses how far these two questions could be answered.

RQ1 How do the architecture and configurability of a manufacturing system affect the transition to platform-based co-development?

To answer this question, Papers B and C illustrate concepts that are relevant for describing *paradigms of co-development*. Through the analysis of the industrial examples, the presented work provides insights into steps companies can take toward *platform-based co-development*.

One of these steps is the introduction of a platform strategy for the manufacturing system. However, trade-offs exist related to the larger context of manufacturing as a whole. In other words, the decision of whether a manufacturing system should be modular or not cannot be made looking at the manufacturing system by itself, as stressed in Paper B.

Thus, although the illustrated paradigms for co-development help position individual examples they do not encompass all relevant factors in the scope of the entire operations of a manufacturing company. Instead, they focus on *architecture*, *configurability*, *interactions* between products and manufacturing systems and modeling of these aspects. This is in accordance with the scope of this thesis, which considers products and manufacturing systems as *technical systems*. The papers therefore do not address the business and engineering processes required for arriving at *platform-based co-development*.

Moreover, the models and theory developed capture the technical systems to a limited *level of detail*. In general, the function-means formalism as applied in Paper B can be used to elaborate the systems further. However, the elaboration of systems and functions has not been driven longer than presented. It is conceivable that a more complex network of interactions evolves from a deeper analysis, which in turn allows other conclusions about the manufacturing system's architecture and configurability. On reflection, the *suitable granularity* in the model should be determined for each individual industry case.

In summary, the research question can be answered with the limitations outlined above. The modular *architecture* and the *configurability* of a manufacturing system can be enablers for platform-based co-development. Their applicability and possible intermediate steps must be considered in an overall business context for platform approaches.

RQ2 How can products and manufacturing systems be represented in an integrated model to support platform-based co-development?

Paper A answers this question in part by proposing to model dependencies by means of *interface* and *interaction*. While the notion is adopted that a mutual effect exists between systems, the idea of interaction is defined more generally here than in the Theory of Technical Systems (Hubka and Eder, 1988). Rather than classifying systems into operand and operator, it is emphasized that systems affect each other regardless of this classification. An interaction is thus modeled more implicitly than the *secondary outputs* proposed as part of a transformation system by Hubka and Eder (1992).

Papers D, E, and, F show some of the benefits of this explicit modeling of the interactions. *Function sharing* across *domains* and *lifecycles* can be identified, and this provides a more comprehensive picture of the interdependencies between the product and the manufacturing system.

Moreover, the *flow-based* view on manufacturing systems is relevant for *understanding* the way they work and to model precedence, for example. Thus, it is not surprising that manufacturing system platforms are expressed in terms of *processes* as presented in Section 2.5.5. However, Paper A does not clarify how state models inside a Configurable Component map to the other modeling elements, such as design solutions and functional requirements. In contrast, the operation element introduced in Paper E and its mapping to design solution are elaborated more clearly.

Allowing a predominantly *state-based* representation of functionality, such as the FRs in the function-means model, in parallel to the *flow-based* description of functionality of the manufacturing operations leads to certain redundancy in the models. That is because not all FRs in the function-means models of the manufacturing systems are *state-based*. Instead, some of them are essentially required transformation functions. Consequently, a clear-cut differentiation with the respective operation is challenging.

That is particularly the case because users of such a model might not be aware of possible variance in the notion of *function* that can be identified as shown by Eckert *et al.* (2011). This can be compared to the difficulties of distinguishing functional requirements and non-functional constraints, which could be observed in the study of Paper E. Here, engineers from the company identified *stiffness* as an FR of the product at the highest level rather than a constraint that leads to FRs further down in the function-means structure, for example. The question of whether these distinctions matter to the applicability of the models was not expounded, but should be considered in future research studies.

Moreover, the distinction between a form feature as an element of the component structure and a design solution is not clarified in Paper E. Instead, in the example of the Rear Header Roof Panel, the design solutions on the lowest level of the function-means structure are essentially form features. In contrast, in the model of the engine component in Paper F this distinction is underlined by the mapping in Figure 38.

On reflection, the distinction may be more valuable for redesigning functionally integrated products where the mapping between functions and parts is not a straightforward one. Moreover, it allows separating how functions are solved in principle and the embodiment design of an explicit instance derived from a product platform.

As stressed in the papers, the deriving of such an instance from the platform is preferably done through configuration. However, configuration requires an information-rich model with parameterized modeling elements to automate synthesis and analysis of possible candidates. The papers that address this research question show configuration in principle only and not as an automated process. Instead, they focus on supporting co-development by providing support for design work. This brings the modeling approaches in this thesis closer to engineering change management as presented in Section 2.5.7.

In summary, the here presented research presents one possible approach to an integrated model of products and manufacturing systems. It answers the research question with the limitations and possibilities for platform-based co-development discussed above.

5.2 Evaluation of the Research Approach

Research Question 2 evolved from earlier work on platform-based development in conjunction with the opportunities identified in Section 2.6. It is the question that drove the research from the start of the project. In contrast, Research Question 1 was added later as the result of two causes. First, while earlier research had thoroughly investigated product modeling, the nature of change and variation in manufacturing systems needed further study. This became evident as the research progressed. Second, the opportunity to study a reconfigurable manufacturing cell presented itself and was thus not planned from the beginning.

A rigidly planned approach to the research would have possibly prevented the project from including and then addressing RQ1. Nevertheless, a more planned and focused research could have secured a more systematic evaluation of the models proposed, for example with a concluding *Descriptive Study II* as prescribed by Blessing and Chakrabarti (2009). Such a study could have corroborated whether the modeling approaches as proposed in fact improve designing.

However, it would have required design engineers and manufacturing engineers to adopt the approach by first preparing a platform model and then testing it in a subsequent development project. Instead, as an intermediate step to validation, Paper F applied the model to a product and manufacturing system different from Paper E. The goal was to test the transferability of the approach to a different product and manufacturing system.

The ambition of the research was to give products and manufacturing systems equal attention and to thus facilitate co-development that may also be driven by the development of the manufacturing system. However, the industrial cases reflect a predominance of product-driven development. As an exception, the study of paper B observed a manufacturing system in the focus of development. In Paper F, the manufacturing concepts aim to some extent at setting a scope for what change and variety is allowed in the product. Nevertheless, a description of the manufacturing system is not part of the concepts. On reflection, a larger number of industrial examples could have been observed with more emphasis on the manufacturing system.

Further, the mode of manufacturing in the studied examples consists primarily of metal forming, machining and weld assembly. Thus, additional studies could have observed a greater variety of manufacturing settings with respect to manufacturing technologies.

However, the papers present studies on make-to-order (Papers A, B, C, and E) and engineer-to-order (Papers C, D, and F) and thus address different settings for development and manufacturing.

In addition to the available studies, the underlying theory has a strong effect on the approach in this thesis. That is because the theories that were considered and introduced in Chapter 2 provide a framework that, by nature, limits the conceptual and theoretical resources that this work resorted to. The research followed the ambition of adapting the existing theory and concepts when possible, for example, to avoid merely renaming already observed phenomena. Nevertheless, it did in fact introduce a limited number of terms, such as *platform-based co-development.* Still, with respect to the modeling elements in the integrated model it adheres to existing concepts. These are adopted but also put into perspective, such as *function sharing* across domains and lifecycles.

5.3 Evaluation of the Results

Maxwell (2005) stresses that, for ensuring the quality of their work, researchers need to be aware of their effect on the individuals studied, an effect known as *reactivity*. The primary objects of study observed here are technical systems, and the attitudes and mindsets of researchers do not affect these. Thus, the data collected directly on these artifacts as objects of study are not affected by reactivity. However, they are analyzed and here presented from the viewpoint described in the first chapters.

Further, the research activities may have had an effect over time on the organizations studied. As part of long-term collaboration between the companies and the research group, in which this research was conducted, they may have contributed to reactivity on the engineers involved. During the last study, engineers at the company were internally attempting to model their products with Configurable Components, for example. They thus adopted ideas and concepts introduced by the researchers in their work, such as functions, design solutions and constraints as framed by research. Therefore, the study at the company may provide a slanted image of industrial practice that does not reflect other companies. However, it also indicates that the research has had an effect on industry.

Apart from addressing questions of reactivity, the following discusses the proposed theory and modeling approaches based on the criteria proposed by Buur (1990) introduced in Section 3.4. Specifically, the criteria are applied here as indicators of validity of the results.

Assessing the *consistency of the theory*, no internal conflicts emerged between its individual elements. Moreover, the results presented above do not violate the underlying assumptions made in this research (see Section 1.3). The assumptions are formulated relatively broadly, and it was not the goal of this research to verify or falsify them.

Reflecting upon the discussion in the previous sections, two reservations must be considered regarding the *completeness* of the approach. First, the scope of the thesis is limited to modeling technical systems, and there are other relevant phenomena in the topic of platform approaches that are not addressed here because of this scope limitation. Second, automatable configuration mechanisms are not explicitly included in the models. However, related works show that configuration can be accomplished in similar models (Edholm *et al.*, 2010; Levandowski *et al.*, 2013). They indicate that configuration is conceivable in the models proposed in this thesis.

Despite these limitations, the proposed modeling approaches are in *agreement with theory*. In Paper A, the approach is consistent with the Configurable Component framework and its underpinnings. The modeling approach in Paper B is, in essence, an application of function-means modeling and is coherent with the original scheme of modeling functions and the means that fulfill them. Likewise, the function-means trees in the models of Papers D, E, and F are consistent with the modeling formalism. Adding component structures, as done in Papers E and F, is consistent with the Chromosome Model.

The operation element that is introduced in Paper E does not directly reflect earlier modeling in the way it connects to other elements. However, it is generally agreed that the manufacturing processes link the design of the product with the manufacturing system (Scallan, 2003; ElMaraghy, 2009). Further, connecting operations in a wider sense to modeling elements of product is for example proposed in Axiomatic Design (Suh, 1990). Thus, the mapping of the operations to design solutions presented here is consistent with the general idea of modeling technical systems.

The *cases* from the studies that contributed to the papers and allowed collecting empirical data are relevant for the presented research. With the limitations mentioned above, the products and manufacturing systems in them can be modeled to bring to light architecture, dependencies, and the rationale of their designs expressed as functions and design solutions.

The cases can be regarded as generic for automated manufacturing cells with operator involvement, such as loading and human process supervision. Moreover, as mentioned above, they study primarily the manufacturing technologies metal forming, machining, and weld assembly. The question of how far the results drawn from these examples are generalizable to other manufacturing systems that apply other technologies must be elaborated on further.

Statements about the *acceptance* of the results from engineers outside academia can be made to a limited extend. With respect to function-means models in Paper C, engineers that participated in the development of the modular manufacturing cell indicated their agreement with the interpretations and the modeling approach.

In the study of Paper F, the company had started their own test modeling of the products with Configurable Components. The engineers who worked on this project agreed with the model presented in the paper, but also pointed out that the product could have been modeled differently using the same modeling approach. This is not surprising, as the modeling of the notional world of functionality is an open task that has multiple conceivable solutions.

Further, engineers from different company-internal backgrounds who were not involved in modeling evaluated the approach differently. Some noted that the models did not capture all the information they deemed relevant, for example a rationale for either buying ingoing parts or manufacturing them in-house. In contrast, others expressed their agreement with the functions and solutions as they were expressed to form a design rationale in the model.

Reflecting on these points, the criteria proposed by Buur (1990) are generally met by the work presented here. However, following the mindset expressed in this thesis, this does not allow deducing the validity of the results. Consequently, individual practitioners, from academia or industry, still need to evaluate for themselves whether the proposed models and theory have a bearing on their challenges and thus can be applied.

6 Conclusions and Future Work

Given the results and their quality as discussed above, a number of conclusions can be drawn. They are presented in this chapter, together with general implications and an outlook on future work.

6.1 Conclusions

Considering the results presented and discussed above, the following conclusions are drawn from the work presented in this thesis:

- The thesis shows that the seamless co-development of products and manufacturing systems remains a challenge despite considerable research and industrial efforts directed toward increased integration. While available modeling solutions include some manufacturing aspects seen from the product's perspective, they do not include the manufacturing system as an artifact to be designed beyond the manufacturing processes. Thus, they fall short of capturing the mutual effects that products and manufacturing systems have on each other.
- The concepts of architecture and configurability are identified as interesting for reusing and redesigning manufacturing systems as well as formulating platform strategies. The thesis here corroborates earlier research on reconfigurable manufacturing systems. Making a welding cell modular renders it suitable for repeated use despite frequent changes in the product design, for example. Consequently, the thesis emphasizes that the architecture and configurability of a manufacturing system need to be considered when a company undertakes platform-based co-development.
- For this purpose, the thesis illustrates how architecture and configurability can be represented in product models and manufacturing system models that

combine function-means trees with component structures. It provides several examples based on industry studies. The evolving models enable platform approaches that are not based on the reuse of physical components only. Rather, they also consider generic resources in the platform, such as solutions in principle that are used across several models or reused over time.

- A prescriptive contribution of this thesis is an integrated model that combines function-means trees, component structures, manufacturing operations, and their interactions. Examples show that using the model helps understand the mutual effect between products and manufacturing systems. For instance, it elucidates the required functions that a product solves together with the manufacturing system during manufacture rather than by itself in its use phase.
- The model allows defining platforms that can be expanded over time and used continually to derive product and manufacturing system designs. Specifically, it can facilitate reuse and redesigning and support the systematic expansion of design bandwidths. Thus, it helps manage change and variety in products and manufacturing systems.

6.2 Future Work

Reflecting on the results and conclusions, several gaps remain that provide opportunities for future research. These research efforts should be directed at the following points:

- Future research should study a larger variety of manufacturing settings and include additional manufacturing technologies. It should be pursued with the ambition of gaining increased understanding of the transferability of the models and theory presented here to different manufacturing companies.
- In additional studies, the emphasis should be put on the manufacturing system with its development and configuration processes. This should be done to further understand the needs of manufacturing engineers, in general, and designers of manufacturing systems, in particular, to realize platform-based co-development.
- Moreover, such studies should be conducted to further expound the question of how an integrated platform model can be used for automated configuration and support design work alike.
- With the understanding gained from these activities the model can be refined or expanded to include additional relevant information. Furthermore, methods for using the model in different modes can be devised. Ultimately, this should aim at decreasing the gap that needs to be bridged for achieving industrial implementation.

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